

5 “Cloud-Aerosol Transport System (CATS) 1064 nm Calibration and Validation” - Pauly, R., J.E. Yorks,
D.L. Hlavka, M.J. McGill, V. Amiridis, S.P. Palm, S.D. Rodier, M.A. Vaughan, P. Selmer, A.W.
Kupchock, H. Baars, A. Gialitaki

10 We received referee comments from two referees and one document with short comments from a member
of the scientific community. Our responses to the comments of two of the referees of our submission: amt-
2019-172: Pauly et al., “Cloud-Aerosol Transport System (CATS) 1064 nm Calibration and Validation” are
below. The referees were very helpful in clarifying our explanation of the method, as well as the
importance to future missions and CATS retrievals. We hope the editor will find our responses address the
major and minor comments of the referees. Our response to the short comments from the member of the
15 scientific community will be provided in a separate document. We believe the manuscript is clearer and
more robust, and we look forward to the new step towards publication. Note that the referee comments
appear in black while our responses appear in red.

Anonymous Referee #4 Comments

20 The paper describes an algorithm for calibrating and validation of CATS 1064nm backscatter coefficient.
Overall, the work presented in this paper is very important because lidar observation at 1064 nm is needed
together with 532 nm for characterizing particle size and other layered aerosol optical properties. The
validation shows that the method appears to work well and gives an uncertainty of 20% when comparing
25 with other lidar observations from different platforms. I would recommend the paper be accepted after
minor to moderate revisions to improve clarity and discuss its broader significance for the research
community.

30 1) equations. the symbols in each equation should be well explained and with unit given (or otherwise
mention unitless). This will help readers understand the equation better. For example, in equation 1,
what is the unit of N_s , r , D , and E . In equation 2, what is the unit of R , beta or backscatter
coefficient. The list goes on for all equations.

a. The appropriate units have been added to the latest version of the manuscript throughout.
You can see examples in the text corresponding to Equation 1 (page 3) and Equation 5 (page
5). Thank you for pointing out where they were missing.

35 2) equation 2. R is defined as aerosol scattering ratio. Should it be lidar ratio due to aerosol scattering?
to separate it from aerosol single scattering albedo? How is it defined? Where does the equation (2)
come from? If M is used to denote molecular, should A be added as a subscript for R because R is
Aerosol scattering ratio? Again, description of unit and physics here will help to improve the clarity
40 here.

a. We have re-worked this section for clarity. We now provide a generic definition for the
particulate scattering ratio (lines 31-34, page 4), which should prevent confusion about lidar
ratio vs. particulate scattering ratio. We have also swapped Equations 2 and 3 so that it is
more obvious how they relate. Finally, we more clearly label the variables as M to denote
45 molecular and P to denote particulate.

50 3) paragraph before 2.2, what is the unit of calibration coefficient? what exactly is calibrated? from
digital count to total attenuated backscatter coefficient? Table 2, the integrated attenuated
backscatter has unit of sr^{-1} ? but for CALIOP level-2 data, the same "total attenuated backscatter"
has an unit of $\text{km}^{-1}\text{sr}^{-1}$. Given the terminologies can be used differently by different groups, it is

important to define them from basic variables (e.g., extinction cross section, scattering phase function, etc) to avoid ambiguity.

- 5 a. The units of the calibration coefficient are now provided on page 6, line 14 (and throughout the paper). More details about what this calibration coefficient is being applied to (the NRB profile) and the result (the ATB profile) are provided on lines 8-9 on page 6. The units of total attenuated backscatter (or attenuated total backscatter), which are $\text{km}^{-1}\text{sr}^{-1}$, are different than the integrated attenuated backscatter (sr^{-1}). In the equation for integrated attenuated

backscatter, $\gamma' = \int_{\text{top}}^{\text{base}} \beta'(r) dr$, the differential range element dr has units of km, so the integrated quantity, γ' , has units of sr^{-1} . These units are the same for both CATS and CALIOP.

- 10 4) conclusions. If the calibration has 20% uncertainty, does that also mean that the total aerosol optical depth derived from CATS will have an uncertainty of 20% at least? It is important to discuss the link between the calibration uncertainty and the level-2 product uncertainty.

- 15 a. In general, yes, a calibration uncertainty of $\pm 10\text{-}20\%$ imposes a lower bound of $\pm 10\text{-}20\%$ on the uncertainty of the optical depth retrievals. We have added some brief text to the conclusion to express this relationship. However, the propagation of calibration errors in the solution of the lidar equation is both nonlinear and non-trivial, hence a more complete discussion of the link between calibration uncertainty and level 2 product uncertainties lies well beyond the scope of this paper. A complete mathematical description of calibration error propagation for elastic backscatter lidar measurements is given by Young et al., 2013 and Young et al., 2016.

- 20 5) finally, either in the introduction or conclusion, it is worthy to mention that lidar has been used to constrain smoke injection height (such as Wang et al., 2013, Atmospheric Research, 122, 486-503) and understand relative distribution of smoke and dust particles in the vertical (Yang et al., 2013, JGR, 118, 12,139-12,157) in the chemistry transport models.

- 25 a. References and discussion of these lidar applications were added to the introduction on page 2, lines 1-2.

30 ***Franco Morenco's Comments (Referee)***

I have read the paper by Rebecca Pauly and co-authors with great interest. The article describes the calibration of CATS 1064 nm attenuated backscatter and depolarization (level 1 data). Calibration is achieved on a per-granule basis, by normalization of nighttime signals with modelled atmospheric backscatter at an altitude of 22-26 km, where account is made for Rayleigh scattering (derived from the MERRA-2 re-analysis) and aerosol scattering (inferred from CALIPSO measurements). Moreover, attenuated backscatter by opaque cirrus clouds is exploited for two further calibrations: daytime calibration, on a monthly basis, is achieved by matching the overall frequency distribution of daytime and nighttime opaque cirrus attenuated backscatter, and the calibration of depolarisation signals, on a yearly basis, is obtained by matching the parallel and perpendicular signals for this type of clouds. The uncertainties that derive from this approach are discussed and quantified, and comparison with a number of validation sources is described: CALIPSO, airborne lidar, and ground-based lidar.

35 This research has a high significance, due to the fact that two and a half years of CATS data have been collected in 2015-2017, on-board the International Space Station. This dataset is still to be exploited in full, and it provides information on global aerosols and clouds, under an unusual orbit type (the one of the ISS)

which permits an investigation on diurnal cycles (as opposed to the more traditional sun-synchronous orbits). It also demonstrates that, depending on instrument design, direct calibration of 1064 nm lidar channels is possible, without needing to transfer the calibration from channels at shorter wavelengths.

The paper is well written but a few more points need to be addressed before it can be published, in order to clarify better the methods to the reader. I feel that there are still a few major points as follows, some of which were already raised in the previous "quick review". Underpinning science to the CATS processing is addressed here and I believe that the explanation of the methodology should clarify all doubts.

MAJOR COMMENTS:

1) I suggest to add more in the conclusions. CATS has been used and will continue to be used for cloud, aerosol, and radiative budget studies that will benefit from the new data version. What are the most significant results obtained so far from CATS datasets? how would they be affected if they were to be reprocessed using V3 data? how does the V3 level 1 calibration affect the level 2 data (before any changes to the V3 level 2 processing)? are there any useful lessons from your research that can be useful for EarthCARE and Aeolus? and for future follow-on missions?

a. More detailed discussion of the most significant results obtained from CATS data so far has been added to the first paragraph of the conclusion, in addition to the text added about how the calibration affects the L2 data products addressing Anonymous Referee #4's comment #4. Most studies using the retrievals of optical properties (e.g. extinction, optical depth) have used the V3-00 data. Since EarthCARE's lidar is a 355 nm HSRL and Aeolus is a 355 nm Doppler wind lidar, the 1064 nm atmospheric normalization technique shown here isn't very helpful for those missions. However, a sentence was added to the second paragraph of the conclusion to elaborate on how decreasing the laser repetition rate of a future CATS-like backscatter lidar could provide a larger data frame, and thus a higher calibration altitude (minor comment #34).

2) In the daytime calibration (section 2.2), you specify that you are looking for a specific type of target: opaque and geometrically thin clouds, and you specify "A layer is classified as opaque if no layer or ground signal is detected below it". In the previous review I raised the question of how you could know that such a cloud is physically thin, since opaque and deep clouds could look similar on a lidar signal. I don't believe that this point has been addressed.

a. What we are really trying to say here is that for strongly scattering, rapidly attenuating opaque cirrus, there should be little difference between nighttime and daytime iATB retrievals. Thus, that is why we selected these types of clouds for the daytime calibration transfer procedure. We have added text in Section 2.2 (first and second paragraphs) to address this and have removed all mention of "physically thin" clouds from the paper and replaced it with the phrase "strongly scattering, rapidly attenuating opaque" clouds.

3) Equation 9: discuss numerical differences between C_{day} and C_{night} and their evolution; what causes them? instrument temperature?

a. The time evolution of the CATS calibration coefficients is correlated to the thermal stability of the cooling loop on the ISS, which in turn is attributed to the changing of the sun's angle with respect to the ISS orbital plane, known as its beta angle. The CATS nighttime calibration coefficients oscillate from 4×10^8 to $1.4 \times 10^9 \text{ km}^3 \text{sr J}^{-1}$ counts with a period of roughly 30-40 days. This oscillation is a result of changes in the CATS laser properties (i.e. wavelength, alignment, energy) due to thermal instability of the cooling loop. The thermal instability of the cooling loop and instrument was monitored by the cold plate temperature. Text has been added to state all of these changes on page 6, lines 30-38. Also, Fig. 3 has been updated to include the entire mode 7.2 dataset (top, April 2015 – October 2017) as well as a subset from January- April 2016 (bottom). The daytime calibration coefficients for each month have been added as red dots. A discussion of

the daytime calibration values, variability, and comparison to nighttime calibration coefficients has been added starting at pages 7, line 36. Unfortunately, the funding for producing CATS data products has expired. But, if we were to ever receive funding to create another version of the CATS data products, we would make more rapid estimates of the daytime calibration coefficients than the current monthly estimates.

4) Section 2, lines 6-26: A few pieces of information on the instrument, that one deduces whilst reading the paper, should go in this section, so that the reader can begin thinking about them. I would discuss the following in this section: (1) how laser 1 and laser 2 are associated with modes 7.1 and 7.2; (2) the difference in PRF between the two lasers (4 and 5 kHz); (3) the signal folding due to the choice of PRF; (4) how this is reflected in the signal acquisition (with a data frame from -2 to 28 km); (5) the raw vertical and temporal resolution; and (6) any integration that is applied to the data prior to the signal processing described in the present paper.

a. All of the requested information has been added to the first paragraph of Section 2.

5) Equation 3: the colour ratio 0.4 is assumed because it is the value also assumed by Hair et al (2008). However, Hair et al do not give any explanation on why this value has been chosen, nor do they provide a reference! This should be discussed, and the error estimate on the colour ratio should be given explicitly. It could be useful to mention that this assumed colour ratio corresponds to a backscatter Angstrom exponent of 1.3, and that it is a colour ratio for "nearly clear air" (so is stated by Hair et al).

a. To the authors' knowledge, the value or variability of the stratospheric aerosol backscatter color ratio is not documented in the literature. For the mean value, we follow Hair *et al.* (2008), so $\chi_p = 0.40$ is taken as a constant for the aerosol loading in the upper troposphere/ lower stratosphere. This value is originally derived from backscatter data shown in Spinhirne et al. (1997). Given that sulfate aerosols are potentially the largest contributor to the stratospheric aerosol loading, this value is also consistent with lower tropospheric measurements of sulfate aerosols. Text has been added to page 5, lines 6-9 that now states this. For the error estimate (variability), we performed an analysis of SAGE III extinction Angstrom exponent, averaged from June 2017 to August 2018 in the CATS calibration region, to find a mean/standard deviation of 1.79 ± 0.10 . We use this standard deviation as a relative uncertainty for the backscatter color ratio, so we assume an absolute uncertainty in the stratospheric aerosol backscatter color ratio of 0.024. This is now explained in the text on page 8, lines 26-33.

6) P5 L12-17: please explain these criteria better: (1) why has each of them been chosen and what do they signify in terms of cloud physics? (2) why do they differ from the criteria used for daytime calibration? (3) how is the temperature determined? (please state if it comes from the reanalysis); (4) clarify how you determine the depolarization delta before you know PGR: are you using a previous data version for this? (5) equation 7 is missing the PGR as a multiplicative constant: have you already incorporated this into NRBperp? If this is the case, it is confusing, and I would recommend to write PGR explicitly, or to call NRBperp' = PGR * NRBperp.

a. These criteria are used to identify scenes with dense cirrus clouds that can be used to compute the PGR. These criteria are VERY similar to those used by CALIOP to identify cirrus clouds for their 1064 nm calibration transfer. We have now updated the text to clarify these things, as well as address 3, 4, and 5. These changes are on page 5, lines 28-34.

7) is the daytime or nighttime calibration coefficient and the PGR stored in the level 1 data files available for download? please state in the paper.

a. Yes, both these values are stored in the Level 1B files, and the paper now states this on page 5, line 23 and page 6, line 28.

5 8) The specifications of the units used is missing in several places: (1) Equation 1, what are the units for Ns? counts? count rate? voltage? and what are the units of NRB (e.g. counts * km² / J)? (2) Equation 8, what are the units for C (e.g. counts * km² * sr / j)? (3) P6 L7, specify the units with the calibration coefficients given here; (4) P7 L9, specify units of iATB values given (e.g. sr-1); Table 1 misses the specification of units (sr-1); etc.

a. **Anonymous Referee #4 also made this point. Thank you for catching this detail. The appropriate units have been added to the latest version of the manuscript throughout. You can see examples in the text corresponding to Equation 1 (page 3) and Equation 5 (page 5).**

10 MINOR COMMENTS:

15 9) The paper uses the normalisation technique to calibrate the signal; however, since aerosols have to be accounted for at the altitudes considered, I suggest that it should not be called a "molecular" normalisation technique. This can be achieved by removing the word "molecular" from lines 17 and 35 (abstract) and in a few places within the manuscript. In the conclusions, line 22, "Rayleigh profile" -> "Rayleigh profile corrected for aerosol contributions".

20 a. **Typically, this technique has always been called the Rayleigh or molecular normalization technique. However, most of the applications in the past were at 532 nm and in altitude regions with small aerosol contributions. Thus, we understand the referee's concerns. We have changed the phrases "Rayleigh/molecular normalization technique" to "atmospheric normalization technique" and "Rayleigh profile" to "Rayleigh profile corrected for aerosol contributions". A sentence on page 4, lines 16-19 defines this name.**

25 10) P2 L26: we have no measurements of crystal size, hence I would either remove the words "comprised of large ice crystals", or I would word it as a caveat (e.g. "thought to be mainly associated with ice crystals larger than the lidar wavelength").

a. **Text was changed as suggested (page 2, line 30)**

30 11) P3 L16: How is the laser energy E determined? Is it measured on-board? Is E an instantaneous value, a nominal one, or an average over a given time period?

a. **The laser energy per pulse is measured, then averaged onboard and reported at 20 Hz. Text was added to specify this (page 3, line 27)**

35 12) P3 L22: "averaging the signal acquired after the signal attenuated by the Earth's surface" add the words "after correction for the signal folding time (see below)".

a. **Text was changed as suggested (page 3, line 35)**

40 13) P4 L6: You earlier specified that the data frame is limited to -2 to 28 km; the fact that you use signals between -2.5 and -4.5 km for the evaluation of the background seems in my opinion to contradict this fact. Please explain, and please specify whether the data frame between -2 and 28 is limited by hardware design (acquisition electronics).

a. **This was a poorly chosen example. We have updated the text to use the example of -2.0 to 0.0 km, which includes signal from 37.5 to 39.5 km (page 4, line 24). Details of why the data frame was chosen to be -2 to 28 km are now provided in Section 2, first paragraph.**

45 14) P4 L23: "28 km" -> "26 km"

a. **Text was changed as suggested (page 5, line 4)**

50 15) P5 L7: remove "reflected" (this is scattered light, rather than reflected).

a. **The language was modified for accuracy.**

- 16) P5 L22: add "(multiplied by PGR)" after "perpendicular"
- a. Text was changed as suggested (page 6, line 9)
- 17) P5 L24: add the following before "To prepare", so as to clarify to the reader better what is the overall approach: "Nighttime calibration is applied on a per-granule basis, where a single calibration coefficient is determined as follows, for each data granule".
- a. New text has been added based on these suggestions and comment #3 from Anonymous Referee #4.
- 18) P5 L33: specify the value used for minimum and maximum thresholds.
- a. These threshold values vary based on the fluctuations shown in Figure 3. We added text specifying this (page 6, line 22).
- 19) P6 L1-4: is there any flagging of cases where the per-granule approach fails and you revert to using the previous week data? or is it exactly coincident with the flagging of files with a poor depolarisation quality?
- a. Yes. The L1B data products include a Quality Control Flag. The 23rd bit of this flag denotes when historical calibration coefficients have been used. The text has been updated to state this (page 6, line 30). This was a very helpful comment.
- 20) P6 L6-13: please explicitly state that an instrument temperature dependence is thought to be responsible for these fluctuations. Do you have any suggestion on which piece of the CATS hardware could be responsible?
- a. Please see our response to comments #3. We believe that the laser, given it is the most impacted by cooling loop temperatures, is leading to the changes in the calibration coefficients, but we don't have enough engineering data to determine what property of the laser is the source (wavelength shift, alignment with telescope, etc.).
- 21) P6 L22: precede line with "Instead,". "singular" → "single". "month": specify if this is calendar month (from 1 to last day of the month) or a rolling 30-day period.
- a. This sentence has been modified based on the referee's comments (page 7, line 12).
- 22) P6 L23: "colder than -20C": how is the temperature determined? see comment 6 on specifying how temperatures are determined.
- a. We added text specifying that the temperature comes from MERRA-2 data (page 7, line 14).
- 23) Figure 4: why does the shape of the distribution change so much? I would only expect a horizontal shift on the plot.
- a. As stated in lines 37-38 of page 7, the changes in distribution are attributed to changes in the layer typing algorithms implemented in CATS V3-00 data. For example, the V3-00 cloud phase algorithm removed the secondary peak in the nighttime distribution at 0.055 sr⁻¹ that was due to misclassification of liquid water clouds. See the [CATS ATBD](#) for more information about the feature identification algorithms. Yorks et al. (in prep) will include an update on these algorithms for V3-00.
- 24) P7 L6: add "on a monthly basis" after "V3-00".
- a. Text was changed as suggested (page 7, line 37)
- 25) P7 L8: I thought that equation 9 would ensure that the bias on the mean would be zero. Please explain better why a residual bias persists.

- a. The bias between the daytime and nighttime iATB is introduced by the temporal resolution of the calibration coefficient at nighttime (1 per file) and daytime (1 per month). This is now stated on page 8, lines 1-4.
- 26) P7 L28: "transmission" before "uncertainty".
- 5 a. Text was changed as suggested (page 8, line 23)
- 27) P7 L37: please give a numerical estimate of $(\Delta C / C)_{\text{sys}}$ before discussing the random error.
- a. The system error is estimated as 7%, and is now reported in the paper on page 8, line 35.
- 28) P8 L11-12: if the multiple scattering factor is the same for daytime and nighttime measurements, does it not cancel out? please explain if it is different for day and night instead.
- 10 a. Yes, you are correct that the multiple scattering factor would cancel out. That entire paragraph in Section 3 has been rewritten.
- 29) P9 L20: scattering ratio of 1.27: how much is the comparison with CATS sensitive to R? discuss the consequences of this assumption and its effect on the estimate of measurement errors; please specify if R is specified at 1064 or 532 nm.
- 15 a. We now specify that the scattering ratio is the 1064 nm particulate scattering ratio (page 10, line 27), and we recognize that this scattering ratio could be a reason for the better than expected agreement between CPL and CATS for this case (line 39, page 10).
- 30) P10 L2: "some of the differences in the ATB signal": I am not sure which differences you are referring to: the two do not look too different from each other!
- 20 a. We have deleted this sentence since it doesn't really add value to the discuss of the comparison of CPL and CATS for the 7-15 km altitude region.
- 31) P10 L30: add "PollyXT" before "1064 nm"
- a. Text was added as suggested (page 11, line 39)
- 32) P10 L39: specify how many profiles are accumulated in 30 min of PollyXT measurements.
- 25 a. PollyXT has a repetition rate of 20 Hz and they accumulate 30 seconds (i.e. 600 laser shots or single profiles). For a 30-min measurement segment, this makes $60 \times 600 = 36000$ single profiles. This is now specified on page 12, line 8.
- 33) P10 L40: add "CATS-like" between "mean" and "signal"
- a. Text was added as suggested (page 12, line 10)
- 30 34) P13 L30: please specify what changes to instrument design could permit the use of a higher calibration region. I suppose that one of them could be a reduction of the laser PRF (responsible for signal folding).
- a. As discussed in our response to comment #1, a sentence was added to the second paragraph of the conclusion to elaborate on how decreasing the laser repetition rate of a future CATS-like backscatter lidar could provide a larger data frame, and thus a higher calibration altitude.
- 35 35) Figures 10 and 11, y-axis: please specify whether this is a relative frequency expressed in % or an absolute frequency distribution. In Figure 11 make the x-axis label consistent with Fig. 10 for a better readability.
- a. We have updated the text to specify that this is a relative frequency and remade Figure 11 with an updated x-axis label.

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Cloud Aerosol Transport System (CATS) 1064 nm Calibration and Validation

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Abstract. The Cloud-Aerosol Transport System (CATS) lidar on board the International Space Station (ISS) operated from 10 February 2015 to 30 October 2017 providing range-resolved vertical backscatter profiles of Earth's atmosphere at 1064 and 532 nm. [The CATS instrument design and ISS orbit lead to a higher 1064 nm signal-to-noise ratio than previous space-based lidars, allowing for direct atmospheric calibration of the 1064 nm signals. Nighttime CATS Version 3-00 data were calibrated by scaling the measured data to a model of the expected atmospheric backscatter between 22 and 26 km above mean sea level \(AMSL\). The CATS atmospheric model is constructed using molecular backscatter profiles derived from Modern-Era Retrospective analysis for Research and Applications, Version 2 \(MERRA-2\) re-analysis data and aerosol scattering ratios measured by the Cloud-Aerosol Lidar with Orthogonal Polarization \(CALIOP\). The nighttime normalization altitude region was chosen to simultaneously minimize aerosol loading and variability within the CATS data frame, which extends from 28 km to -2 km AMSL. Daytime CATS Version 3-00 data were calibrated through comparisons with nighttime measurements of the layer integrated attenuated total backscatter \(iATB\) from strongly scattering, rapidly attenuating opaque cirrus clouds.](#)

The CATS nighttime 1064 nm attenuated total backscatter (ATB) uncertainties for clouds and aerosols are primarily related to the uncertainties in the [CATS nighttime calibration](#) technique, which are estimated to be ~9%. Median CATS V3-00 1064 nm ATB relative uncertainty at night within cloud and aerosol layers is 7%, [slightly lower than](#) these calibration uncertainty estimates. CATS median daytime 1064 nm ATB relative uncertainty is 21% in cloud and aerosol layers, similar to the estimated 16-18% uncertainty in the CATS daytime cirrus cloud calibration transfer technique. Coincident daytime comparisons between CATS and the Cloud Physics Lidar (CPL) during the CATS-CALIPSO Airborne Validation Experiment (CAVE) project show good agreement in mean ATB profiles for clear-air regions. Eight nighttime comparisons between CATS and the Polly^{XT} ground based lidars also show good agreement in clear-air regions between 3-12 km, with CATS having a mean ATB of 19.7 % lower than Polly^{XT}. Agreement between the two instruments (~7%) is even better within an aerosol layer. Six-month comparisons of nighttime ATB values between CATS and the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) also show that iATB comparisons of opaque cirrus clouds agree to within 19%. Overall, CATS has demonstrated that direct calibration of the 1064 nm channel is possible from a space based lidar using the [atmospheric](#) normalization technique.

1 Introduction

Deleted: The CATS instrument design and ISS orbit lead to a higher 1064 nm signal to noise ratio than previous space based lidars, allowing for direct 1064 nm calibration using the molecular normalization technique. Nighttime CATS Version 3-00 data were calibrated by normalizing the signal between 22-26 km above mean sea level to molecular profiles derived from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) re-analysis data. This altitude region was chosen primarily because the CATS data frame is -2 to 28 km AMSL due to the high CATS laser repetition rate. While this altitude region provides sufficient molecular scattering for the Rayleigh normalization technique, the aerosol loading in this altitude region must be quantified to improve the accuracy of the CATS nighttime calibration. Daytime CATS Version 3-00 data were calibrated through comparisons with nighttime thin, opaque, cirrus cloud layer integrated attenuated total backscatter (iATB).

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Lidar plays a crucial role in observing the Earth's atmosphere as it enhances our understanding of the roles clouds and aerosols play in the climate system by providing vertical profiles of backscatter coefficient and other optical properties. Lidar have been utilized to study [the vertical distribution and injection heights of smoke plumes \(e.g. McGill et al., 2003, Wang et al., 2013, Rajapakshe et al., 2017\)](#), [properties and transport of mineral dust aerosols \(e.g. Papayannis et al., 2009, Yang et al., 2013, Haarig et al., 2017\)](#), and [layer and optical properties of clouds \(e.g. Yorks et al., 2011, Avery et al., 2012, Haarig et al., 2016, Noel et al., 2018\)](#). Lidar, particularly from a spaceborne platform, has the capability to provide these vertical profiles of cloud and aerosol optical properties globally.

To derive optical properties of clouds and aerosols from backscatter lidar systems, the signal must be accurately calibrated. [While various methods have been used for calibrating lidar measured signal, the preferred method is the Rayleigh normalization technique, with minor if any corrections for aerosol contributions, as described in Russell et al. \(1979\)](#). Ground based lidars (e.g. Micro-Pulse Lidar Network (MPLNet) (Welton et al., 2001)) calibrate by normalizing their signal to the molecular profile, but require knowledge of the aerosol optical depth of the atmosphere between the instrument and the calibration region (Welton et al., 2002). [Since the MPLNet lidar sites are co-located with Aerosol Robotic Network \(AERONET\) \(Holben et al., 1998\) sites, the aerosol optical depth can be derived directly from the AERONET column optical depths measured by sun photometers.](#)

High altitude airborne and spaceborne lidars have the benefit of weak aerosol loading in the atmosphere between the instrument and the calibration region. Spaceborne lidars (e.g. Lidar In-Space Technology Experiment (LITE) (Winker et al., 1996), the Geoscience Laser Altimeter System (GLAS) (Spinhirne et al., 2005), and the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) (Winker et al., 2010) have used a similar [Rayleigh normalization technique to calibrate their 532 nm signals. Due to the weaker molecular signal to noise ratio \(SNR\) at 1064 nm compared to 532 nm for these instruments, calibration techniques for the 1064 nm attenuated total backscatter \(ATB\) calibration are based on the 532 nm ATB calibration \(Vaughan et al., 2019\).](#)

Operationally, LITE did not calibrate its 1064 nm channel. GLAS and CALIOP use variants of the cirrus cloud calibration scheme proposed by Reagan et al. (2002). The CALIOP algorithms first calibrate the 532 nm data by normalizing the data between 36-39 km (Kar et al., 2018) to a modeled molecular density profile derived from the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) re-analysis meteorological profiles (Gelaro et al., 2017). The 1064 nm signal is calibrated utilizing the 532 nm calibrated signal within cirrus clouds. [Clouds are identified for use in the calibration algorithm based on thresholds applied to the magnitude of the 532 nm layer-integrated attenuated backscatter \(\$sr^{-1}\$ \), cloud base and top altitudes, cloud temperature, and the layer-integrated 532 nm volume depolarization ratio \(Vaughan et al., 2019\).](#) Using cirrus comprised of [ice crystals assumed to be larger than the lidar wavelength](#) ensures that the in-cloud backscatter coefficients at 1064 nm and 532 nm are essentially identical (Reagan et al., 2002, Vaughan et al., 2010, Haarig et al., 2016), thus enabling calculation of a 532-to-1064 calibration scale factor for each qualifying cirrus cloud identified in the CALIPSO backscatter data. These calibration scale factors are then composited into a continuous time history using a two-dimensional moving window averaging scheme that spans multiple orbits. For any individual profile, the CALIPSO 1064 nm calibration coefficient is simply the product of the interpolated instantaneous value of the scale factor time history and the corresponding 532 nm calibration coefficient (Vaughan et al., 2019).

The Cloud-Aerosol Transport System (CATS) (McGill et al. 2015) onboard the International Space Station (ISS) is unique in that its strong nighttime SNR at 1064 nm enables calibration of the 1064 nm nighttime data directly by normalizing the range corrected signal to a modeled molecular profile. There are three factors that enable the direct calibration of CATS 1064 nm data. First, CATS utilizes photon counting detectors that provide sufficient detection sensitivity at 1064nm (Yorks et al., 2016).

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Second, the combination of low pulse energies (1-2 mJ) and higher repetition rate (4-5 kHz) lead to a higher output power (~8W) than all previous spaceborne lidars. Third, the CATS orbit on the ISS is considerably lower than other spaceborne lidars at ~405 km above mean sea level (AMSL). Section 2 of this paper discusses the CATS instrument, algorithms, and calibration. Section 3 discusses the uncertainties in the CATS calibration coefficients and attenuated total backscatter (ATB) measurements.

Comparisons with airborne, ground-based, and space-borne lidar are presented in Sect. 4. Concluding remarks are given in Sect. 5.

2 The CATS Instrument

CATS is an elastic backscatter lidar onboard the ISS, which operated nearly continuously from 10 February 2015 to 30 October 2017. With the ISS 51° inclination orbit, CATS provided diurnally varying measurements of clouds and aerosols. Over the course of the CATS lifetime, it operated in two modes. The first, mode 7.1, featured two fields-of-view with backscatter and depolarization information at both 1064 nm and 532 nm. Mode 7.1 utilized laser 1, which had a repetition ratio of 5 kHz and an output energy of ~1 mJ/pulse at both wavelengths. CATS operated in mode 7.1 for only 40 days due to a failure in laser 1 electronics, after which operations switched to mode 7.2. Mode 7.2 featured a single field of view, backscatter profiles at 1064 and 532 nm, and depolarization measurements at 1064 nm. Mode 7.2 used the second laser, which had a repetition ratio of 4 kHz and an output energy of ~2 mJ/pulse at 1064 nm. The different laser repetition rates yielded signal folding windows (see Section 2.1 for more details) of 30 km (mode 7.1) and 37.5 km (mode 7.2). To comply with ISS data rate limitations and simplify data system designs, the CATS data frame was set to -2.0 to 28 km (the lower of the signal folding windows of the two modes) for all modes. CATS data is reported at a vertical sampling interval of 60 m for both modes, with a temporal resolution of 20 Hz (~350 m horizontal given the speed of the ISS), which required onboard integration of 200 laser shots in mode 7.2 (250 for mode 7.1). Since the majority of the CATS data was collected in mode 7.2, this paper primarily focuses on results from mode 7.2, although the calibration process is the same for both.

CATS Version 3-00 data products, which are the focus of this paper, consist of two primary data processing levels. To create Level 1 (L1) data products, the raw CATS signal is range corrected, geolocated, corrected for detector non-linearity, and normalized to laser energy (measured onboard and averaged/reported at 20 Hz), producing the normalized relative backscatter (NRB). The NRB, in units of $\text{km}^2\text{J}^{-1}\text{counts}$, can be defined as:

$$NRB(r) = \frac{[N_s(r) * D] - N_B}{E} r^2, \quad (1)$$

where r is the range (meters), N_s is the geolocated CATS signal (photon counts), D is the correction term for detector non-linearity (unitless), and E is the laser energy (Joules). Since the detectors employed by CATS have a deadtime of 28 to 30 ns for a discriminator maximum count rate on the order of 30 MHz, and CATS has a photon count rate of less than 35 MHz 99% of the time below 28 km, D is less than 1.10 for most atmospheric profiles (Yorks et al., 2015). N_B is the photon counts from solar background, which can be determined by averaging the background signal acquired after the laser signal attenuated by Earth's surface and after the correction for the signal folding. Next, the signal is calibrated using the molecular profile derived from MERRA-2 meteorological re-analysis data. The calibration coefficients, determined through the methods described below, can be found in each CATS L1B data file (also called granule). For Level 2 (L2) data products, aerosol and cloud layers are detected and optical properties are determined. Descriptions of the L2 algorithms are beyond the scope of this paper, but more information about both L1 and L2 processing algorithms can be found in the CATS Algorithm Theoretical Basis Document (ATBD) (Yorks et al., 2015).

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2.1 CATS Nighttime Calibration

CATS exhibits high nighttime 1064 nm SNR, enabling 1064 nm attenuated total backscatter (ATB) direct calibration by normalizing the CATS signal to the Rayleigh profile corrected for aerosol contributions. Fig. 1 shows the CATS 1064 nm SNR for both night and day as compared to those of CALIOP 1064 nm. The CATS nighttime SNR is approximately an order of magnitude higher than that of CALIOP throughout the measurement column. On the other hand, the daytime CATS SNR is approximately a factor of 2 lower than CALIOP's, necessitating a different calibration technique for daytime data, as described in Section 2.2. The CATS nighttime signal is calibrated in the region between 22-26 km AMSL. There are two factors that determined this altitude region: (1) the CATS data frame is -2 to 28 km AMSL because the CATS laser 1 repetition rate of 5 kHz creates a 30 km atmospheric window for scattering from a single laser shot, and (2) testing of the highest possible altitude regions (based on #1) showed better performance in the 22-26 km than the 23-27 km region. While this altitude region provides sufficient molecular scattering for the Rayleigh normalization technique, the aerosol loading in the lower stratosphere (22-26 km) is also higher than the 36-39 km region used to calibrate 532 nm CALIOP data. To improve the accuracy of the CATS nighttime calibration, the aerosol loading in the calibration region must be quantified, along with the ozone transmission profile, molecular backscatter profile, and polarization gain ratio (PGR). Additionally, the background signal must be removed from the data. Since the CATS data is normalized to the Rayleigh profile corrected for aerosol contributions, more so than previous projects that have employed a similar technique, we will refer to the CATS nighttime calibration technique as the "atmospheric normalization technique" in this paper.

The nighttime atmospheric normalization technique is complicated by molecular folding of the raw signal caused by CATS' high repetition rate laser. Molecular folding refers to the fact that the CATS raw photon count at altitude, z , where $z < 28$ km, has scattering contributions from the atmosphere at heights $z + Nx$, $N=1,2,3$, etc., where x equals 37.5 km for mode 7.2 since laser 2 had a repetition rate of 4 kHz. The implications of this are that the region below the surface return (from -2.0 to 0.0 km), which is used for determining the background signal, also has molecular signal from 37.5 to 39.5 km. If this folded signal is not removed from the background signal, most of the signal in the calibration region will be removed by the background removal process. A correction term was implemented to account for this molecular folding. The folded signal is computed from instrument parameters and the known molecular attenuated backscatter cross section between 37.5 km and 39.5 km and subtracted from the signal in the background region (0.0 to -2.0 km below the ground). For nighttime data, this can affect the profile slope of the average signal above 20 km. If too much folding is removed, the slope will be greater than the molecular slope and if too little is removed, the average signal slope will be less than the molecular slope. In the data processing, a scaling factor in the folding equation is adjusted until the slope difference is less than 3.5%. The potential error introduced by this correction is discussed further in Sect. 3. For more information about molecular folding corrections, see the CATS ATBD (Yorks et al., 2015).

Depending on the profile location of the calibration region, the aerosol loading at those altitudes can introduce uncertainties in the computation of the calibration coefficient of any lidar system (Powell et al., 2009, Vernier et al., 2009, Kar et al., 2018). Thus, the CATS algorithm improves the calibration accuracy by incorporating a range-dependent particulate scattering

ratio (unitless fraction), $R_\lambda(r) = \frac{\beta_m(r) + \beta_{p,\lambda}(r)}{\beta_{m,\lambda}(r)} = 1 + \frac{\beta_{p,\lambda}(r)}{\beta_{m,\lambda}(r)}$, where λ indicates the wavelength of the measurement and $\beta_{m,\lambda}(r)$ and $\beta_{p,\lambda}(r)$ are, respectively, the volume backscatter coefficients for molecules and particulates (units $\text{km}^{-1} \text{sr}^{-1}$) at range r , with particulates being understood to represent either cloud or aerosol particles. No space-based sensors provide stratospheric particulate scattering ratios at 1064 nm on a global scale. However, since robust estimates of the 532 nm scattering ratios in the CATS vertical

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calibration zone can be readily derived from the CALIOP V4 Level 1 data, the CALIOP data is used to estimate the spatially and temporally varying 1064 nm scattering ratio at these altitudes (Fig. 2). Every 15 days, the CATS team computed 30-day zonal averages of the CALIOP 532 nm scattering ratios between 22 and 26 km. Given an estimate of the particulate (i.e., aerosol)

$$\text{backscatter color ratio (unitless fraction), } \chi_p = \frac{\beta_{p,1064}(r)}{\beta_{p,532}(r)} \quad (2)$$

1064 nm scattering ratios can then be computed from the 532 nm scattering ratios, which have been interpolated to the CATS vertical resolution, using

$$R_{1064}(r) = 1 + \frac{\chi_p \beta_{m,532}(r) (R_{532}(r) - 1)}{\beta_{m,1064}(r)} \quad (3)$$

where, following Hair *et al.* (2008), $\chi_p = 0.40$ is taken as a constant for the aerosol loading in the upper troposphere/ lower stratosphere. This value is originally derived from data shown in Spinhirne *et al.* (1997). Sulfate aerosols are potentially the largest contributor to the stratospheric aerosol loading (SPARC-ASAP, 2006; Vernier *et al.*, 2015; Kresmer *et al.*, 2016), and this value is also consistent with lower tropospheric measurements of sulfate aerosols (Groß *et al.*, (2013)). The ozone transmission, $T_o^z(r)$, is determined from the MERRA-2 ozone mass mixing ratios and meteorological profiles. The ozone transmission is calculated using

$$T_o^z(\lambda, r) = \exp[-2c_o(\lambda) \int_H^r \varepsilon_o(r') dr'] \quad (4)$$

where $\varepsilon_o(r)$ is the column density of ozone and $c_o(\lambda)$ is the Chappius ozone absorption coefficient (in cm^{-1}) obtained from a lookup table found in Iqbal (1984). The 1064 nm ozone coefficient is $\sim 0.0 \text{ cm}^{-1}$ leading to the ozone transmission at 1064 nm being 1.0 and negligible to the 1064 nm signal calibration.

The molecular backscatter coefficient is calculated using the relationship to atmospheric temperature and pressure (Collins and Russell, 1976), with

$$\beta_M = \frac{p}{KT} (5.45 \times 10^{-32}) \left(\frac{\lambda}{550}\right)^{-4.09} \quad (5)$$

where T is temperature (K), p is the atmospheric pressure (Pa), and K is the Boltzmann constant ($\text{m}^2 \text{ kg s}^{-2} \text{ K}^{-1}$). The atmospheric profiles of temperature and pressure are obtained from the MERRA-2 re-analysis data. The atmospheric profiles are interpolated to the 60 m vertical resolution of the CATS lidar backscatter data. The molecular extinction coefficient (σ_M , units km^{-1}) is determined through the relationship:

$$\sigma_M = \beta_M \left(\frac{8}{3}\right) \pi \quad (6)$$

The PGR, which is reported in the Level 1B data files as metadata, is required to account for relative gain between the CATS parallel and perpendicular channels in the receiver. The PGR is determined from the scattered solar background radiation ratio of the parallel-to-perpendicular channels from dense cirrus clouds following the methodology from Liu *et al.* (2004). It can be assumed that the difference in solar background counts between the two channels is negligible because scattered solar radiation from dense ice clouds is unpolarized (Liou *et al.*, 2000). The CATS PGR is computed through the ratio of the sum of all parallel and perpendicular profiles in a daytime granule containing dense ice clouds. The profiles with dense ice clouds used in this computation, which are similar to those used in the CALIOP 1064 nm calibration technique as outlined in Vaughan *et al.* (2010), are identified through the following criteria:

- 1) Mid-cloud temperature $< -35 \text{ C}$, as reported by MERRA-2
- 2) Cloud layer integrated ATB (iATB): $0.008 < \text{iATB} < 0.044 \text{ sr}^{-1}$

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$$\chi_p = \frac{\beta_{p,1064}(r)}{\beta_{p,532}(r)} = 0.4. \rightarrow \text{-----} ($$

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3) Layer integrated depolarization ratio **NRB data** (δ_{1064}): $0.3 < \delta_{1064} < 0.8$

where:

$$\delta_{1064} = \frac{\sum_{\text{layer}} \text{NRB}_{\text{perp}} \text{PGR}_{\text{hist}}}{\sum_{\text{layer}} \text{NRB}_{\text{par}}} \quad (\text{where } \text{PGR}_{\text{hist}} \text{ is a historical PGR value}) \quad (7)$$

4) Cloud optical depth > 1.75 (estimated using the iATB and assumed lidar ratio of 25 sr)

5 These criteria were only used to identify cirrus clouds that would be suitable for calculating the PGR. Historical calibration coefficients and PGR values were used to estimate iATB, depolarization ratio, and optical depth. These historical values were not applied to the raw data during the actual PGR calculation. Because the CATS instrument ceased operation prior to the processing of CATS V3-00 data, a singular yearly average PGR value was used for 2015, 2016, and 2017 equaling 0.9839, 0.9768, and 0.9708 respectively. The PGR is applied as a multiplicative factor to the perpendicular channel NRB data. The perpendicular (multiplied by the PGR) and parallel NRB data are added together to arrive at the total NRB.

10 A single calibration coefficient for nighttime data is applied to the NRB profile on a per file, or granule, basis, using the methodology as follows to obtain the attenuated total backscatter ($\text{km}^{-1} \text{sr}^{-1}$) profiles. To prepare for calibration, the CATS night granules are separated into six segments averaging 7.8 minutes each, depending on the length of the granule. Granules are the files for the CATS data that span about half of the ISS orbit and contain only daytime or only nighttime observations. For calibration, the total NRB profile is averaged within each segment. The average total NRB profile is divided by the ozone transmission and scattering ratio of the corresponding wavelength as a function of height. The profiles of calibration coefficient (C), in units of $\text{km}^3 \text{sr J}^{-1}$ counts, for each segment within a file are determined by normalizing the mean NRB signal which has been corrected for aerosol loading and the ozone transmission, β_{CN} , to the mean molecular backscatter ($\beta_{\text{M}} T_{\text{M}}^2$) (Russell *et al.* 1979, Del Guasta 1998, McGill *et al.* 2007, Powell *et al.* 2009), via

$$C_{\lambda}(r) = \frac{\frac{\text{NRB}(r)}{T_{\text{O}}(r) R(r)}}{\beta_{\text{M}}(r) T_{\text{M}}^2(r)} = \frac{\beta_{\text{CN}}(r)}{\beta_{\text{M}}(r) T_{\text{M}}^2(r)} \quad (8)$$

20 The final calibration coefficient for the segment is the average coefficient in the calibration region profile (i.e. an average of $C(r)$ from 22 to 26 km). Each coefficient is compared to minimum and maximum threshold values, which vary based on the fluctuations shown in Fig. 3, to determine if the calculated value is within acceptable bounds. If the coefficient is not, it is discarded, and not used in the final calibration calculation. The calibration thresholds were determined through prior experience calibrating airborne lidar as well as through testing on CATS data during which outliers that negatively impacted the total calibration were identified. All good calibration values within a file are then averaged. On average, 67% of calibration values within a given granule are accepted and used for determining the final calibration coefficient for that file. If less than 15% of calibration values are accepted, a default calibration coefficient is used for that granule, computed as the mean of the calibration coefficients from the previous week of data. These files represent 3% of CATS data, typically when the laser was recently turned on after being off for more than 2 hours, and are noted in the Quality Control Flag variable in the CATS LIB data products. The final calibration coefficient, which is also reported in the Level 1B data files, is then applied to all NRB profiles within the granule to compute the ATB.

25 The time evolution of the CATS nighttime calibration coefficients is correlated with the thermal stability of the cooling loop on the ISS, which in turn is attributed to the changing of the sun's angle with respect to the ISS orbital plane, known as its beta angle. The CATS nighttime calibration coefficients oscillate from 4×10^8 to $1.4 \times 10^9 \text{ km}^3 \text{sr J}^{-1}$ counts with a period of roughly 30-40 days. This oscillation is a result of changes in the CATS laser properties (i.e. wavelength, alignment, etc.) due to thermal instability of the cooling loop. The thermal instability of the cooling loop and instrument was monitored by the cold plate temperature. Fig. 3 shows the daily average nighttime calibration coefficient (black x's and black line) and CATS cold plate

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temperature (blue) for the entire mode 7.2 dataset (top, April 2015 – October 2017) and for a subset from January- April 2016 (bottom). The changing value of the calculated calibration coefficient follows the same pattern as the cold plate temperature. The daily average nighttime calibration coefficient and cold plate temperature have a correlation coefficient of 0.8066 during the period of January- April 2016.

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2.2 CATS Daytime Calibration

Because CATS daytime data exhibits lower SNR due to solar background noise, calibrating the daytime granules through the atmospheric normalization method is not possible. Therefore, the daytime calibration coefficients are determined through calibration transfer from the nighttime calibration (Eq. 9). In previous CATS data versions, the daytime calibration was determined through a manual normalization to the Rayleigh profile corrected for aerosol contributions that required periodic assessment and updates. For V3-00 CATS data, a single daytime calibration coefficient was determined for each calendar month of CATS data through an assessment of the iATB (sr^{-1}) in strongly scattering opaque cirrus clouds that have a mid-layer temperature colder than -20°C (based on the MERRA-2 reanalysis data) and a layer integrated depolarization ratio between 0.25 and 0.7. Only highly scattering, rapidly attenuating clouds (CATS signal attenuated in 2 km or less) were used in the assessment.

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It was found that using a month of data provided enough data points to compute a calibration value while also reasonably capturing the temporal variability of calibration coefficients. The assessment of cirrus cloud properties was done using V2-01 CATS data in which the layer detection and optical properties algorithms were already run. A layer is classified as opaque if no layer or ground signal is detected below it. The iATB is calculated through the cloud until the point of signal attenuation. For the strongly scattering, rapidly attenuating opaque cirrus selected for the daytime calibration transfer procedure, there should be little difference between nighttime and daytime iATB retrievals. This characteristic of cirrus clouds has been observed in CALIOP data as shown in Young et al. (2018). Young et al.'s CALIOP comparisons of opaque cirrus at 532 nm showed substantial iATB similarities for both nighttime and daytime measurements, with a peak iATB of $\sim 0.03\text{ sr}^{-1}$ in both cases. Given that there is relatively little difference in the backscatter from cirrus clouds between 532 nm and 1064 nm (Vaughan et al., 2010, Haarig et al., 2016), one would expect that the daytime and nighttime iATB distributions from 1064 nm retrievals should also be similar.

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The daytime calibration coefficient is computed as

$$C_{day} = \frac{\frac{1}{N_{day}} \sum_{k=1}^{N_{day}} iNRB_k}{\frac{1}{N_{night}} \sum_{k=1}^{N_{night}} iATB_k} \quad (9)$$

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where both the nighttime iATB and daytime iNRB were computed over each calendar month of CATS data. The left panel of Fig. 4 demonstrates the CATS daytime calibration for the month of August 2016. In the CATS V2-01 data, the daytime cirrus iATB distribution is shifted higher than the nighttime distribution, with a peak at 0.05 sr^{-1} . For the V3-00 CATS processing, the daytime calibration coefficient for August 2016 was increased from 6×10^8 to $9 \times 10^8\text{ km}^3\text{sr J}^{-1}\text{ counts}$ and was applied to all August 2016 daytime granules. As seen in the right panel of Fig. 4, this change resulted in the peak of the daytime cirrus iATB distribution moving to $\sim 0.03\text{ km}^{-1}\text{sr}^{-1}$ with better agreement with the nighttime distribution. Overall, it was found that a change of $\sim 1 \times 10^8\text{ km}^3\text{sr J}^{-1}\text{ counts}$ in the calibration coefficient results in a shift of $\sim 0.01\text{ sr}^{-1}$ in the iATB. This method was applied to all CATS mode 7.2 daytime data in V3-00 on a monthly basis. Changes in the nighttime cirrus iATB distributions between versions are attributed to improvements in the layer type classifications within the L2 processing (Yorks et al., in prep.).

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Most of the CATS daytime calibration coefficients range from 6×10^8 to $9.0 \times 10^8 \text{ km}^3 \text{ sr}^{-1} \text{ counts}$, with less variability compared to the nighttime calibration values given they are monthly-mean values (less temporal resolution than the nighttime values since it is computed every month and not every granule). The loss of this temporal resolution of the daytime calibration coefficients introduces a bias compared to the nighttime calibration coefficients. Overall, the daytime calibration method results in average biases of roughly 10%, based on the mean, median, and mode daytime iATB values with respect to nighttime of 0.000168, -0.001215, and -0.00258 sr^{-1} , respectively (Table 1). The mean absolute error (MAE) values also indicate that, overall, the distribution statistics between night and day granules are similar, with MAE values equating to 8-13% error in the peak of the distribution and 17% error in the standard deviation of the distribution.

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3 Error Analysis

There are two types of error that contribute to the uncertainty in the CATS calibration: systematic and random errors. There are four sources of uncertainty included in the systematic error calculation (Yorks et al., 2015). They are: uncertainties in the scattering ratios (R) at 22-26 km from CALIOP, including assumptions of backscatter color ratio, uncertainties in the molecular backscatter (β_M) computed from MERRA-2 data, uncertainty in the modeled two-way transmittance (T^2) from atmospheric molecules and ozone, and errors introduced by the CATS optical system. The optical system error can be reduced through corrections such as deadtime correction and energy normalization to less than 0.1% and is therefore negligible. The total systematic error in the calibration, following the method outlined by Powell et al. (2009), can be defined as

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$$\left(\frac{\Delta C}{C}\right)_{\text{sys}} = \sqrt{\left(\frac{\Delta R}{R}\right)^2 + \left(\frac{\Delta \beta_M}{\beta_M}\right)^2 + \left(\frac{\Delta T_M^2}{T_M^2}\right)^2 + \left(\frac{\Delta \chi_p}{\chi_p}\right)^2} \quad (10)$$

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The errors in the molecular backscatter and background transmission are assumed to be constant, equaling 3% and 0.2% respectively. Regan et al. (2002) estimates transmission uncertainty for the 532 nm molecular backscatter coefficient of 3% and uncertainty at 1064 nm at a nominal cirrus cloud top altitude of 0.2%. Thus, the constant 3% molecular backscatter uncertainty is conservative, and results from uncertainties in GMAO-derived temperatures from the upper troposphere that are estimated to be less than 1 °C (Campbell et al., 2015). Omitting the King factor, which accounts for the anisotropy of molecules, in our molecular backscatter computation leads to an additional error of 1-3% in the molecular backscatter error (Hostetler et al., 2005). This additional error contributes to less than 1% error in the total systematic calibration, making is far less important than other factors covered in this paper, especially given that the 1064 nm molecular backscatter uncertainty is likely overestimated. The error in the scattering ratio is dominated by the uncertainty and variability of the CALIOP nighttime scattering ratios, which ultimately results from the uncertainty in the CALIOP nighttime calibration, estimated to be $1.6\% \pm 2.4$ (Kar et al., 2018). The final source of systematic error is the assumption that the backscatter color ratio of the stratospheric aerosols between 22 and 26 km is constant at 0.40. To the authors' knowledge, the variability of the stratospheric aerosol backscatter color ratio is not documented in the literature, but an analysis of Stratospheric Aerosol and Gas Experiment (SAGE) III extinction Angstrom exponent averaged from June 2017 to August 2018 in the CATS calibration region yields 1.79 ± 0.10 . Thus, we assume an absolute uncertainty in the stratospheric aerosol backscatter color ratio of 0.024. Applying Eq. (10) to these values, the total systematic relative uncertainty in the CATS calibration coefficients is estimated at 7%.

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The random error in the CATS calibration is primarily caused by noise in the lidar signal during the calibration normalization. The random error can be determined through the variability of the NRB signal within each calibration segment (Welton and Campbell, 2002) and is calculated through

$$\left(\frac{\Delta C}{C}\right)_{ran}^2 = \left(\frac{\text{stdev}(NRB(r))}{\sqrt{N}}}{NRB(r)}\right)^2, \quad (11)$$

where N is the total number of NRB values used. For CATS, the 7.8 min averaging interval equals 9,360 profiles. This averaging interval was chosen because it reduced the random error of each individual calibration value within a granule, but still provided sufficient values (at least 6) to compute the granule mean calibration coefficient. Uncertainties in background subtraction and other CATS correction terms (discussed in Sect. 2) are included in the NRB variability. The mean random error in the calibration coefficient is 6%. The total error is determined through

$$\left(\frac{\Delta C}{C}\right)_{tot}^2 = \left(\frac{\Delta C}{C}\right)_{sys}^2 + \left(\frac{\Delta C}{C}\right)_{ran}^2 \quad (12)$$

and thus, comes to a total relative uncertainty in the CATS nighttime calibration ($\Delta C/C$) of ~9%.

The daytime calibration uncertainty can be estimated from the variability of the NRB signal and the nighttime calibration error. The nighttime calibration already contains several systematic uncertainties that are inherited during the calculation of the daytime calibration coefficients. Additionally, since strongly scattering cirrus clouds are used in the daytime calibration, uncertainties in the multiple scattering factor, η , should also be considered. Multiple scattering occurs when laser light emitted by the lidar interacts with more than a single particle within a scattering volume. Multiple scattering can lead to higher detected signals and is corrected using the appropriate value of η (Platt, 1979, Garnier et al., 2015). For CATS, η for cirrus clouds was determined to be 0.52 through comparisons with the Cloud Physics Lidar (CPL). The magnitude of multiple scattering contributions to the backscattered signal depends critically on both instrument viewing geometry and particle phase function. However, since neither of these factors is expected to show any discernable diurnal variability, we assume that uncertainties in our knowledge of η can be neglected when assessing the error sources for the CATS daytime calibration. Since a constant daytime calibration coefficient is determined for each month of CATS data and is based on comparisons with nighttime data, the total systematic error for the daytime calibration can be estimated to be the same as the average nighttime calibration uncertainty over the month.

The daytime random error is estimated from the variability in the NRB signal. Therefore, the total daytime error can be shown through the equation

$$\left(\frac{\Delta C}{C}\right)_{day}^2 = \left(\frac{1}{N_{day}}\right)^2 \sum_{k=1}^{N_{day}} (\Delta iNRB)_{day,k}^2 + \left(\frac{1}{N_{night}}\right)^2 \sum_{k=1}^{N_{night}} (\Delta iNRB)_{night,k}^2 + \frac{1}{N_{night}} \sum_{k=1}^{N_{night}} (\Delta C)_{night,k}^2 \quad (13)$$

The daytime random error due to the noise in the NRB is estimated to be ~15%, leading to a total daytime calibration uncertainty of ~16-18%.

The ATB uncertainties are computed using a propagation of errors from the NRB uncertainties. ATB is calculated through

$$ATB = \frac{NRB}{C}. \quad (14)$$

NRB uncertainties (ΔNRB) are calculated using the methodology outlined in Welton and Campbell (2002). By utilizing a standard propagation of errors from the NRB uncertainty and the calibration uncertainty, the ATB uncertainty was computed and can be expressed as

$$\Delta ATB = \sqrt{\left(\frac{1}{C}\right)^2 \Delta NRB^2 + \Delta C^2 \left(\frac{NRB}{C^2}\right)^2}. \quad (15)$$

As part of the NRB error, there is error associated with the molecular folding correction factor (see Sect. 2.1) which impacts the ATB profile. Since the correction factor acts by matching the slope of the measured signal to that of the modeled

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molecular profile within the calibration region, the error was assessed through the amount of error introduced lower in the CATS profile for given errors in the calibration region slope. In V3-00, the majority of corrected slopes in the calibration region have an error of less than 3.5%. However, in very few cases, the slope is different from the molecular slope by 10% in the calibration region. The assessment of this “worst case” calibration region slope error showed that the maximum error introduced in the profile is ~4% in the 17-18 km region. The error in the profile then decreases as the signal approaches the surface, introducing ~2% error.

The CATS 1064 nm ATB uncertainties for clouds and aerosols at night are primarily related to the uncertainties in the atmospheric normalization technique. Features such as cloud and aerosol layers with higher backscatter intensities tend to have lower ATB uncertainty, while clear air regions, with lower scattering intensity and lower SNR, have higher ATB uncertainty.

The median CATS 1064 nm ATB relative uncertainties from the Mode 7.2 V3-00 data products within cloud and aerosol layers are 7% at night and 21% during daytime. For clear-air regions, there is large variability (20% to over 100%) in the CATS 1064 nm ATB relative uncertainties, since the SNR varies as a function of altitude at night due to molecular scattering and scene during daytime due to the noise introduced from the solar background.

4 Data Comparisons

4.1 Airborne Lidar Comparisons

During the CATS-CALIOP Airborne Validation Experiment (CCAVE) in August 2015, the NASA ER-2 conducted several ISS under flights. As part of the CCAVE payload, CPL was able to collect coincident data with CATS. CPL is an airborne backscatter lidar that has participated in over thirty field campaigns, including several satellite instrument validation projects (McGill et al., 2002). CPL data products include ATB from both 1064 and 532 nm. Similar to nighttime CATS data, CPL is calibrated by normalizing the signals acquired between 15 km and 17 km to a modeled molecular attenuated backscatter profile derived from MERRA-2 reanalysis data. A 1064 nm particulate scattering ratio of 1.27 is applied in the calibration region for 1064 nm data, based on the work of Vaughan et al. (2010), and the estimated aerosol loading within a standard atmospheric profile in the northern hemisphere.

Fig. 5 shows the coincident flight from the CCAVE project which occurred at 01:37 UTC on 7-8 August 2015 during the day over western Nevada. CPL flew beneath CATS with clear sky conditions, although this scene is made more complicated due to variations in the terrain and background smoke aerosols due to wildfires in the region, as can be seen in the curtain plot (Fig. 5-left). The CATS average is comprised of 165 profiles which spans 55 km, and is calibrated using the daytime cirrus cloud calibration transfer technique. The CPL mean profile is an average of 280 profiles. Despite the complicated terrain and smoke, the mean ATB profiles from CATS and CPL still shows good agreement in the clear sky region above the smoke, with the average CPL and CATS mean ATB between 7-15 km equal to $4.1927 \times 10^{-5} \text{ [km}^{-1}\text{sr}^{-1}\text{]}$ and $4.0972 \times 10^{-5} \text{ [km}^{-1}\text{sr}^{-1}\text{]}$ respectively, meaning the CATS average ATB was 2.28% below CPL. This agreement is surprising since the CATS daytime calibration uncertainty is ~16-18%, but this case occurred near local twilight when CATS SNR is higher and the 1.27 value of the 1064 nm particulate scattering ratio used for CPL could be too low, introducing errors in the CPL 1064 nm ATB profile.

Another daytime underpass occurred at 20:31 UTC on 20 August 2015 over northern Utah near Great Salt Lake. The CPL curtain plot and the mean ATB profile from both CATS and CPL centered around the overpass time can be seen in Fig. 6. The CPL data was averaged to six minutes (360 ATB profiles) which covers a distance of about 70 km. The CATS data were averaged over the same distance and is comprised of 210 ATB profiles, and like the 7-8 August 2015 case is calibrated using the daytime cirrus cloud calibration transfer technique. As shown in the CPL curtain plot, the underpass segment was in clear-sky

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conditions (no clouds) with a well-defined smoke aerosol layer from nearby wildfires. Both instruments observed the top of this aerosol layer around 5 km AMSL. The differences in SNR are also apparent as the CATS profile is noisier than the CPL profile. The average CPL ATB value between 7-15 km was $4.2967 \times 10^{-5} [\text{km}^{-1} \text{sr}^{-1}]$ and the average CATS ATB was $5.1939 \times 10^{-5} [\text{km}^{-1} \text{sr}^{-1}]$, 20.88% higher than CPL. These differences are expected given the 16-18% CATS daytime calibration uncertainty.

The greater noise in the CATS signal on the 20 August case should be noted as compared to the 7-8 August case. This is likely attributed to the different times of day the two flights occurred. The 7-8 August flight occurred in the early evening, which will minimize the noise induced by solar background due to the lower sun angles, while the 20 August flight occurred closer to local noon, which will maximize noise from sunlight. For both under-flights, the error in the CATS ATB compared with CPL is well within the uncertainty estimates of both instruments.

4.2 Ground-based Comparisons

In addition to the coincident airborne CPL data, CATS was also compared to ground-based systems. CATS frequently passed over (or close to) the European Aerosol Research Lidar Network (EARLINET) sites. The Polly^{XT} lidar (Baars et al., 2016; Engelmann et al., 2016) is a Raman lidar developed by at the Leibniz Institute for Tropospheric Research (TROPOS), Leipzig, Germany and is used at some EARLINET sites. The Polly^{XT} systems emit laser pulses at 1064, 532, and 355 nm with elastic backscatter detectors at each wavelength, as well as Raman channel detectors at 386.73 and 607.4 nm. There are Polly^{XT} lidars all across Europe as part of the EARLINET, but only data collected from the Leipzig, Germany (51.3N; 12.4E) and the Athens NOA (National Observatory of Athens) (37.97 N; 23.71 E) sites were used in this study.

Raw EARLINET data are processed through the Single Calculus Chain (SCC) (D'Amico et al., 2015). The first part of the SCC is the EARLINET Lidar Pre-Processor (ELPP) where the raw lidar signal is range and deadtime corrected, the background signal is subtracted, and molecular extinction and transmission profiles are computed from meteorological radiosonde data or the standard atmosphere (D'Amico et al., 2016). The second part of the SCC is the EARLINET Lidar Data Analyzer (ELDA) (Mattis et al., 2016). In the ELDA the backscatter coefficients, extinction coefficients, and lidar ratio are derived. During the backscatter coefficient calculation, the EARLINET data is calibrated by normalizing it to the molecular using an assumed aerosol free region, which is determined by the ELDA algorithms.

Using the particulate backscatter and particulate extinction profiles derived from the Polly^{XT} data, "CATS-like" ATB profiles were calculated following the methodology outlined in Mona et al. (2009) where the attenuated backscatter coefficient can be defined as

$$\beta'(z) = \beta_{\text{tot}}(z) T_{\text{par}}^2(z) T_M^2(z). \quad (16)$$

β_{tot} is the total backscatter coefficient comprised of contributions from particles, molecules, and ozone. T_{par}^2 is the particulate transmittance and is calculated through

$$T_{\text{par}}^2(z) = \exp\left(-2 \int_z^{z_s} \alpha_{\text{par}}(\zeta) d\zeta\right), \quad (17)$$

where α_{par} is the particulate extinction and z_s is the CATS altitude. The particulate backscatter was computed from the Polly^{XT} 1064 nm and 607 nm signals through the methodology described in Proestakis et al. (2019). The uncertainty in the backscatter coefficient retrieval is estimated to be between 5-20% (Ansmann et al., 1992; Whiteman et al., 2003; Povey et al., 2014). The particulate extinction coefficient was calculated using the Klett method (Klett, 1981; Fernald, 1984) using assumed lidar ratios between 30 - 35 sr. Sun photometer data was used, wherever possible, to estimate the lidar ratio. The molecular signal and attenuation profiles were computed from the temperature and pressure profiles found within the CATS L1B HDF5 file corresponding to the overpass.

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Fig. 7 shows the mean ATB profiles from the nighttime CATS overpass of the Leipzig Polly^{XT} site on 24 September 2015 at 01:13:34 UTC. CATS passed 31 km from the Leipzig site. The mean profiles consist of forty CATS ATB profiles (~10 km) and thirty minutes of Polly^{XT} data (36,000 profiles). This difference in number of averaged profiles is a contributing factor to the difference in the noise between the two instrument profiles. The CATS mean ATB profile was 7.7 % higher than the Polly^{XT} mean CATS-like signal between 3-12 km. Another nighttime overpass, shown in Fig. 8, occurred on 30 July 2015 at 00:18:19 UTC ~41 km away from the Leipzig site. In this overpass, CATS ATB was 14.1% lower than the Polly^{XT} data between 3-12 km.

Overall, eight clear-sky, nighttime overpasses were used in this analysis. The average difference from 3-12 km between CATS and Polly^{XT} ATB was 19.7% with an average CATS distance from the Polly^{XT} site of 40 km (Fig. 9). Fig. 9 also shows the CATS and Polly^{XT} ATB scatter plot from all eight overpasses. The correlation coefficient between the two instrument retrievals is 0.75. The difference between the two instruments falls within the uncertainties in the CATS ATB (Sect. 3) and the uncertainties in the Polly^{XT} retrievals. In addition to the clear sky comparisons, one overpass which had strong aerosol scattering within the planetary boundary layer (PBL) was assessed. The center-most 1.25 km of the PBL depth retrievals were compared to avoid spatial inhomogeneities in the PBL top and ground height. CATS underestimated Polly^{XT} by 7%, supporting the ATB uncertainty assessment in Sect. 3 of lower ATB uncertainties (~8%) within stronger backscattering layers. Given the high SNR of CATS 1064 nm nighttime signal (Fig. 1), these differences can be primarily attributed to the ~9% uncertainty in the CATS nighttime atmospheric normalization calibration technique.

Previous studies have investigated the validity of using EARLINET for spaceborne lidar validation (Mamouri et al., 2009; Papagiannopoulos et al., 2016; Proestakis et al., 2019) and have found it is a useful method for lidar validation. A major source of the variability between the ground-based and spaceborne measurement results was found to be the variances in the atmospheric scene observed due to the spatial and temporal differences in the measurements. In a CALIOP validation study by Mamouri et al. (2009), it was found that for comparisons where the over pass was within 100 km from the EARLINET site the variability of the aerosol loading introduced a discrepancy on the order of 5%.

4.3 CALIOP Comparison

In addition to coincident data, statistical comparisons with CALIOP measurements can be used to further assess the CATS calibration. However, differences in instrument design can make the interpretation of these comparisons somewhat challenging. CALIOP measures the total backscatter in the 1064 nm channel using a single avalanche photodiode (APD), which simultaneously delivers a desirable high quantum efficiency and a less desirable high dark noise count rate that has been increasing linearly over the course of the mission (Hunt et al., 2009). CATS, on the other hand, uses a pair of photon counting modules to separately measure the 1064 nm backscatter components polarized parallel and perpendicular to the polarization plane of the CATS laser. The difference in detector performance is illustrated in Fig. 10, which shows the occurrence frequencies of the attenuated backscatter coefficients measured by CATS and CALIOP between 1 April and 30 September 2016 at all latitudes between 51.8° N and 51.8° S. This comparison was designed to investigate distributions of cirrus cloud backscatter intensity, so the data are restricted to nighttime measurements extending from 0 to 5 km above the point where the atmospheric temperature in any profile first drops below -40° C.

Because CATS uses photon counting detectors, the molecular backscatter signals in the CATS distribution appear as a sharp, well-confined peak at $\sim 2.5 \times 10^{-5} \text{ km}^{-1} \text{ sr}^{-1}$. The substantial broadening of the CALIOP distribution in this region is a consequence of the high APD dark noise levels in the CALIOP detectors. The distributions begin to converge above $\sim 0.008 \text{ km}^{-1}$

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¹ sr⁻¹, although the CATS occurrence frequencies remain persistently lower than CALIOP throughout. Approximately 99.7% of all attenuated backscatter coefficients measured for both lidars lie below 0.025 km⁻¹ sr⁻¹. Some of the differences at higher ATB values may be a consequence of the fact that these are not coincident measurements; because the two instruments fly in very different orbits, they sample different regions of the atmosphere at different times of day. CALIPSO flies in a sun-synchronous 98° orbit with a 16-day repeat time, and thus CALIOP measurements are acquired at approximately the same time of day at any given location along the orbit track (Hunt et al., 2009). The ISS flies in a 52° precessing orbit with a 3-day repeat time, so that CATS measurements at identical locations will occur at many different times of the day. This precessing orbit allows CATS data to be used to assess the diurnal variability of clouds and aerosols.

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To avoid the confounding effects introduced by APD dark noise contamination of the weaker signals measured by CALIOP, a second study was conducted comparing the iATB from opaque cirrus detected by the two sensors. This study used CATS and CALIOP data acquired between 1 March and 31 December 2016, with the latitude range once again confined to between 51.8° N and 51.8° S. The following cloud selection criteria were applied uniformly to both data sets.

- (a) All layers must be classified as opaque ice clouds and be the uppermost (and only) layer in the column.
- (b) All layers must be detected at a nominal 5-km horizontal averaging resolution.
- (c) The mid-layer temperature for all layers must lie below -37° C (see Campbell et al., 2015).
- (d) Only nighttime measurements are used.

A comparison of the resulting frequency distributions is shown in Fig. 11. Descriptive statistics of the iATB values measured by each lidar are given in Table 2. In both Fig. 11 and Table 2, the mean CATS iATB is seen to underestimate CALIOP by ~11.8%. However, direct comparisons of mean iATB measured in opaque cirrus cannot fully characterize the calibration differences between the two instruments. In particular, any comprehensive evaluation must consider differences in the contributions of multiple scattering to the backscattered signals. Instrument-specific causes for these differences include different laser spot sizes, different receiver fields of view, and different orbit altitudes.

The iATB for opaque layers can be expressed in terms of the layer extinction-to-backscatter ratio, S (more commonly known as the lidar ratio), and a dimensionless, instrument-specific multiple scattering factor, η , using Platt's equation (Platt, 1973):

$$iATB = \frac{1}{2\eta S}. \quad (18)$$

Aggregating 10 months of nighttime measurements acquired within the same time frame and latitude limits yields very large sample sizes for both data sets, so we can reasonably assume that the distribution of lidar ratios observed by CATS and CALIOP are essentially identical. But we cannot assume that the CATS and CALIOP multiple scattering factors are identical, as they depend not only on the phase functions of the measurement targets (in this case, cirrus clouds) but also on instrument design and viewing geometry (Winker, 2003). As mentioned in Sect. 3, the value of η for CATS ($\eta_{\text{CATS}} = 0.52$) has been determined empirically via comparisons to coincident CPL measurements. The cirrus multiple scattering factors applied in the CALIOP V4.10 data release were also determined empirically using extensive coincident measurements made by the CALIPSO infrared imaging radiometer (Garnier et al., 2015). Unlike CATS, η_{CALIOP} is not a fixed constant, but is instead implemented as a function of cloud temperature.

For the opaque cirrus clouds sampled by CALIOP in this study, $\eta_{\text{CALIOP}} = 0.55 \pm 0.06$. Assuming that both instrument teams have accurately characterized cirrus multiple scattering effects on their respective systems, enforcing the assumption that the lidar ratio distributions observed by CATS and CALIOP are essentially identical, we can establish the relative difference in attenuated backscatter measurements between the two lidars using $(i\text{ATB}_{\text{CALIOP}} \times \eta_{\text{CALIOP}}) / (i\text{ATB}_{\text{CATS}} \times \eta_{\text{CATS}}) = (0.0313 \times 0.55) / (0.0280 \times 0.52) = 1.182$. This result is consistent with the previous PollyXT comparisons. In “clear air” regions, [the difference between CATS V3-00 L1B data products and PollyXT measurements of ATB is ~19.7%](#). In opaque cirrus, [differences between CATS V3-00 L1B data products and CALIOP measurements of iATB is ~18.2%](#).

5 Conclusion

This study presents the CATS 1064 nm calibration algorithm, as well as validation using three different data sources. Cloud and aerosol layers have strong backscatter intensities and high SNR, so the CATS 1064 nm ATB uncertainties in these layers are primarily related to the uncertainties in the CATS calibration. At night, CATS V3-00 median 1064 nm ATB relative uncertainty is 7% in cloud and aerosol layers, [slightly lower than the estimated ~9% uncertainty in the atmospheric normalization technique](#). The daytime cirrus cloud calibration transfer technique has an estimated uncertainty of 16-18%. CATS V3-00 median daytime 1064 nm ATB relative uncertainty is 21% in cloud and aerosol layers. Coincident flights with the airborne CPL instrument showed that even in conditions with peak solar background noise and lowest SNR, CATS data agrees to within 25% with CPL. The CATS ATB was also compared with the ground based EARLINET systems and found to be within 20% of the calibrated EARLINET data. Finally, CATS was compared in a statistical sense with CALIOP, another spaceborne lidar utilizing a different 1064 nm calibration method than CATS, and also found ATB agreement to ~18%. The comparisons between CATS, CPL, PollyXT, and CALIOP 1064 nm ATB fall within the combined estimated uncertainties for the all the instruments. The results shown in this paper [are critical to understanding the uncertainties in CATS 1064 nm Level 2 data products, as the calibration uncertainties from backscatter lidars generally impose a lower-bound on the uncertainties in cloud/aerosol extinction and optical depth retrievals from such instruments \(Young et al. 2013; 2016\)](#). To date, the CATS [cloud and aerosol top/base heights](#) have been used for various applications, including volcanic plume transport (Hughes et al 2016), above cloud aerosol properties (Rajapakshe et al. 2017), [pyrocumulonimbus smoke heights \(Christian et al., 2019\)](#), and cloud diurnal variability (Noel et al. 2018). [More recently, CATS cloud and aerosol optical properties \(e.g. extinction, optical depth, ice water content\) from Level 2 V-3.00 data have been compared to EARLINET aerosol products \(Proestakis et al., 2019\), used to estimate thin cirrus radiative forcing \(Dolinar et al., 2019\), and demonstrated the diurnal variability of aerosol properties \(Lee et al. 2019\)](#).

CATS has demonstrated that direct calibration of 1064 nm from spaceborne lidar is possible given the appropriate instrument design and orbit. The CATS design and ISS orbit yielded data that exhibits high nighttime SNR, enabling the direct calibration of the nighttime CATS 1064 nm ATB by normalizing the signal to the Rayleigh [profile corrected for aerosol contributions](#). The primary strength of this technique is that it does not require assumptions about cirrus cloud 1064-532 nm backscatter color ratios, as is the case with the CALIOP 1064 nm calibration technique (Vaughan et al., 2019). The accuracy of the [atmospheric](#) normalization technique, which is also used for CALIOP 532 nm data, is dependent on an accurate estimate of the aerosol loading in the calibration altitude region. A weakness of the CATS 1064 nm [atmospheric](#) normalization technique is that assumptions about the 1064-532 nm backscatter color ratio for stratospheric aerosols is used because accurate measurements of the 1064 nm aerosol loading in the 22-26 km altitude region, which has higher aerosol loading than the 36-39 km region used for CALIOP, were not available in same timeframe as CATS operations. To improve the calibration of future space-based lidar missions, especially at 1064 nm, a higher calibration altitude region should be prioritized. [This could be achieved by choosing a laser repetition rate of 4 kHz \(or lower\) and setting a data frame of 37.5 km \(or greater\) to reduce the aerosol scattering ratio to](#)

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[<1.10. Also, coincident passive measurements of stratospheric aerosol backscatter or extinction at a similar wavelength should be considered.](#) Implementing these into a mission design would likely reduce the [nighttime](#) calibration uncertainties by a factor of two, which would then improve the accuracy of the resulting layer information and aerosol/cloud optical properties derived from the calibrated signal. Accurate backscatter lidar data is critical to improve our understanding of various physical properties of the atmosphere, specifically how clouds and aerosols radiatively impact our earth in the infrared.

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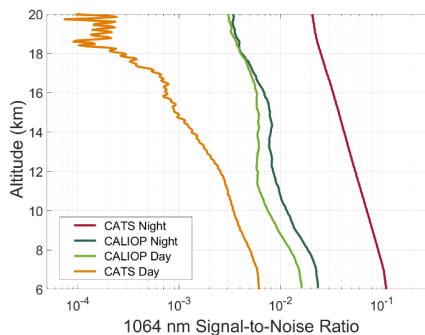
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Moved (insertion) [1]

Moved up [1]: Yorks, J. E., Palm, S. P., Hlavka, D. L., McGill, M. J., Nowotnick, E., Selmer, P., and Hart, W. D.: The Cloud-Aerosol Transport System (CATS) algorithm theoretical basis document, http://cats.gsfc.nasa.gov/media/docs/CATS_ATBD.pdf, 2016b.

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Figure 1: The CATS and CALIOP 1064 nm signal to noise ratios for both daytime and nighttime data. The CATS nighttime SNR is nearly an order of magnitude greater than CALIOP (day and night), while the CATS daytime SNR is lower than CALIOP. The CATS profiles are computed for data acquired at a laser pulse rate of 4 kHz and averaged to 350 m horizontally. The CALIOP profiles are calculated for individual laser pulses acquired at 20.16 Hz, equivalent to a horizontal resolution of 335 m. The initial vertical resolution for all profiles is 60 m. All profiles are subsequently smoothed using a 2-km (34 point) running average.

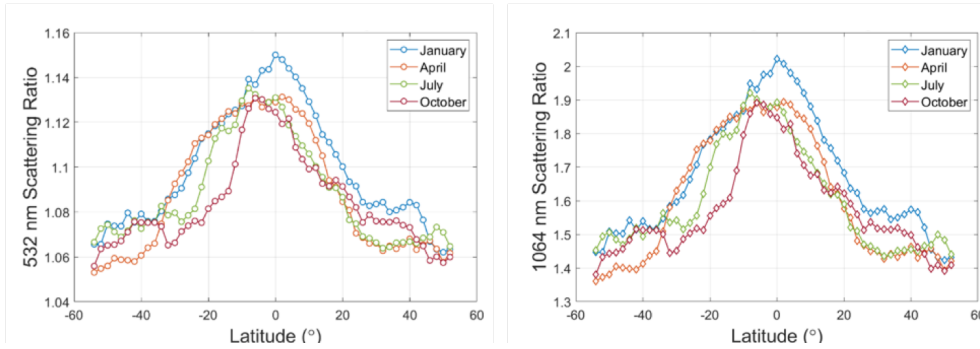


Figure 2: The 532 nm scattering ratios measured by CALIOP within the CATS calibration region (left) and the 1064 nm scattering ratios estimated from the 532 nm retrievals (right) from 2016. These plots show the temporal and latitudinal variability within the calibration region where 1064 nm estimated scattering ratios can range from below 1.4 to above 2.0 depending on the time of year and geographical location.

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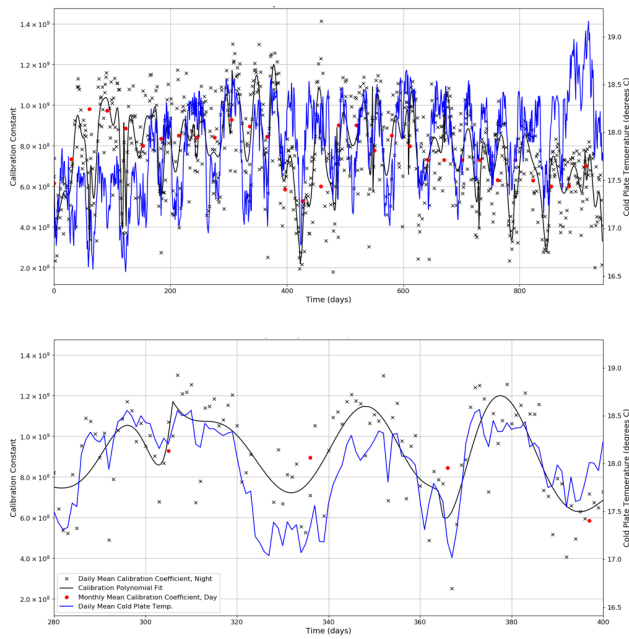


Figure 3: The average CATS nighttime calibration coefficient for each day (black x), polynomial fit of the average calibration coefficient with time (black line), the CATS monthly daytime calibration coefficient (red circle), and the daily average cold plate temperature (blue line) for the entire mode 7.2 data record (April 2015 through October 2017) in the top panel. Zooming into a smaller time period (January 2016 through April 2016, bottom panel) demonstrates the correlation between calibration values and the instrument cold plate temperature. The correlation coefficient between the daily average nighttime calibration coefficient and cold plate temperature for the January-April 2016 period is 0.8066.

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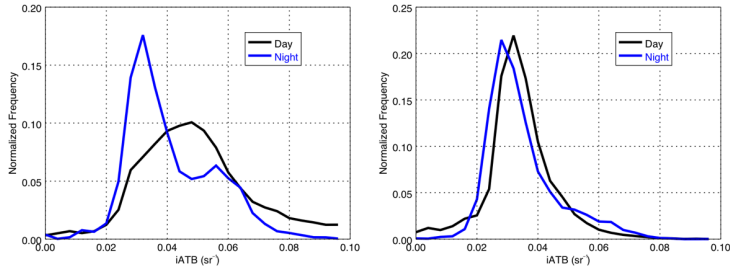


Figure 4: Distributions of CATS **strongly scattering, rapidly attenuating opaque** cirrus iATB distributions from V2-01 (left) and V3-00 (right). These plots demonstrate the CATS daytime calibration method using calibration transfer from the nighttime calibration.

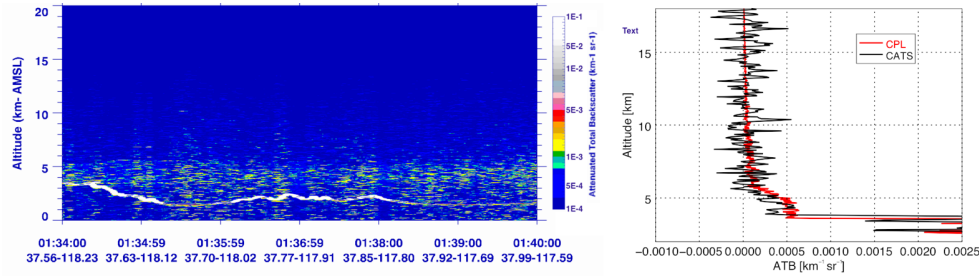


Figure 5: The CPL curtain plot of ATB centered around the 01:37 UTC coincident point from the 7-8 August 2015 CCAVE flight (Left). The mean ATB profiles from CATS and CPL during this under flight (right).

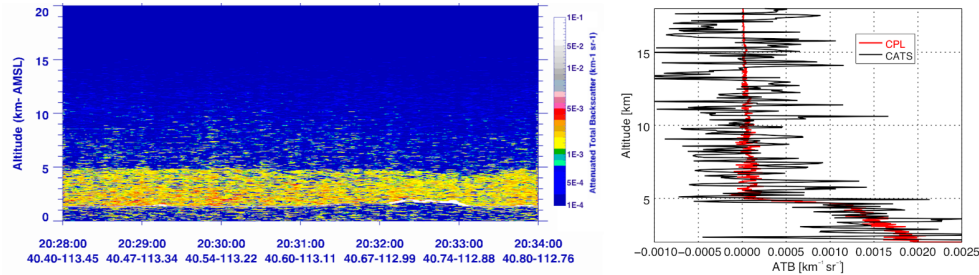


Figure 6: The 20 August 2015 CATS/CPL coincident flight. The CPL 70 km coincident segment curtain plot (left) was used to compute the mean ATB profile (right) from CPL along the same path as CATS. The CATS and CPL data show good agreement despite higher noise levels in the CATS profile due to daytime retrieval limitations.

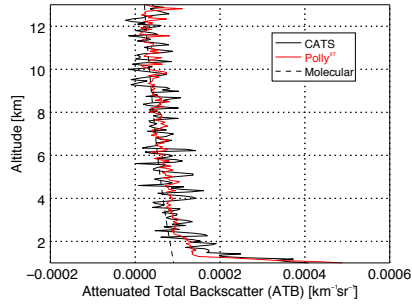


Figure 7: The mean CATS and Polly^{XT} ATB profiles from the CATS overpass of the Leipzig, Germany EARLINET site at 01:13:34 UTC on 24 September 2015. CATS passed within 31 km of the EARLINET site.

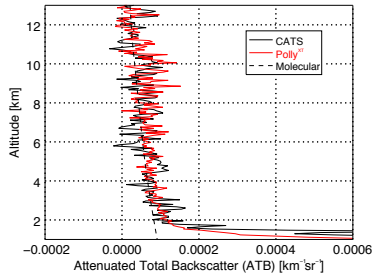


Figure 8: The mean CATS and Polly^{XT} ATB profiles from the CATS overpass of the Leipzig, Germany EARLINET site at 00:18:19 UTC on 30 July 2015. CATS passed within 41 km of the EARLINET site.

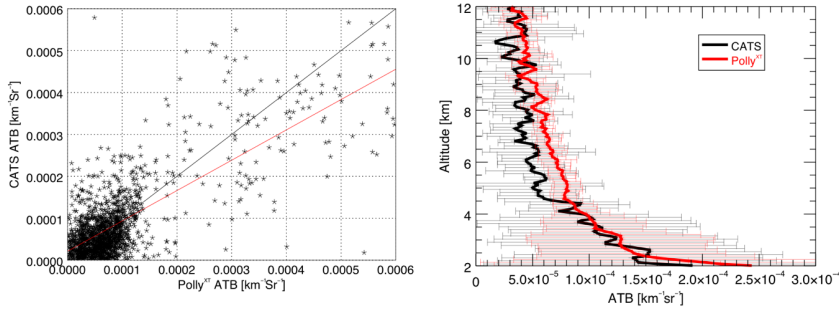


Figure 9: Scatter plot of all eight Polly^{XT} /CATS comparison overflights (left). The black line is the one-to-one line while the red line is the line fit of the data set. The correlation coefficient is 0.75. The average ATB profile from all eight Polly^{XT} /CATS comparison cases (right) shows the CATS mean profile is on average 19.67% lower than Polly^{XT} from 3-12 km. The horizontal lines show the standard deviations of the mean profile for both CATS and Polly^{XT}.

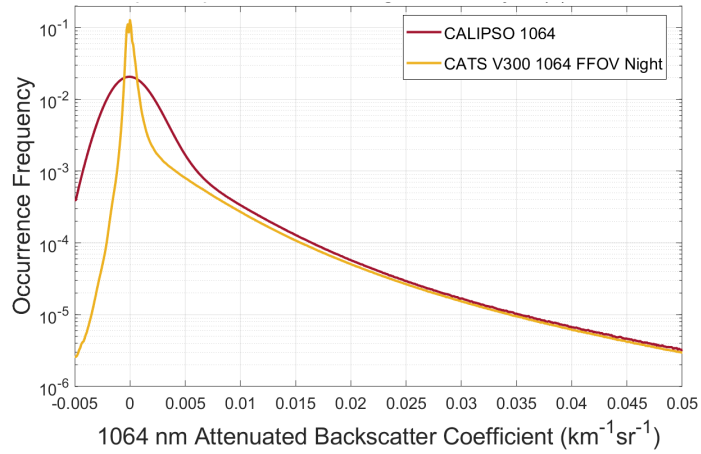
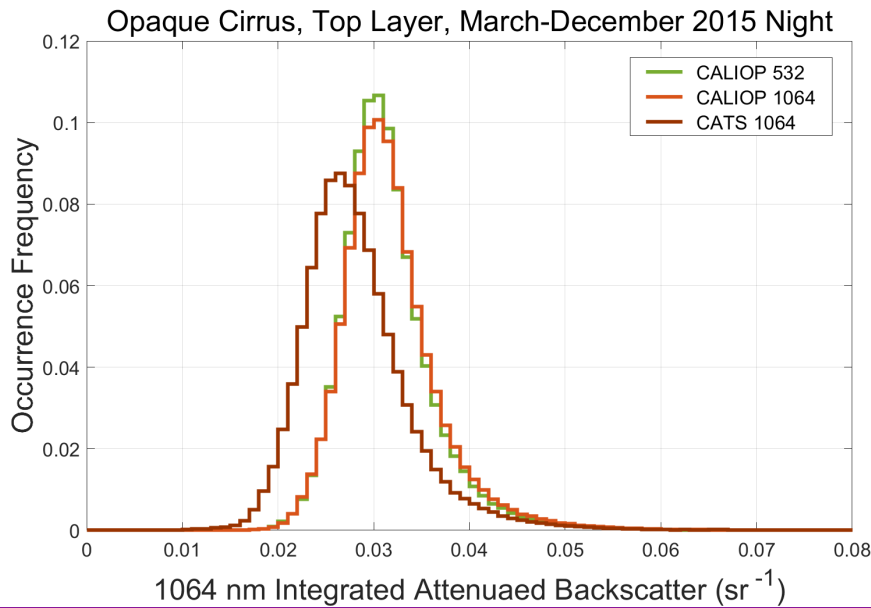


Figure 10: Relative frequency distributions of 1064 nm attenuated backscatter coefficients measured by CALIOP (V4.10) and CATS (V3-00) from April through September 2016 at night with temperatures less than -40 C.



5 Figure 11: Relative frequency distributions of March-December 2015 nighttime integrated attenuated backscatter for opaque cirrus clouds measured by CALIOP at 532 nm and 1064 nm and by CATS at 1064 nm only.

	Night	Day	Mean Bias (Night-Day)	MAE
Mean	0.03840 sr^{-1}	0.03823 sr^{-1}	0.000168 sr^{-1}	0.003419 sr^{-1}
Median	0.03559 sr^{-1}	0.03681 sr^{-1}	-0.001215 sr^{-1}	0.003289 sr^{-1}

Standard Dev.	0.01386 sr^{-1}	0.01390 sr^{-1}	$-3.969\text{e}^{-5} \text{sr}^{-1}$	0.002430 sr^{-1}
Mode	0.02981 sr^{-1}	0.03239 sr^{-1}	-0.00258 sr^{-1}	0.00413 sr^{-1}

Table 1: Mean, median, mode and standard deviation of the day and night iATB distributions of rapidly attenuating, opaque cirrus clouds from all V3-00 CATS data. The mean bias, and mean absolute error (MAE) were also calculated between the day and night distributions.

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	CALIOP 532 nm	CALIOP 1064 nm	CATS 1064 nm
minimum	0.0017 sr^{-1}	0.0015 sr^{-1}	0.0001 sr^{-1}
maximum	0.1189 sr^{-1}	0.1248 sr^{-1}	0.1794 sr^{-1}
median	0.0303 sr^{-1}	0.0305 sr^{-1}	0.0270 sr^{-1}
MAD	0.0036 sr^{-1}	0.0038 sr^{-1}	0.0045 sr^{-1}
mean	0.0310 sr^{-1}	0.0313 sr^{-1}	0.0280 sr^{-1}
standard deviation	0.0050 sr^{-1}	0.0053 sr^{-1}	0.0071 sr^{-1}
samples	333,228	333,228	268,806

Table 2: Descriptive statistics for the integrated attenuated backscatter of opaque cirrus clouds detected during nighttime granules by CATS and CALIOP during the period from 1 March to 31 December 2015 (MAD = median absolute distance).