Response to Referee Comment #1 on

Characterization of dark current signal measurements of the ACCDs used on-board the Aeolus satellite

The authors thank reviewer #1 for carefully reading the first author's response. In the following, referee comments are repeated in green and answers by the authors are provided directly below in black.

General comments:

This is a second review. In general, I'm satisfied with the answers and I think that the article can be published with minor corrections indicated below. However, I'd like to address the questions of the authors they posed in the reply regarding the test I made to show that the retrieval procedure could define the peak position on the ACCD with a sufficient accuracy even if the hot pixel information were not used at all.

The authors write "*The figure does not consider the full Mie fringe shape which is spread over all 16 ACCD pixels – even at the edges of the ACCD the values do not approach zero. For simulation studies, this could be approximated with an Airy function*." As for the fringe shape spread over all 16 ACCD pixels, the previous simulation used a Gaussian which was also spread over all pixels. The halfwidth of this Gaussian was selected in such a way that the shades of grey in Fig. 1b of (doi:10.5194/amt-2020-458-RC1) resembled those of Fig.1 of the manuscript. For the second exercise shown below (Fig. 1), I took an Airy function and compared the results with Gaussian. One has to note that in general the sliding profile approach is not sensitive to the shape of the function as long as the function varies at the considered interval and its shape is known with high accuracy.

Then, the authors write that "*On top of that, also the spectrally broad bandwidth Rayleigh signal and the solar background are part of the Mie signal*." The broad features and constant offsets do not affect the peak position retrieval accuracy if the sliding profile approach is used.

The next comment is important, though: "*Apart from that, it is not clear which values for the atmospheric signal levels and hot pixel amplitudes were used in your simulation. Typical values for the Mie channel are 15 LSB and 5 LSB (both measurement level) for the atmospheric signal level and the hot pixel offset, respectively*". Indeed, the discretization is important and in the previous exercise this was not taken into account properly, I apologize for overlooking it. If one assumes that the peak value of Mie detector is 15 LSB, then the absolute errors of peak position retrieval in units of ACCD detector row change from ~1.5e-3 to ~1e-1 that corresponds to ~2 m/s (Fig. 1). This is somewhat smaller than the random errors reported for Aeolus wind product, and the comparability of the profiles retrieved for a "healthy" detector with those retrieved from the simulations with hot pixels excluded tells us that the approach of skipping the hot pixels proposed in the first review is still valid. I do not require to include more discussion on this topic than what is already included in the present version of the manuscript (lines 441-444), it's just to draw an attention to this technique that works surprisingly well for different physical phenomena.

Response to General Comments:

Thank you very much for your comments. It is highly appreciated that you addressed our points on your simulation study to mitigate hot pixel effects in the Mie channel and even extended it. Looking at your Fig.1, the comparability of the curves, especially for the Airy function with and w/o hot pixels, indeed looks very convincing. It seems to us that the sliding profile approach might be worth to be considered for future studies to improve the wind retrieval of the Mie channel.

Specific comments:

Lines 98-103: new text states that the read-out noise values were determined during pre-launch tests and then the discussion is based on this value measured on the ground. I understand that normally the noise of the amplifier should not change, but are there any estimates for an onboard read-out noise?

The determination of the total read-out noise requires special test modes which cannot be performed in space due to technical limitations. As a result, only numbers for the total read-out noise based on pre-launch tests are available. However, it is expected that these numbers have not changed significantly in-orbit. Specific measurements for the total noise (read-out noise + dark current noise) could be performed during periods with no laser operation, but are still under evaluation. We have no indications of enhanced noise sources for the detector.

The manuscript was changed as follows:

> available avalanche photodiodes or photomultipliers. In the case of Aeolus, special CCDs are used, so-called accumulation CCDs. This allows the accumulation of backscatter atmospheric signals for consecutive laser pulses already on the chip in a dedicated memory zone to reduce the impact of read-out noise. The total read-out noise was determined during pre-launch tests to be in the range between 3.9 e- and 4.7 e- root-mean-square (rms) error around a zero mean (Reitebuch et al., 2018). Note that the determination of the total read-out noise requires special test modes which cannot be performed in space due to technical limitations. However, there are no indications that the total read-out noise has significantly changed in-orbit.

Lines 197: I would specify the actual numbers for the proton fluxes

Information about the proton energy and fluence levels were added to the manuscript.

vacancy-interstitial pairs. Most of the pairs recombine but some of them may form stable displacement damages in the lattice. Displacement damage can lead to a degradation of the CTE and an increase of the dark current. So-called "hot pixels", pixels with enhanced dark current signals over a longer period of time, may evolve. In addition, displacement damage may also introduce burst noise, e.g. Random Telegraph Signals (RTS)-noise. RTS noise causes the dark current to change its state between two or more discrete levels at random and unpredictable times (Hopkins and Hopkinson, 1993; Smith et al., 2004). Hot pixels in combination with RTS phenomena were also observed for the CCD detectors of the Global Ozone Monitoring by Occultation of Stars (GOMOS) instrument on-board ENVISAT (Keckhut et al., 2010). In the framework of the Aeolus ACCDs development, proton tests (even at higher radiation doses as seen in-orbit) at different energy and fluence levels (for 30 MeV: $2 \cdot 10^9$ protons/cm², $1.35 \cdot 10^9$ protons/cm²; for 100 MeV: $4.2 \cdot 10^9$ protons/cm², $2.7 \cdot 10^9$ protons/cm²) have been performed to evaluate the probability of occurrence of such hot pixels and RTS pixels at an operating temperature of -30 °C showing the presence of one-post irradiation RTS pixel. However, it has to be noted that the operation mode with regard to the timing settings during the tests was not fully comparable with the settings used in-orbit. Moreover, the dark signal acquisition and the applied post-processing sensitivity was not optimized to detect low frequency and low amplitude dark signal variations as observed in space. Transient radiation effects occur due to ionization-induced generation of charges within the CCDs and do not cause lasting damage. However, these effects might be visible as spurious signal spikes on one or more pixels and thus,

Lines 199-200: what exactly was different and how this should affect the results?

The dark signal acquisition during the test was not optimized to track the same low frequency dark signal variations as observed in-space (only 512 observations were acquired). In addition, a different timing diagram compared to in-orbit was applied to operate the ACCD. This had the effect that the residence time of the charges in the memory zone was different. Finally, the applied post-processing sensitivity algorithm was not good enough to detect dark signal anomalies with amplitudes as low as observed in-orbit. All these points limit the significance of the tests when discussing in-orbit dark signal anomalies. This information was added to the text (see screenshot above).

Lines 301-303: "a more sophisticated" and "a simple 3-sigma" look strange in one sentence.

You are right. The sentence was rephrased as follows:

The motivation for a detailed characterization of permanent dark current anomalies is twofold: a) it supports investigations for the underlying root causes of the hot pixel issue and b) the number and magnitude of dark signal shifts define the impact on the wind observations and the DUDE correction. In order to fulfill b) it is not only necessary to differentiate between normal and hot pixels but also to exactly characterize hot pixels~~a more sophisticated algorithm such as a simple 3-sigma test, which can differentiate between normal and hot pixels, is necessary~~. The presented algorithm is ~~also~~ capable of detecting temporal

Lines 441-444: "each pixel indispensable in the wind retrieval". This is strange. Even though the authors use a different approach than the one used in my exercises, the information content of the whole row is still large, and the absence of a single pixel should not dramatically change the picture. One can carry out a simple "Gedankenexperiment", which usually is proven in real life with the real data. Imagine that a human eye observes a continuous function, or a continuous shape, or a graphic pattern. Next, let's imagine that a small patch covering 5% of the image is applied. No doubt that the brain will recover the original shape from this picture, especially if the shape is known. Of course, the bigger the patch, the poorer the accuracy, but for the objects like those shown in Fig. 1 of the manuscript a loss of up to 10% of information should not be critical. If so, the programming algorithm should exist which mimics the brain's algorithms and recovers the shape. The realization depends on the task, but the general idea should be clear. I believe that it can be realized in the framework of the authors' method, too. In *any case, since the "hot" pixels are not completely erroneous, the authors' approach works, and this itself is a good achievement.*

It is important to mention the information content of each pixel strongly depends on the pixel position w.r.t to the ACCD column. For the Mie channel the key information is contained in the three to four central ACCD pixels covering the fringe. For the Rayleigh channel the pixels covered by the two Rayleigh spots pixels (three to four pixels for each spot) are important for the wind retrieval. To be able to omit hot pixels from the wind retrieval, one must know the model function at a very high accuracy. Here, also the high sensitivity of the measured wind speed towards change in the response of the instrument comes into play (Mie: 1 pixel → 17.7 m/s LOS). So, errors in the model function have large impact on the error of the wind retrieval. But, as mentioned in the manuscript, the hot pixels still contain information which can be used in the wind retrieval in combination with regular dark signal calibration measurements.

Lines 497-501: In general, the operational retrieval should not exclude the post-processing, during which the data quality might be improved. At this stage, one can impose different physical constraints and analyse/correct the retrieved data using ancillary information. Even in the current setup we observed an evolution of the products associated with the corrections introduced after validation.

As mentioned in the text, the NRT processing chain is setup in way that it is strictly sequential which implies that for instance no wind-speed information from the L2B products can be used in the dark signal correction that is part of the L1B processor. To make this possible a complete re-design of NRT processing chain would be required which is not possible due to timeliness requirements of the wind products and operational constraints. For the reprocessing, we approach the methodology proposed by the reviewer and use ancillary information. Here, the flexibility is higher and information about wind errors can be used to analyse and further mitigate dark signal anomalies. It is planned to summarize product improvements achieved in the reprocessing in a dedicated manuscript in the future.

Line 787: It is not clear whether the on-ground tests will reveal the root cause of the hot pixel issue. The problem was not revealed during the pre-flight tests, so it would be good to know what changes are planned in the new experimental setup compared to the previous one.

We assume that your comment is related to line 777 and not line 787. It is true that previous on-ground tests did not reveal the problem. However, the performed on-ground tests were not designed in a way to allow to distinguish between radiation-induced and CIC hot pixels. As mentioned in the discussion of the manuscript, on-ground sensitivity tests with identical ACCDs where the operating temperatures and clocking parameters of the ACCD are varied would be needed. However, for safety reasons such tests cannot be performed in-orbit. Moreover, setting up such a campaign is not straightforward as no spare ACCD of the same batch as the in-orbit one is available. But, it is expected that the knowledge gained from this detailed in-orbit dark signal investigations will help to improve on-ground testing CCD testing campaigns of future space missions such as Aeolus follow-on.

Line 157, Table 3, last two lines: I would rewrite it as (a÷b) e- rms or (a±Δ) e- rms

Thank you very much for the suggestions but e authors decided not to change the format of the noise specifications in Table 1 of the manuscript.

Lines 805, 809, 817, and 819: italicized fonts look strange in some of PDF viewers

The italicized font as headers for these paragraphs is part the AMT Word template and thus, should not be changed.

Response to Referee Comment #3 on

Characterization of dark current signal measurements of the ACCDs used on-board the Aeolus satellite

The authors thank reviewer #3 for carefully reading the manuscript and providing useful comments. Although it is the second review iteration, the reviewer came up with a lot of new points. Nevertheless, the authors tried their best to capture the comments as best as possible in the revised version of the manuscript. However, it also has to be considered that the focus of the manuscript is not solely on the technical aspects of the hot pixel generation but also on the effects on the quality of the measured winds. In the following, referee comments are repeated in green and answers by the authors are provided directly below in black.

General comments:

As well described in the paper, the working principle of ACCD implies the accumulation of collected charges into a given column of pixels into a transfer row. The charge transfer in the memory zone follows.

1/ Does the charge transfer occur from the transfer row to the range gate #1 before being transfer from #1 to #2 until #25 or does the first transfer row is stored in range gate #25? This question points out the CTI issue in the memory zone that could be impacted by the radiations. Depending on the operation mode, DCNU could reveal the worst degradation for memory gates resulting from several transfers. Moreover, it appears that the charge retention time varies from a range gate to another. Has the range gate DCNU been investigated by looking at the dark signal with no transfer from the CCD?

2/ The author also well described that the memory zone plays a role in the global dark current. I agree with this statement, which is explained in the paper by the generation centres into the storage structure. However, regarding the charge retention time (i.e. depending on the range position) which can reach 0.4s, it appears that the leakage current from these storage nodes can impact the global dark current signal. The authors are invited to give their analysis regarding this leakage which could lead to a loss of collected charges and therefore implying a decrease of the signal and even partially compensate for the dark current increase from the CCD. As a complex structure, the quantification of such DC sources is not required. However, the paper could include a detailed description of the dark current sources in the ACCD to provide a better overview of the underlying mechanisms.

Response to General Comments:

1)

The charge for each range gate is binned into one row of the memory transfer section then moved down the memory transfer section followed by the binned charge from the next range gate until all the range gate signals have been captured. When the memory transfer section is filled with signals from this first laser pulse the set of charges are transferred sideways into the corresponding pixels of the memory storage section. This process is repeated until signals from typically 20 laser pulses have been captured. The accumulated signal is then read out. Please note that Fig.1 (left) of the manuscript is a simplified sketch which only shows the 16 storage rows of the memory zone. The charge retention time is therefore essentially the same for all range gates at approximately 20x the laser pulse period. As a result, no range gate dependent features of the DCNU were observed. Uniformity of dark signal in various operating modes was investigated in pre-flight testing but the instrument does not have the flexibility to do this in flight.

2)

As explained above the charge retention time is not a strong function of the range gate number but is essentially the same for all range gates. The total duration of the acquisition of echoes for each pulse is much less than the pulse repetition period and signals from typically 20 pulses are added.

A leakage mechanism leading to loss of charge stored in a CCD pixel is not often considered and the analysis of this effect is certainly beyond the scope of this paper. Here, we only want to state the several on-ground tests were performed to assess the “accumulation efficiency” of the Aeolus ACCDs. During these tests the signal level at the CCD output are compared when charge generated by several LED pulsed was accumulated by two different methods. The first was a simple integration of 50 pulses in the image section followed by a standard readout. The second was transfer of the signal from each of 50 identical LED pulses individually to the memory storage section for accumulation; with readout of this accumulated signal. The signal level from a large number of exposures was averaged in this test which was performed at three different accumulated signal levels of 1k 10k and 100k electrons per pixel. It is believed that the lack of a difference between the signal levels obtained in these two modes provides some evidence that we did not have any significant recombination when accumulating charge in the memory section but it is not fully conclusive.

Specific comments:

Lines 101-105: This part could include the CVF to account for the number of collected charges. It is specified later. Retention time might be more appropriate rather than residence time. I agree with the statement that the noise is dominated by the read-out noise. The authors are invited to specified “before the mission” or “before radiation exposition”.

To be consistent with the noise estimation, the mean dark signal is now also expressed in e-/s. The authors do not see a problem using residence time to describe the amount of time of charges in the memory zone.

Note that the determination of the total read-out noise requires special test modes which cannot be performed in space due to technical limitations. However, there are no indications that the total read-out noise has significantly changed in-orbit. Considering the PRF of 50.5 Hz, ~~and~~ 19 pulses per measurements and conversion factors for the Mie and Rayleigh channel of 0.68 LSB/e- and 0.44 LSB/e-, the in-orbit dark current signal rates are 0.55 e-/s – 0.72 e-/s~~0.49 LSB/s and 0.24 LSB/s for the Mie and Rayleigh channel~~. Given the Poisson distribution of the dark charges these values correspond to 0.75 e- – 0.86 e- rms dark current noise for a residence time of the signals in the ACCD of one measurement which is 0.376 s. Thus, it becomes

Lines 105-110: Is this ACCD from Teledyne a COTS or a custom design? Can the reference of this ACCD be specified here? The number of lost charges (CTI) depends on the collected charges. The authors are invited to specify "at the typical integration time" or "based on typical operation".

The CCD is designated CCD69 and is a custom design for Airbus D&S and ESA. There is no intent to make it commercially available. Charge transfer inefficiency results in charge being delayed from the correct pixel and read out in the corresponding following pixel of the row or column. Detailed measurements of any charge loss were performed at a range of signal levels by Teledyne –e2v before delivery of the devices to Airbus.

The manuscript was changed as follows:

> Two ACCDs manufactured by Teledyne e2V and customly designed for the ALADIN instrument are used to detect the signals in both channels. Table 1 lists the main specifications of the Aeolus ACCDs. Each ACCD is a thinned back-illuminated silicon CCD and is mounted in a thermo-controlled housing with a 45 mm x 25 mm sized window (see Fig. 1, right). The ACCDs provide a high quantum efficiency of about 85 % optimized at a wavelength of 355 nm and a Charge Transfer Efficiency (CTE) based on typical operation of 99.99 %, meaning that only $1 \cdot 10^{-4}$ of all charges are lost per transfer of one row. The

Lines 110-115: The authors are invited to compare the pixel pitch to the required fringes resolution. Does smaller pixel pitch could work and what could be the limit (Full Well Capacity and/or sensitivity). Charge accumulation can be preferred to signal accumulation.

Analysis regarding the trade-off between pixel size and the full well capacity were performed during pre-launch tests. However, the description of the outcome of these tests is considered to be beyond the scope of this paper.

Lines 115-120: The authors are invited to specify the operating mode of the CCD (rolling shutter) as well as how the memory zone is operated from a frame to another. Moreover, it looks like the limiting parameter in this application is the ADC frequency which implies storing several columns of accumulated frames in a memory zone. A brief description of this part would be appreciated.

The operation mode of the CCD is described in the comments above and is also explained in the manuscript. The description of the operation mode in the manuscript was slightly extended to improve the understanding of the CCD (see screenshot below). However, it should be noted that the operation mode is not a conventional rolling shutter. Moreover, it is not the ADC performance which limits the pixel readout rate but the increase in the readout noise of the CCD output circuit with frequency and therefore bandwidth (Janesick, 2001).

It illustrates how the two circular Rayleigh spots from the FPI and the Mie fringe from the FIZ are imaged on the ACCDs imaging zone. In the imaging zone the atmospheric return signal is integrated over time based on the settings for the vertical range gate timings. In Aeolus operations the range gate timings can be varied from 2.1 µs to 16.8 µs which correspond to a vertical sampling of 250 m to 2000 m, respectively, considering the 35° off-nadir viewing angle of the instrument. Subsequently~~,~~ the ~~signals~~ charges of the imaging zone are pushed downwards, ~~and~~ accumulated in the transfer row and then moved down into the transfer columns of the memory zone followed by the charges from the next range gate. The image zone is completely shifted within 1.0 µs. ~~Afterwards, the signals are moved in the transfer columns where~~In the memory zone of the ACCD each of the 25 rows corresponds to one vertical range gate of the atmospheric profile. Once the signals of all range gates are acquired in the transfer section of the memory zone, the ~~signals~~ charges are horizontally shifted from the transfer columns into corresponding pixels of ~~to~~ the storage columns of the memory zone. This concept allows on-chip signal accumulation over multiple successive atmospheric returns to the so-called "measurement" level. The number of accumulated pulses can be varied between 1 and 50. For the herein analyzed dark current measurements the number of pulses was 19 until

Jan 2019 and then 18 to avoid a potential conflict in the onboard data management. The resulting residence time of the signals in the memory zone is on the order of 0.4 s, considering the PRF. After each accumulation sequence, the charges of the memory zone are read-out via the read-out register at a very low frequency of 48 kHz to minimize read-out noise and are further transferred to the Detection Electronics Unit (DEU) (Reitebuch et al., 2018). Here, the accumulated charges are digitized with 16-bit accuracy and converted into units of Least Significant Bits (LSB). The conversion rate of this process, also called radiometric gain, is about 0.68 LSB/e- and 0.44 LSB/e- for the Mie and Rayleigh channel, respectively.

Lines 135-140: Do the virtual pixels allow to monitor the applied offset?

ALADIN uses two "overscan" pixels, which are generated at the end of each row by applying more clock pulses to the register than the total number of physical register pixels, to monitor the so-called Detection Chain Offset (DCO). These pixels provide a nominally zero charge reference level which can be used to adjust the working point of the ADC to ensure that even in the presence of random noise no negative values are output.

Lines 145-150: What limits the size of the memory zone? Does a direct quantification of the transfer row possible? The authors are invited to specify the link with the readout circuit.

The size of the memory zone was defined on the basis of the vertical spatial resolution required for the instrument. 25 rows give 25 range bins within the atmosphere. An increase in the number of range bins is being proposed for future instruments but this tends to be at the expense of SNR as the echo signal is spread over more pixels in case higher vertical resolutions are applied.

Lines 160-165: "the random as well as systematic error budget of CCD based measurements." Noise or additional dark current shot noise could be preferred to random. Moreover, it does not appear clear to me what the budget means here. "the noise contributions are related to the signal itself" Total noise comprises DC noise and read-out noise. "The noise of Aeolus signals is dominated by the Poisson distributed shot noise as the levels for dark current and read-out noise" The dark current noise is also a shot noise. This sentence needs to be rephrased.

The authors intended to say that the systematic and random errors of CCD based lidar measurements usually depend on the dark signals of the CCD. To be clear, the sentence was rephrased (see screenshot). Random error is considered to be the correct antonym for systematic error which is why this was not changed in the manuscript. Moreover, the noise arising from the signal itself was specified as photon shot noise in the manuscript.

> Even in the absence of light, a relatively small amount of thermally generated electrons is collected in the CCD. This is known as dark current and causes a non-negligible background signal on CCDs. In general, dark current signals play an important role for ~~the~~ random as well as systematic errors ~~budget~~ of CCD based measurements.
> On the one hand, the dark signal affects the random error budget by dark current signal noise. For a typical optical CCD instrument, the noise contributions are related to the signal itself, the noise of the dark current signal, and the read-out noise. The noise of Aeolus signals is dominated by the Poisson distributed photon shot noise as the levels for dark current and read-out noise are very low (see Table 1). Thus, the technique used for Aeolus is referred to as "quasi-photon" counting.

Lines 165-170: "Thus, the technique used for Aeolus is referred to as "quasi-photon" counting." It does not appear that this device can integrate and measure a single photon. The noise is dominated by a readout shot noise, but photon-counting required other characteristics that are not met here. Systematic errors could be corrected easily with an appropriate offset correction. The main issue may lie in the need to evaluate the DC along with the mission as well as the DC non-uniformity along with the pixel array. The authors are invited to introduce these concepts as well as the possible impact on the reduction of the dynamic range which might impact the minimum flux detection that could affect the mission.

In addition to the Poisson photon shot noise from the signal itself, the main electronic noise contributor from the ACCD is read-out noise (4 e- – 6 e- rms). For number of P=19 laser pulses the number, the noise for one laser pulses can be calculated by dividing the read-out noise by $\sqrt{P}$ which results in a value of about 1 e-/pixel/laser pulse. As 1 electron-hole pair is produced for 1 photon at the wavelength of 355 nm (Janesick, 2001) , the equivalent noise is in the order of 1 generated photon. Hence, this technique is referred as "quasi-photon" counting due to the low read-out noise.

Systematic errors originating from dark signal anomalies in the memory zone are successfully corrected by the introduction of dedicated dark signal calibration measurements that performed four times per day. This concept is introduced in Sec. 3.3 of the manuscript. The dark signal calibrations measure the DSNU of the 25x16 memory zone pixel array which is used to correct subsequent measurement signals.

Lines 170-175: "Dark current anomalies" Dark current increase and RTS are expected for this kind of mission. The term dark current increase should be preferred to Dark current anomalies where or not it has an RTS behaviour or not. Main comment: DC origin and impact on the measurement must be explained with the operation mode used by the instrument. A clear description of the DC accumulation over the SNR can highly facilitate understanding. More importantly, the accumulated dark charges are stored in the memory area for almost half a second (0.4s). such retention time makes the leakage current very important in this structure and can potentially lead to a reduction of the total stored charges implying a negative offset on the signal. Authors are invited to explain how important this leakage current is on the output signal and, if applicable, how it can to a certain extend compensate the DC.

The dark current anomalies refer to an increase in dark signal and in particular hot pixels which are apparently not consistent with the expected increase due to radiation. However, in the manuscript the information is added that dark signal anomalies are defined as dark signal increase (see screenshot below). The impact of dark signal anomalies on the Aeolus wind measurements is depicted in Sec. 3.3 of the manuscript where the effects on both measurement channels are discussed.

Lines 170-175: Why CMOS imagers have not to be used for such applications? Space qualification history and legacy from other missions need to be highlighted.

The detector was designed and manufactured over 20 years ago when the maturity of CMOS technology was much lower. The mission was unfortunately delayed due to problems with the development of the laser. Even today there is no obvious architecture for a CMOS imager to achieve the binning and accumulation of laser echoes apart from the implementation of CCD structures in a CMOS technology. Please note that there is also the PhD thesis "Estimation and modelling of key design parameters of Pinned PhotoDiode CMOS image sensors for high temporal resolution application by Alice Pelamatti (Pelamatti, 2015).

Lines 175-180: A clear distinction between solar events, trapped particles, and cosmic rays should be made here. Cosmic rays are also referred to as heavy ions due to their mass.

The reviewer's suggestion was introduced as follows:

harsh radiation conditions, radiation-induced effects are an important issue. In particular, the effects of high-energy particles such as cosmic electrons, ions, neutrons, and protons passing through CCDs have to be considered (Hopkinson et al., 1996). These particles can be categorized into particles trapped in the Van Allen radiation belt (Feynman and Gabriel, 2000) and the transient environment. Particles trapped in the Van Allen belt are composed of energetic protons, electrons as well as heavy ions and the transient radiation consists of galactic cosmic rays and solar events ~~are mainly of solar and interstellar origin and are often trapped and accumulate in the Van Allen radiation belt (Feynman and Gabriel, 2000)~~. The geographic region where the inner Van Allen belt comes closest to the Earth's Surface is called South Atlantic Anomaly (SAA). The SAA is a region of reduced magnetic intensity where satellites in Low Earth-Orbits (LEO) (< 1000 km altitude) are exposed to strong radiation (Anderson et al., 2018) and thus this region is of potential harm for satellite measurements ~~particular interest~~. Typically, the SAA is situated at an altitude of 200 km to 800 km over the Earth's surface (Nasuddin et al., 2018). A significant increase of dark signal levels in the region of the SAA has been observed on the CCDs of the Hubble Space Telescope which is operated

Lines 180-185: SAA, a "region of particular interest" The authors are invited to briefly describe this intertest. Either it is for scientific purposes or a better understanding of the impact on electronics. The Hubble dark current increase rather lies in the repetitive flyby of the area implying an increase of the deposited dose. Transient effects are photogenerated charges coming from the ionizing radiation during the flyby.

The author's intention was to state that the SAA is a region where low-orbit satellites are exposed to higher radiation than usual and thus might affect the measurements of the satellite. For Aeolus measurements these effects are discussed in Sec. 4.3 of the manuscript. Please notice that some previous European space LEO missions have been dramatically impacted by displacement damages generated by SAA larger protons fluence, such as GOMOS on board Envisat ESA mission (Keckhut et al., 2010) and MIR channel on board Spot 4 / 5 CNES missions. The section about the SAA was changed as follows:

~~are often trapped and accumulate in the Van Allen radiation belt (Feynman and Gabriel, 2000)~~. The geographic region where the inner Van Allen belt comes closest to the Earth's Surface is called South Atlantic Anomaly (SAA). The SAA is a region of reduced magnetic intensity where satellites in Low Earth-Orbits (LEO) (< 1000 km altitude) are exposed to strong radiation (Anderson et al., 2018) and thus this region is of potential harm for satellite measurements ~~particular interest~~. Typically, the SAA is situated at an altitude of 200 km to 800 km over the Earth's surface (Nasuddin et al., 2018). A significant increase of dark signal levels in the region of the SAA has been observed on the CCDs of the Hubble Space Telescope which is operated

Lines 185-190: Dielectric materials could be preferred to oxide layers.

Agreed, it is at the interface between the oxide and nitride layers in the gate dielectric where most charge is trapped.

In general, radiation-induced effects can be categorized into three groups: ionization damage, displacement damage and transient effects. Ionization damage can lead to an increase of trapped charges in the dielectric materials ~~oxide layer~~ of the CCD and thus, may lead to an increased dark current and to a shift in the optimum operating voltages of the CCD. Displacement damage is caused by energetic particles (mainly protons) passing through the CCDs which may displace atoms from their

Lines 190-195: Vacancy-interstitial pairs, also called Frenkel pairs recombine at room temperature. It must be specified here that it is still the case at -30. "Random Telegraph Signals (RTS)-noise" RTS is a signal – as specified in the name - not a noise. This terminology lies in the description of the signal from the mathematical point of view. Therefore, the preferred terminology is DC-RTS or RTS. Some papers used RTN for random telegraph noise when studying transistor RTS (trap-detrap mechanisms in the canal) and DC RTS (generation centres) at the same time. Level should be preferred to state which rather lies in a defect configuration.

The information about the Frenkel pairs was added to the manuscript (see screenshot below). We agree that RTS are signals, however, the expression RTS noise is an industry standard terminology and is widely understood. However, to be correct the terminology in the manuscript was changed as follows:

In general, radiation-induced effects can be categorized into three groups: ionization damage, displacement damage and transient effects. Ionization damage can lead to an increase of trapped charges in the dielectric materials ~~oxide layer~~ of the CCD and thus, may lead to an increased dark current and to a shift in the optimum operating voltages of the CCD. Displacement damage is caused by energetic particles (mainly protons) passing through the CCDs which may displace atoms from their lattice and create vacancy-interstitial pairs, also referred to as Frenkel pairs (Janesick, 2001). Most of the pairs recombine (also at the ACCD operating temperature of -30° C) but some of them may form stable displacement damages in the lattice. Displacement damage can lead to a degradation of the CTE and an increase of the dark current. So-called "hot pixels", pixels

Lines 195-200: "In the framework of the Aeolus ACCDs development, proton tests (even at higher radiation doses as seen in-orbit) have been performed to evaluate the probability of occurrence of such hot pixels and RTS pixels at an operating temperature of -30 °C showing the presence of one-post irradiation RTS pixel. However, it has to be noted that the operation mode regarding the timing settings during 200 the tests were not fully comparable with the settings used in-orbit." If neither results nor conclusions can be extracted from this test campaign, it should be withdrawn from the paper. It could eventually be mentioned in the discussion section.

The authors decided to keep the information about the proton tests in the manuscript mainly to highlight the importance of proper on-ground testing campaigns for potential follow-on missions.

Lines 200-205: "Transient radiation effects occur due to ionization-induced generation of charges within the CCDs and do not cause lasting damage. "I do not agree with this statement. SEE does result in remaining TID and DDD and can even lead to latchup. "quite efficiently shielded from ionization damage." The authors are invited to specified until which TID level. Globally, TID and DDD exposition are not reported in the paper.

Teledyne-e2v CCDs, unlike CMOS detectors are not susceptible to latchup. There are no NPNP thyristor like structures between power supplies.

In the framework of the Aeolus development, simulations have been performed to determine the shielding for the six instrument faces (±X, ±Y, ±Z) as seen by the detector. Equivalent shielding figures from 2 mm to 8 mm per face have been found for the most exposed ACCD, plus the 2.5 mm thickness BK7 window. The TID and TNID levels are respectively about 0.3 krad(Si)/year and 5E6 MeV/g(Si)/year for 400 km circular orbit, maximum solar activity being considered for the whole mission duration. Please notice that Aeolus altitude has been decreased to 320 km, reducing even more the radiation levels. However, it is considered to be beyond the scope of this manuscript to confront the AMT readers with TID and DDD exposition levels.

Lines 210-215: Integration time could be preferred to timing settings.

It is preferred to keep the term "timing settings" as "integration time" is used in the manuscript to describe the vertical range gate resolution of the manuscript.

Lines 210-215: RTS must be preferred to transient events.

This paragraph describes the impact of transient events, and not RTS signals on the Aeolus measurements.

Lines 255: "at measurement level." This term must be specified> Does it refers to data processing or analogue correction?

The term "measurement level" is introduced in Sec. 2.1 of the manuscript and describes the temporal resolution (0.4 s) of the signals after the on-board accumulation of charges in the memory zone. A reference to Sec. 2.1 was added to the sentence:

> current measurements is restricted to periods where the laser is operated in a lower mode and not emitting laser pulses
>
> In this paper, DUDE measurements obtained from the quasi raw Aeolus L1A data products were analyzed (Reitebuch et al., 2018). The specific L1A data product is generated after each DUDE characterization and contains geo-located but unprocessed dark current signals of both channels for 25 range gates and 16 pixels at the measurement level (as introduced in Sec. 2.1), i.e., in the same format as nominal wind lidar measurements which allows for a DSNU characterization. In a first step, the DCO was subtracted from each pixel value at measurement level. Next, the measurements were averaged to observations by calculating the mean over the measurements per observations.

Lines 391: Transition must be preferred to dark signal spike/peaks.

Agreed. The manuscript was changed accordingly:

3.2 Detection of transient dark current anomalies

As outlined in Sect. 2.2 transient effects which cause spurious dark signal ~~spikes~~ transitions may occur on the CCD. In contrast to the detection of permanent dark current anomalies (see Sect. 3.1), the detection of spurious spikes is performed at measurement level. Typically, transient events appear as isolated signal peaks only present in one measurement and show a

Lines 460-465: Could also lie in a small temperature shift during the dark measurement and the collected data.

The ACCD temperatures were investigated and no significant temperature shift could be observed.

Lines 465-470: 4 minutes is very short to account for RTS. Most of the high RTS amplitudes cannot be seen in such a small period. Additional references on RTS in the CMOS literature might give a global overview of expected RTS behaviours.

Yes, it is correct that 4 minutes are short to analyse RTS. This is why, we analysed the concatenated data stream of DUDE measurements which allows to derive an estimate about the RTS amplitudes. Moreover, for some hot pixels it also possible to see RTS effects in the wind measurement signals (see Fig. 8 (bottom) of the manuscript). The paragraph about RTS in Sec. 2.2 of the manuscript was extended and additional references were added:

current signals over a longer period of time, may evolve. In addition, displacement damage may also introduce burst noise, e.g. Random Telegraph Signals (RTS) ~~noise~~. RTS ~~noise~~ causes the dark current to change its state between two or more discrete levels at random and unpredictable times (Hopkins and Hopkinson, 1993; Smith et al., 2004; Srour and Palko, 2013). RTS is observed in CCD as well as in Complementary metal-oxide-semiconductor (CMOS) devices (Goiffon et al., 2009; Woo et al., 2009). The time spent on the different levels can be in the range between seconds to days and also the RTS amplitudes typically cover a wide range (Virmontois et al., 2013; Liu et al., 2020; Capua et al., 2021). Hot pixels in combination with RTS phenomena were also observed for the CCD detectors of the Global Ozone Monitoring by Occultation of Stars (GOMOS) instrument on-board ENVISAT (Keckhut et al., 2010) or for the CCDs used in BRITE Nano-satellite image sensors (Popowicz, 2018). In the framework of the Aeolus ACCDs development, proton tests (even at higher radiation doses as seen

Lines 480-485: RTS can show period lasting from seconds to hours and even days and this is much more important as the temperature decrease. This is the main reason why the correction is not possible.

Yes, it is correct that due to RTS pixels only a mitigation of hot pixel effects can be achieved.

dark current signal level. However, there remains a problem for the near-real-time (NRT) processing when dark current transitions occur between two DUDE measurements which may happen for RTS-type hot pixels. The uncorrected signal intensity (dashed red line) shows a dark current induced signal decrease of about 8.0 LSB at 14:15 UTC. Here, the dark current calibration based on the DUDE measurement from 13:15 UTC is still active. Thus, the dark current signal is overestimated and the dark signal corrected signal intensity (solid red line) shows the signal dip. This holds true until the new DUDE measurement is performed and gets used for the dark current calibration of the orbit which starts around 20:30 UTC. Afterwards, the dark signal corrected signal intensity is again at the same level as before.

Lines 540-545: “not perfectly linear.” The data are linear, but the interesting parameter here could be the total mean dark current over the pixel array. Moreover, DDD and TID ranges must be specified and compared to other results in the literature if possible.

To the authors the temporal evolution of hot pixels is not truly linear as there are periods with enhanced hot pixel rate. However, the overall tendency appears to be somewhat linear. It should be noted that this manuscript is more focused on the impact of dark current anomalies on the quality of the wind measurements. Thus, the mentioned aspects are considered to be out of scope. However, it is planned to prepare a follow-on paper with a focus on the root-cause and the technical aspects after end of the mission lifetime. In the framework of this analysis, aspects like the evolution of the mean dark current, DDD and TID can be discussed.

Lines 545-550: "the hot pixel generation rate does not change with time" Unless for RTS pixels…

The assumption of the linear extrapolation is that the hot pixel generation rate stays at the same level (one new hot pixel every 14.68 days) throughout the mission lifetime.

Lines 605-610: "RTS pixels show more than two levels." Usually the case for DDD-induced RTS.

This is correct. The information with the corresponding reference was added to the text.

4.2.1 RTS characteristics

The majority of the hot pixels which were defined as RTS pixels show more than two levels which is usually the case for displacement damage induced RTS pixels (Virmontois et al., 2011). RTS characteristics with two distinct levels were only

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observed in 27 % of the cases. Apart from that, it is apparent that the RTS levels are quite different from each other. An

Lines 605-625: These on-flight observations are consistent with RTS observed in other imagers CCD/CMOS. References here could support these observations and confirm that these results are not surprising but highlight the need to perform more investigation on RTS in imager for space applications. RTS behaviors present an infinity of different shapes that cannot be described. This is the reason why other studies use high-resolution imagers to outline major trends on thousands of RTS. See recent RTS studies in CMOS imagers.

It is correct that these observations are consistent with other missions. This section was changed as follows:

4.2.1 RTS characteristics

The majority of the hot pixels which were defined as RTS pixels show more than two levels which is usually the case for displacement damage induced RTS pixels (Virmontois et al., 2011). RTS characteristics with two distinct levels were only

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observed in 27 % of the cases. Apart from that, it is apparent that the RTS levels are quite different from each other. Overall, the observed RTS features are consistent with RTS observed in other CCD-based satellite instruments such as the CoRoT or PARASOL mission (Gilard et al., 2010; Bardoux et al., 2017). For both missions a continuous increase of hot pixels (including RTS) throughout the mission lifetime could be observed.

Lines 705-710: CIC does exhibit RTS but with a much smaller RTS amplitude. The different RTS signatures between DDD-induced RTS and CICI-RTS can be made base on the RTs amplitudes. DDD-induced RTS amplitudes are more important. Reported results show large RTS amplitudes that can be linked to DDD RTS. Another method could be to use temperature dependence to extract activation energies. Again, the authors are invited to see the last published RTS studies on CMOS imagers.

The authors were not aware of the fact that it is possible to distinguish between CIC and DDD-induced effects based on the RTS amplitudes. However, from Fig. 14 of the manuscript which shows the RTS amplitudes it does not seem straightforward to identify a threshold for the amplitudes which would allow a categorization of RTS pixel into CIC- and DDD-induced RTS.

Lines 750-755: Can a high-resolution imager with a smaller pixel pitch be foreseen to maintain sufficient sensitive pixels along the column while disabling RTS ones?

Alternative architectures are being considered for a future LIDAR instrument which will provide a near-real-time hot pixel map to minimise the impact of RTS type hot pixels.

References:

Janesick, J. R.: Scientific Charge-coupled Devices, SPIE Press, 936 pp., 2001.

Keckhut, P., Hauchecorne, A., Blanot, L., Hocke, K., Godin-Beekmann, S., Bertaux, J.-L., Barrot, G., Kyrölä, E., van Gijsel, J. a. E., and Pazmino, A.: Mid-latitude ozone monitoring with the GOMOS-ENVISAT experiment version 5: the noise issue, 10, 11839–11849, https://doi.org/10.5194/acp-10-11839-2010, 2010.

Pelamatti, A.: Estimation and Modeling of Key Design Parameters of Pinned Photodiode CMOS Image Sensors for High Temporal Resolution Applications, Federal University of Toulouse Midi-Pyrénées, Toulouse, 214 pp., 2015.