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Atmospheric Measurement Techniques Discussions
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Interactive comment on "Measurement of aerosol optical depth and sub-visual cloud detection using the optical depth sensor (ODS)" *by* D. Toledo et al.

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Reviewer #1: Synopsis: This paper provides a description of a rather innovative instrument to estimate aerosol optical depth. Readers are first reminded that this Optical Depth Sensor (ODS), was originally designed to fly on a mission to Mars. Thus, the instrument must be robust (preferably no moving parts), and must be able to account for changing calibration, such as when dust collects on windows. To a certain degree the authors appear to be successful. The ODS is based on the ratio of zenith scattered radiation at zenith to total radiation at all other geometries over the course of a day. This is performed at near UV and red wavelengths. Since their retrievals are based on this ratio, direct calibration drops out. The test this instrument for nearly a year at the Ouagadougou Africa site side by side with a Cimel sun photometer within the

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AERONET program. The use of the instrument for moonlit night applications is a nice byproduct. While I give the authors for developing a simple instrument that should be able to work on a Mars lander, the instruments core methodology has many shortcomings from terrestrial applications-some of which are near fatal. These are listed below. Perhaps this paper be rewritten into a short note, specifically on the Mars applications. In these cases, the authors could wave away the earth based problems. Under those circumstances I think it is publishable.

Author's note: In response of reviewer comments 2-3 and the synopsis, we would like to point out here that ODS instrument is selected in the METEO meteorological station on board the ExoMars 2018 Lander, and consequently measurements in Mars are not yet available. We have indicated this in the abstract (line 11).

"Recently, ODS has been selected in the METEO meteorological station on board the ExoMars 2018 Lander. In order to study the performance of ODS under Mars-like conditions. . .".

Referee comment 1: Most notably, this method is based on inversions of diffuse to total radiation and thus must assume or correct for diffuse radiation from clouds. Since there are nominally no clouds on Mars, or if there are they are likely cirrus-like in nature, this is not a problem. Similarly for airborne dust over mars, spatial homogeneity is a fair assumption. But for terrestrial use, clouds are often in scenes, and we don't know based on the data when that is. From their own data "cloudy skies" have significantly more errors than clear. But a way to deal with this is not given. In fact, it is taught to tell from the paper, when there were clouds in the first place. All that is said was that for cloud conditions there were higher frequency signals in the data. This is hardly quantitative. Further, there are many cases, such as in the presence of cirrus or alto clouds where there would be no high frequency signal.

Author's response: Regarding the presence of clouds, two different scenarios are possible: 1) A cloud out of ODS field of view, 2) a cloud within ODS field of view. In the first

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case ODS measurements would not be affected by the diffuse radiation coming from such cloud since the cloud is not within ODS field of view. The only possibility would be that the scattered light coming from the cloud is scattered again by the particles falling within ODS field of view. However, we remark here that this is a negligible effect in the measurements, since ODS observations are mainly affected by the light scattered by the particles falling within its field of view. In the second case, we agree with the reviewer about the fact that diffuse radiation from clouds would introduce errors in the retrievals. For this reason, ODS observations affected by the presence of clouds are directly removed from the ODS signal that is subsequently analyzed by the retrieval procedure. As said in the manuscript, the presence of clouds within ODS field of view infers fast variations in the time evolution of ODS signal (page 9619, lines 2-6). In order to identify the variations produced by the presence of clouds within the field of view of ODS, we first estimate the daily average AOD by doing a best fit between simulations and observations. Subsequently, we represent the time variation of the squared difference between observations and simulations. The upper panel of Figure 1a shows the time variation of blue ODS signal measured one day during the campaign and that simulated using the daily average AOD retrieved for that day. The lower panel of Figure 1a shows the time variation of the squared differences, and where we can observe big increases between 07:00 and 11:00 UTC. In order to know if such increases are produced by clouds or by variations in AOD, we selected different days of measurements with variations in AOD during the day (according to AERONET measurements). One of those days is illustrated in the upper and lower panels of Figure 1b where variations of up 0.4 in AOD were observed (according to AERONET measurements). In this case, however, we do not observe the big increases illustrated in the lower panel of Figure 1a. Note also that those big increases would appear even by doing a best fit considering only the observations acquired between 07:30 and 11:00 UTC. Once identified the variations produced by the presence of clouds, the final AOD is retrieved considering only the part of ODS signal not affected by the clouds, in the present case the observations acquired between 11:00 and 16:30 UTC. Since fewer observations are used in the retrieval procedure to estimate the AOD, the first consequence of the cloudy days is an increase of the errors in the estimation of this parameter. We understand that maybe this point is not totally clear in the manuscript and consequently we have changed lines 2-11 of page 9619 by the following text:

“As seen on Fig. 8, the ratio between scattered flux and total scattered and direct sunlight highly depends on the AOD. Therefore, given an ODS signal we can provide an AOD relative measurement independent of instrument calibration by searching the optimal value of this parameter that provides the best fit between observations and simulations. In present case, the AOD is of 0.6 on 5 December 2004 and 0.45 on 16 January 2005. The major difference between these days is the presence of clouds within the ODS FOV in Fig. 8b inferring fast variations. Since such variations introduce errors in the estimation of AOD, they must be removed from the signal before the analysis. The identification of ODS observations affected by the presence of clouds is carried out in different steps. Firstly, the daily average AOD is derived by doing a best fit between observations and simulations. Subsequently, we calculate the squared difference between observations and the ODS signal simulated using the AOD retrieved in the previous step. By comparing the time variation of these differences with those obtained under variations of AOD we can identify the observations affected by the presence of clouds. Once these observations are removed from ODS signal, the final AOD value is estimated using the filtered signal. Since fewer observations are used in the retrieval procedure to estimate the AOD, the first consequence of the cloudy days is an increase of the errors in the estimation of this parameter.”

Finally we would like to indicate that the presence of cirrus or alto clouds would produce fast variations in ODS signals since these clouds introduce shadows in ODS FOV (mostly when ODS receives direct light).

Referee comment 2: Second, the relationship between aerosol optical depth and the parameter of diffuse to total radiation is inherently dependent on some form of retrieval based on assumed optical properties, notably single scattering albedo and something related to phase function. Errors along their assumption is likely present in Figure 14, where there is a drop off in retrieved AOT for at higher values. This is likely a multiple scattering effect that highlights a bias in the assumed optical properties. You can see it right on que at 0.8. I think For the use of this instrument then, they used the retrievals from Dubovik. What if you don't have a retrieval side by side? If you did, you would not need ODS. Perhaps a more rigor error analysis (perhaps even assuming some Mars values) is probably in order than just a few test cases.

Author's response: ODS measurements are mainly affected by AOD, being the single scattering albedo and the phase function secondary parameters. Note that this result is mainly caused by the large field of view of ODS, originally designed for this reason. This fact allows us to define regionally these two parameters in our model and retrieve the opacity at locations where there is not operating a photometer (see the analysis illustrated in Figure 15). Therefore, we emphasize here that we did not use the scattering properties retrieved by the CIMEL located at Ouagadougou. The principal reason of such drop off in retrieved AOD for high values of this parameter is the strong variability of AOD during Saharan dust storms. While the daily average AERONET AOD is calculated taking the instantaneous measurements of AOD during the day, ODS AOD is retrieved by using observations acquired during the whole day. Therefore, for days with high variability of AOD during the day, ODS and AERONET daily average measurements can differ due to this reason. In order to deal with these discrepancies, we estimated two values of AOD from ODS measurements for days with a daily average AOD above 0.8. This is to say, one AOD value is estimated using only half of ODS signal (roughly from 7:30 to 12:00) and the second value from the observations acquired the rest of the day (roughly from 12:00 to 16:30). Figure 2a shows the evolution of ODS blue signal measured on 05 January 2005 and those simulated for the AOD values retrieved using ODS observations acquired between 7:30 and 11:50 UTC (AOD=1.57), and between 11:50 and 16:30 UTC (AOD=1.34). A similar analysis as shown in Figure 14b was carried out but in this case two AOD values were estimated for the days with a daily average AOD above 0.8 (Figure 2b). The correlation between AERONET and ODS improves to 0.97 and the MBE and MABE parameters to (-13.82±0.9) and (15.01±0.7). Therefore, these results point out the need of retrieving two values of AOD for days with a high variability of this parameter.

Figure 2 has been added in the manuscript as well as the following text in page 9626 (line 6): "We observe also in Fig. 14 a larger underestimation of ODS measurements in respect to AERONET for AOD values larger than 0.8. The main reason of this is the strong AOD variability during dust storms. While the daily average AERONET AOD is the mean of instantaneous measurements of during the day, the ODS AOD corresponds to ODS observations acquired during the whole day. For days of high AOD variability, ODS and AERONET might be thus very different. To deal with these differences between instruments, two half day AOD ODS values have been retrieved for days of AOD larger than 0.8,respectively in the morning from 7:30 to 12:00 UTC and the afternoon from 12:00 to 16:30 UTC. Fig. 15a shows, an example of the ODS blue signal evolution on 5 January 2005 and those simulated for the two AOD values retrieved using half day only signal. A similar analysis as shown in Figure 14 was performed for this case of two AOD values larger than 0.8. The correlation between AERONET and ODS is shown in Fig. 15b where the R2 coefficient improves to 0.97 and the MBE and MABE parameters to -13.82±0.9 and 15.01±0.7,respectively. Despite the AOD underestimation the results are showing that ODS measurements are reliable over a large range of AOD."

In addition, lines 13-17 in page 9628 (conclusions section) have been changed as follows: “The AOD in Ouagadougou is found highly variable ranging between 0.1-1.7 displaying strong maxima during Saharan dust storms. Under such conditions, we found necessary to retrieve two AOD values per day for days of AOD larger than 0.8.”

Referee comment 3: On the thin cloud detection side, there is no evidence presented that these are clouds, or what their real properties are. We are given a number of cloud detected, but no real verification analysis. Also, the authors don’t seem to realize that cirrus can be inhomogeneous and relatively thick. But again, if they make a case for

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thin top of the atmosphere clouds on Mars, I would give them some slack.

Author's response: We know that cirrus clouds can be thicker. However, this work is focused on the detection and characterization of optically thin cirrus clouds, as it is pointed out in the abstract (lines 5 and 6). We agree with the reviewer about the need of comparing these results. Unfortunately, during the campaign we couldn't compare these measurements against other instruments such as lidars. Note that this is indicated in conclusions section (lines 6-9): "In this regard, these retrievals need to be verified against lidar measurements in order to fully analyze the potential of these measurements. This comparison would allow us to better understand the limitations of the retrieval proce- dure as well as to identify the different error sources."

Referee comment 4: In general, error analysis is a bit optimistic. First, I would prefer that they use root mean square error over chiËĘ2-the later having a noise assumption built into it. With RMSE, we know what the signal is. Similarly, I would also prefer rËĘ2 to r, as rËĘ2 explains fractional variance. The authors could also go further on looking at the effect of shorter term variations. AERONET data is every 15 minutes, so it would be good to look at how much data do you really need in order to do retrieval.

Author's response: We thank the reviewer for pointing out this issue to us. The main reason we didn't included in the analysis the root mean square error was because this study is focused on the comparison with AERONET. However, we agree with the reviewer about the need to provide this parameter in order to give information about the fit between observations and simulations. Figure 3 shows the RMSE values obtained in the fits carried out for the days with a daily average AOD above 0.8 and whose values are illustrated in Figure 2b. We found a value of 0.013 in average and with a standard deviation of 0.003. We have included these results in the text modified in the reviewer comment number 2 (page 9626, line 6):

"We observe also in Fig. 14 a larger underestimation of ODS measurements in respect to AERONET for AOD values larger than 0.8. The main reason of this is the strong AOD variability during dust storms. While the daily average AERONET AOD is the mean of instantaneous measurements of during the day, the ODS AOD corresponds to ODS observations acquired during the whole day. For days of high AOD variability, ODS and AERONET might be thus very different. To deal with these differences between instruments, two half day AOD ODS values have been retrieved for days of AOD larger than 0.8,respectively in the morning from 7:30 to 12:00 UTC and the afternoon from 12:00 to 16:30 UTC. Fig. 15a shows, an example of the ODS blue signal evolution on 5 January 2005 and those simulated for the two AOD values retrieved using half day only signal. A similar analysis as shown in Figure 14 was performed for this case of two AOD values larger than 0.8. The correlation between AERONET and ODS is shown in Fig. 15b where the R2 coefficient improves to 0.97 and the MBE and MABE parameters to -13.82±0.9 and 15.01±0.7,respectively. In addition, for each estimated AOD we calculated the root mean square error in order to evaluate the goodness of the fit. We found a value of 0.013 in average and with a standard deviation of 0.003. Despite the AOD underestimation the results are showing that ODS measurements are reliable over a large range of AOD."

Regarding the effect of short-term variations in AOD in the retrievals, we have seen in the response of comment 2 the need to retrieve two half day AOD ODS values for AOD values larger than 0.8 due to the AOD variability.

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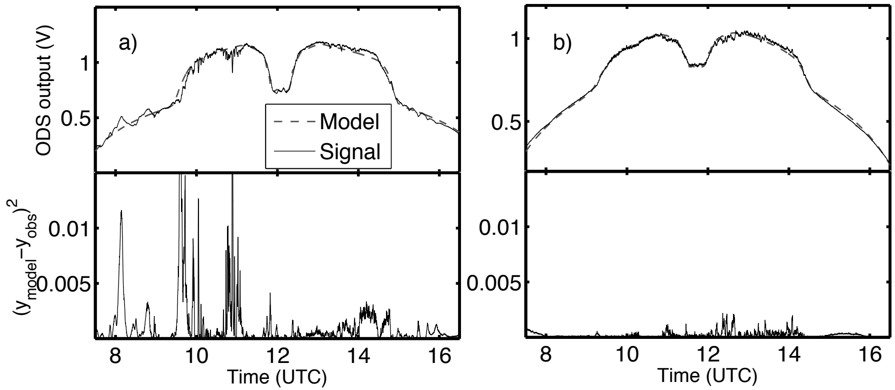

Fig. 1. Figure 1. (Upper panels) Evolution of ODS signal measured two different days during the campaign and those simulated for the AOD values obtained by the retrieval procedure of dust opacity. (Lower pane

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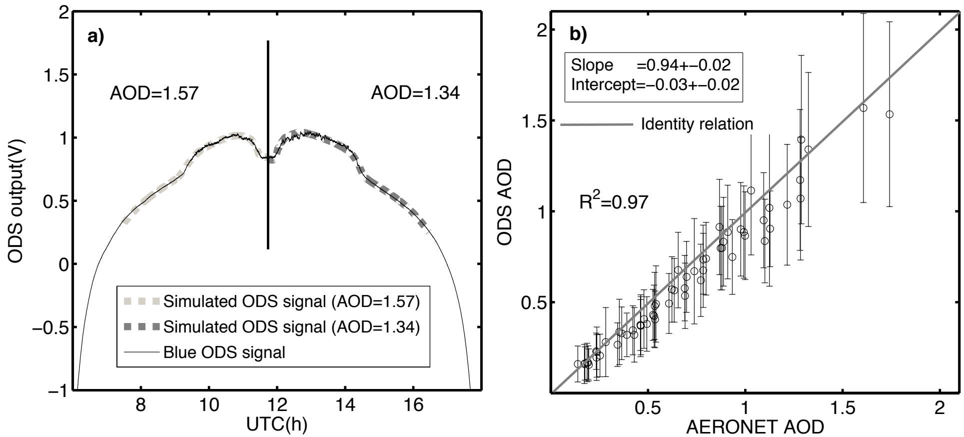

Fig. 2. Figure 2. (a) Evolution of ODS signal measured on 5 January 2005 and those simulated for the AOD values obtained by the retrieval procedure of dust opacity using only half of the day. (b) Correlation

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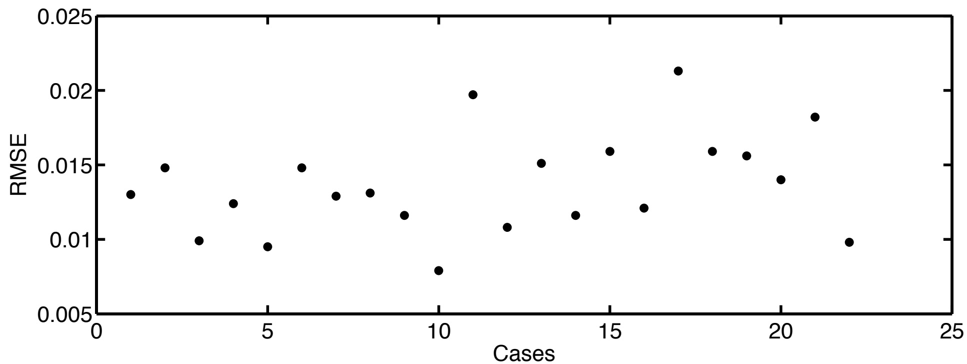

Fig. 3. Figure 3. Root mean square errors obtained in the fits carried out for the days with a daily average AOD above 0.8.

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