Response to Referee Comment #2 on

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

The authors thank reviewer #2 for carefully reading the paper and providing valuable input. On the one side, your seed questions support the on-going root cause analysis of the Aeolus hot pixel issue and other side, they are also very useful to further improve the quality of the manuscript and provide the impetus for a potential follow-on paper focused on root-cause analysis. In the following, referee comments are repeated in green and answers by the authors are provided directly below in black.

General comments:

The focus of this paper is on analysing the on-orbit hot pixel characteristics and emergence trends in the novel ACCD launched on the space-based wind lidar ADM-Aeolus, and mitigation of hot pixel effects on wind retrieval accuracy. Though the paper does not draw any firm conclusions about the potential root cause(s) of hot pixel emergence, this paper nicely sets the stage for such a discussion. Most of my comments are geared towards this discussion. I should mention that, in my opinion, a discussion of the root cause(s)/damage mechanism(s) is optional, as the authors' description of the strategies for mitigating the impact of hot pixels on wind retrievals, and detailed characterization of these anomalies, make this a valuable work in its own right. In fact, the author could consider de-scoping some of the discussion on the root cause from this paper, and deferring it to a future work, if the author so wishes. A more detailed discussion of the root cause might be beyond scope, but I offer the following comments/questions to address (optionally) that might aid a future publication/study on the issue, or satisfy a curious reader of this paper. General questions: -

How much shielding exists around the ACCDs on Aeolus, and/or what is the shielded radiation environment/dose (yearly DDD, TID)?

In the framework of the Aeolus development, simulations have been performed to determine the shielding for the six instrument faces ($\pm X$, $\pm Y$, $\pm Z$) 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.

Has there been a detectable, steady trend/increase in the dark current observed over the course of the mission for pixels that have not experienced an anomaly?

No, there has not been an observable increase of the mean dark current signal for ACCD pixels that were not classified as hot pixels. Figure 1 below indicates the dark signals at observation level of an ACCD pixel (Rayleigh pixel [15,13]) which did not exhibit an anomaly. This plot does not show an increase of the dark current signal. Another example of a hot pixel time series with nominal behaviour is shown in Figure 4 (top) of the manuscript. In this case also no increase of the dark current signal could be observed.

To make this clear in the manuscript. The following sentence was added to Sec. 4.2 of the manuscript:

4.2 Hot pixel signal levels

Figure 13 shows the median dark signal value of the Mie and Rayleigh hot pixels in ascending order of their dark current level. In order to show the spread of the dark signal values, the scaled MAD is indicated by the black error bars. Given that the dark signal values of pixels that show nominal behavior are Gaussian distributed (see Fig. 4), it might seem reasonable to use a hot pixel threshold based on the standard deviation and the mean. Thus, the dashed black lines in Fig. 13 indicate the median value + 3* scaled MAD of dark signal values obtained from all ACCD pixels after removing hot pixels which is 2.28 LSB and 1.54 LSB for the Mie and Rayleigh channel, respectively. It should be noted that no increase of the dark current of pixels which were not categorized as hot pixels over the mission lifetime was observed. Due to the fact that many Aeolus hot pixels only show very small shifts in the mean dark signal and even return to a normal dark signal after some time (see Sect. 4.2.2), many hot pixels would have been undetected using this simple threshold technique. This points out the necessity to use the sophisticated detection algorithm as introduced in Sect. 3.1.

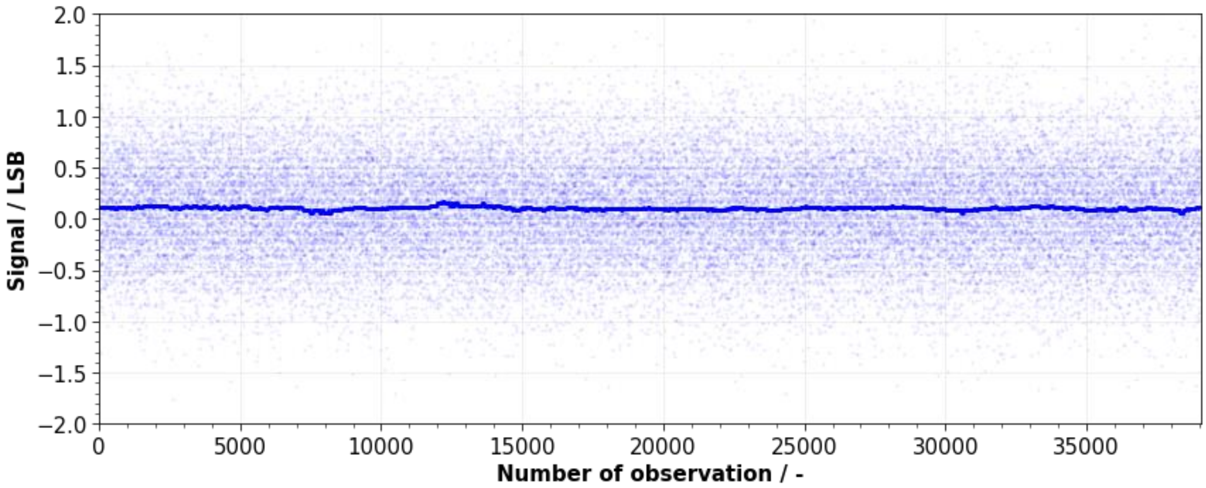

Figure 1: Dark signals of Rayleigh pixel [15, 13] with nominal dark signal behaviour. The blue dots indicate dark signal intensities at observation level. The solid blue indicates the median filtered signal (window size: 1000 observations).

What design deltas between the ACCD and previously flown CCDs (e.g., Hubble) might explain the observed anomalies? Inversely, what design elements do the ACCDs share with the CCD detectors of GOMOS on ENVISAT?

Please find below a summary of the most important characteristics of the Hubble CCD43 and the GOMOS CCD26:

Hubble (WFC3-UV): Inverted mode operation (IMO), back-illuminated, 2048 x 4096 pixels (15 µm x 15 µm pixel size) multi-pin-mode-operation (Windhorst et al., 2011)

GOMOS CCD26: IMO, back-illuminated, 143 x 1353 pixels (20 µm x 27 µm pixel size) (ESA, 2000)

The build of these devices in terms of silicon resistivity, dielectric thickness and doping levels is very similar to that used for the Aeolus detectors. Also, the channel doping is probably similar. But the Hubble CCD43 would have been IMO rather than Advanced-IMO (AIMO) with the barrier implant under the whole of the poly 3 electrode rather than just under one edge. As a consequence, the dose of the barrier implant is likely to have been lower so the potentials in the silicon and the numbers of holes at the surface under a low clock could be slightly different. This may have an impact on CIC generation.

However, the major difference between the Aeolus CCDs and anything previously designed or built by T-e2v is the memory section. This is almost unique in that the clock phases are cycled a large number of times with the surface going into pinning but without the charge being transferred. Any local generation site for CIC generation will therefore be able to give a hot pixel rather than distributing the charge over a complete column.

What radiation testing was conducted on the ACCDs prior to launch (proton energies and fluence steps, TID dose steps, heavy ion, un/biased, un/cooled, etc.), and what were the results? Does the observed, on-orbit rate of hot pixel emergence, or anomalous behaviour, align with expectations from ground testing? I assume not, but am curious as to why.

In the framework of the Aeolus ACCDs development, proton tests have been performed to evaluate the probability of occurrence of such hot pixels and RTS pixels at an operating temperature of -30 °C (also mentioned in Sec. 2.2 of the manuscript). On-ground proton tests were performed at different temperatures between -30°C and 20°C in 2004 and fluence levels. Two samples were irradiated with 30 MeV protons (fluence: 2E9 protons/cm² and 1.35E9 protons/cm²) and two other samples were irradiated with 100 MeV protons (fluence: 4.2E9 protons/cm² and 2.7E9 protons/cm²). A significant increase in dark signal was observed at the maximum dose (~10x the beginning-of-life value for Aeolus. Despite the much higher radiation dose as in space only three anomalies were observed: one post-irradiation RTS pixel in one device + two suspicious pixels with increased dark current signals for another detector sample. It should however be noticed that the dark signal acquisition duration has not been optimized to track low frequency variations of the dark current signals (only 512 frames have been acquired continuously) and the operation mode with regard to the timing settings during the tests was not fully comparable with the settings used in-orbit. In addition, the post-processing algorithm sensitivity was not good enough to detect abnormal pixels amplitudes as low as observed in-orbit. Overall, the results show one post-irradiation RTS pixel in one device and two suspicious pixels with increased dark current signals observed for another detector sample.

A few details about the proton tests were added to Sec. 2.2 of the manuscript.

The memory zone pixels are ∼half the area of the imaging pixels. Are they "hit" half as often, or is it impossible to tell?

It should be mentioned that each row of the memory zone of the ACCD consists of 16 transfer and 16 storage pixels. The 16 transfer pixels are the equivalent to the imaging zone and the form the transfer section of the memory zone. The storage pixels form the memory storage section in which the signal accumulation is performed. This is why the memory zone pixels are half of the area of the imaging pixels. However, for the dark signal generation the residence time of the signals in the imaging and the memory zone is more important than the size of the pixels (also explained in Sec. 2.1 of the manuscript). The residence time in the memory zone is with 0.4 s much longer compared to the residence in the imaging zone which is between 2.1 µs to 16.8 µs, depending on the range gate timing settings. Thus, the focus lies on hot pixels of the memory zone.

As mentioned in Sec. 2.3 of the manuscript, there are two specific measurement procedures to characterize the dark current in the imaging and memory zones of the ACCD. Both procedures were defined to be performed while the laser is not operating (e.g. before the switch-on). To overcome this problem and measure the dark current of the memory zone during continuous laser operation so-called "DUDE" measurements were introduced. This was possible by cleverly adjusting the range gate settings. However, mainly due to technical restrictions it is not possible to acquire dark signal measurements of the imaging zone while the laser is operating. As a result, the availability of imaging mode measurements is restricted to periods where the laser was in a lower measurement mode (e.g.

before the switch on). Thus, it is not possible to properly characterize the dark current signals of the imaging zone.

Section 2.3 of the manuscript was changed accordingly:

> After the first identification of hot pixels in the nominal Aeolus wind lidar measurements, a new procedure to allow dark signal characterization of the memory zone during continuous laser operation was introduced, so-called DUDE (Down Under Dark Experiment)-measurements. During DUDE measurements the range gate timing settings are adjusted such that the theoretical return signal is acquired from below the Earth's surface. Figure 2 illustrates the difference in the data acquisition between wind (a) and DUDE (b) mode. In that way, dark current signals of all pixels of the memory zone can be measured without lidar signal contributions apart from the solar background signal. Due to technical limitations it is not possible to characterize the dark current of the imaging zone in the same way as for the memory zone. Thus, the availability of the imaging zone dark current measurements is restricted to periods where the laser is operated in a lower mode and not emitting laser pulses.

Will a version of these ACCDs fly on ATLID/EarthCARE? Have the observations/findings in this paper inform the design, testing, or con-ops of ATLID? Will similar mitigation strategies as herein need to be employed for ATLID?

The ATLID detectors were designed, tested by T-e2v and delivered to Airbus before the hot pixel issue on Aeolus was identified. There was therefore no possibility to influence the design of the CCD. During testing at T-e2v hot pixels associated with the flushing of the memory transfer register were identified and the proposed clock sequence for the flight instrument was modified to remove unnecessary flushing cycles. For the ATLD in-orbit operation, regular dark current calibration measurements will be carried out.

Referring to Section 4.1: Which space weather variables were considered for correlation with the rate of damage/hot pixel emergence? (Line 512)

As possible indicator for space weather, the information from www.spaceweatherlive.com has been checked. The "activation" of a hot pixel could not be correlated with the given scale of K-index, i.e., no threshold of activity could be identified.

Sec. 4.1 of the manuscript was changed as follows:

> The temporal evolution of the first appearance of the hot pixel anomaly (as listed in Table 2) is displayed in Fig. 12. It can be seen that the increase of the hot pixel number with time is not perfectly linear. On the one side there seem to be periods where hot pixels occurred at a higher rate (e.g. 2019-01 to 2019-02) but on the other side there are also periods with very few anomalies (e.g. 2019-10 to 2020-01). However, no correlation between the hot pixel emergences and space weather activity (www.spaceweatherlive.com) was found. The "activation" of a hot pixel could not be correlated with the given scale of the K-index which is a measure of the disturbances of the horizontal component of the Earth's magnetic field, i.e., no threshold of activity could be identified. The mean time difference between two anomalies is 14.68 days with a rather large standard

Can damage events be geolocated, like was done for the transient events in Section 4.3 (Fig. 18)? This might be helpful to show. Did damage occur more frequently on the day/nightside of the orbit? If no correlation with the poles or SAA is observed, this might be suggestive of damage by untrapped particles, either energetic solar protons or galactic cosmic rays (GCRs). A day/night difference might be suggestive of a spacecraft charging connection. An anti-correlation of rate of hot pixel accumulation with solar activity, with a lag of a few months, might suggest a GCR connection. Data from the Alpha Magnetic Spectrometer on ISS might also be a good resource for GCR/high energy flux on-orbit.

Absence of correlation with these variables might be worth mentioning to the reader if already considered.

For some hot pixels it is possible to identify the exact time stamp and geolocation of the hot pixel activation. This can be done by analysing Aeolus wind measurement signals (ALD_U_N_1A signals) for sudden hot pixel induced signal jumps. In the framework of root-cause analysis of the Aeolus hot pixel issue, we already performed this kind of analysis. First results gave a slight hint for an accumulation of activation events in the region of the SAA. However, due to the relatively low number of hot pixels and the resulting low statistical significance it was decided not to include this analysis into the manuscript. It might be better to redo this analysis again at the end of mission lifetime of Aeolus with more hot pixels. In this framework, also possible correlations with solar activity or data from Alpha Magnetic Spectrometer could be investigated in more detail.

Referring to Section 4.3: Is there evidence for radiation-induced light emission (e.g., fluorescence, phosphorescence, Cherenkov, electroluminescence) originating from the ACCD cover glass, or other upstream optics/surfaces? This may be an explaining mechanism for the ~50% of transients that were observed to affect more than one pixel simultaneously, assuming the pixels were clustered.

As stated in Sec. 4.3 of the manuscript, it is not surprising that transient events affect multiple pixels simultaneously as cosmic rays passing through the ACCDs are likely to hit more than one pixel. Figure 2 down below shows an example of one dark signal measurement obtained in the region of the SAA. The Rayleigh ACCD shows an interesting pattern with multiple transient hits across several range bins in the centre of the ACCD. However, except for the well-known beta/gamma emission from the ^{40}K radioactive element part of the BK7 window, no other radiation effect coming from other instrument parts is known to the authors.

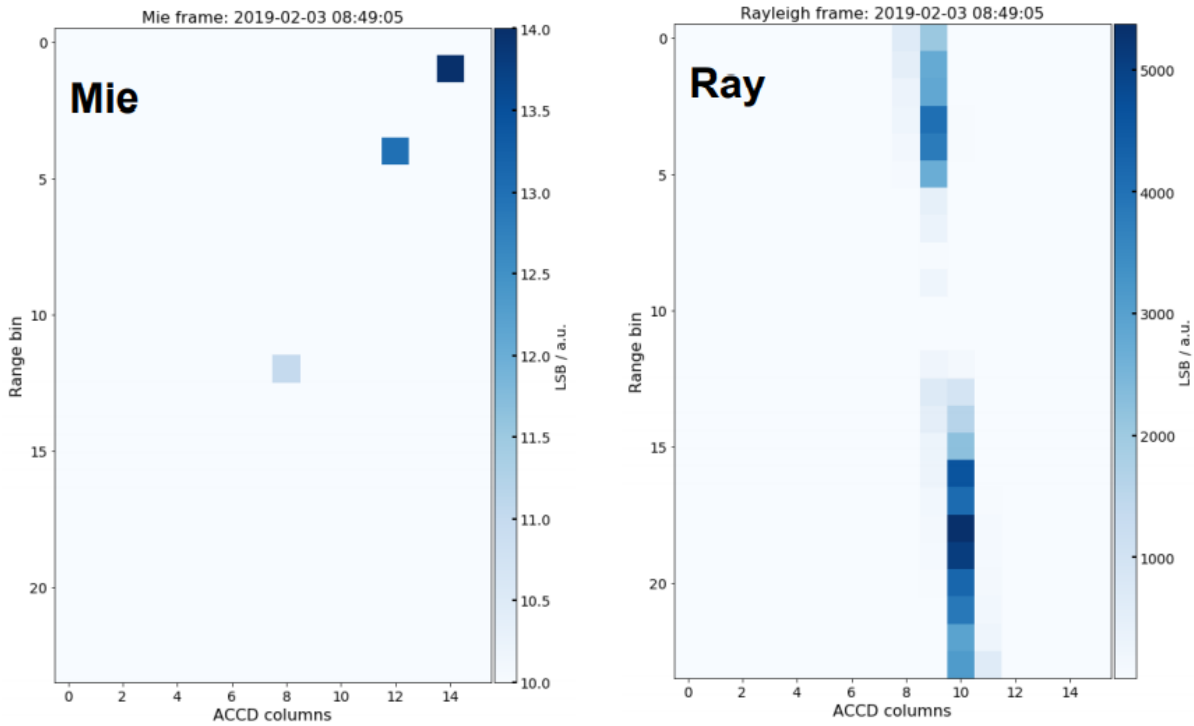

Figure 2: A measurement of the dark signal of the Memory Zone obtained in the SAA with multiple transients observed at the same time.

Were any transients clustered? Can the timescale of the transients be resolved, or do they appear in exactly one range bin? If radiation-induced light emission has been ruled out by the author, some discussion of that fact may still benefit the reader.

The timescale of transient events can be resolved as they occur in single Aeolus measurements (temporal granularity of 0.4 s). Note that the analysis of transient events in the manuscripts is also performed at measurement level. As mentioned above, it was observed that in many cases multiple pixels are affected at the same time. But not in all cases a clustering such as shown in Figure 2 could be observed. Temporal clustering of transients was only observed in the region of the SAA (see Figure 18 of the manuscript).

Is there evidence for latent damage? That is, do any pixels begin to exhibit damage hours, days, or even weeks after they experience an initial transient?

A detailed analysis to analyse the relationship between transient events and the occurrence events still needs to be performed. It might be worth to analyse accumulated number of transient events of a hot pixel before it became "hot" and compare this number to nominal pixels. In the discussion (Sec. 5) of the manuscript it is mentioned that the relationship between transients and the emergence of hot pixels is still unclear. This analysis could be performed for follow-on discussion paper about the root-causes of the Aeolus hot-pixel issue.

References:

ESA: ENVISAT GOMOS An Instrument for Global Atmospheric Ozone Monitoring, https://orfeo.kbr.be/bitstream/handle/internal/5299/Berteaux(2001a).pdf?sequence=1, 2000.

Windhorst, R. A., Cohen, S. H., Hathi, N. P., McCarthy, P. J., Ryan, J., Yan, H., Baldry, I. K., Driver, S. P., Frogel, J. A., Hill, D. T., Kelvin, L. S., Koekemoer, A. M., Mechtley, M., O'Connell, R. W., Robotham, A. S. G., Rutkowski, M. J., Seibert, M., Tuffs, R. J., Balick, B., Bond, H. E., Bushouse, H., Calzetti, D., Crockett, M., Disney, M. J., Dopita, M. A., Hall, D. N. B., Holtzman, J. A., Kaviraj, S., Kimble, R. A., MacKenty, J. W., Mutchler, M., Paresce, F., Saha, A., Silk, J. I., Trauger, J., Walker, A. R., Whitmore, B. C., and Young, E.: The Hubble Space Telescope Wide Field Camera 3 Early Release Science data: Panchromatic Faint Object Counts for 0.2-2 microns wavelength, https://doi.org/10.1088/0067-0049/193/2/27, 2011.