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EARLINET evaluation of the CATS L2 aerosol backscatter coefficient product

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Abstract. We present the evaluation activity of the European Aerosol Research Lidar Network (EARLINET) for the quantitative assessment of the Level 2 aerosol backscatter coefficient product derived by the Cloud-Aerosol Transport System (CATS) onboard the International Space Station (ISS). The study employs correlative CATS and EARLINET backscatter measurements within 50 km distance between the ground station and the ISS overpass and as close in time as possible, typically within 90 min., from February 2015 to September 2016. The results demonstrate the good agreement of CATS Level 2 backscatter coefficient and EARLINET. Three ISS overpasses close to the EARLINET stations of Leipzig-Germany, Évora-Portugal and Dushanbe-Tajikistan are analysed here to demonstrate the performance of CATS lidar system under different conditions. The results show that under cloud-free, relative

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homogeneous aerosol conditions CATS is in good agreement with EARLINET, independently of daytime/nighttime conditions. CATS low negative biases, partially attributed to the deficiency of lidar systems to detect tenuous aerosol layers of backscatter signal below the minimum detection thresholds, may lead to systematic deviations and slight underestimations of the total Aerosol Optical Depth (AOD) in climate studies. In addition, CATS misclassification

5   of aerosol layers as clouds, and vice versa, in cases of coexistent and/or adjacent aerosol and cloud features, may lead to non-representative, unrealistic and cloud contaminated aerosol profiles. The distributions of backscatter coefficient biases show the relatively good agreement between the CATS and EARLINET measurements, although on average underestimations are observed, 22.3 % during daytime and 6.1 % during nighttime.

10 **1 Introduction**

The Cloud-Aerosol Transport System (CATS) is a satellite-based elastic backscatter lidar developed to provide near-real time, vertically resolved information on the vertical distribution of aerosols and clouds in the Earth's atmosphere (McGill et al., 2015). Developed at the NASA's Goddard Space Flight Center, CATS is based on the Cloud Physic

15 Lidar (CPL; McGill et al., 2002) and the Airborne Cloud-Aerosol Transport System (ACATS; Yorks et al., 2014), designed to operate onboard the high-altitude NASA ER-2 aircraft. CATS operated as a scientific payload onboard the Japanese Experiment Module - Exposed Facility (JEM-EF), utilizing the International Space Station (ISS) as a space science platform (Yorks et al., 2016). Starting from 10 February 2015, CATS provided aerosol and cloud profile observations along the ISS flight track for more than 33 months until 30 October 2017 when the system

20 suffered an unrecoverable fault.

To assess the quality of CATS lidar observations a large-scale and dense network of ground-based lidars is required due to the ISS orbital characteristics, the CATS near-nadir viewing (0.5º off nadir), the lidar narrow footprint (14.38 m diameter), and the limited number of ISS overpasses. The European Aerosol Research Lidar Network (EARLINET) consists a unique infrastructure for assessing the validation needs for spaceborne lidar missions.

25 EARLINET currently operates in the framework of Aerosols, Clouds and Trace Gases Research Infrastructure (ACTRIS) as a pan-European effort to develop a coordinated lidar research infrastructure (Pappalardo et al., 2014). EARLINET employs advanced Raman lidar systems and is characterized by extensive geographical coverage.

In this paper, we utilize EARLINET for the evaluation of CATS Level 2 aerosol backscatter coefficient product at 1064 nm. The paper is structured as follows: in section 2 we introduce aspects of CATS and EARLINET relevant to

30 the study and additionally the methodology is presented and discussed. Specific study cases are evaluated and discussed in section 3. Section 4 presents the generic intercomparison results between CATS and EARLINET, while the concluding remarks on the CATS-EARLINET backscatter coefficient evaluation are summarized in section 5.

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2 Data and methodology

2.1 EARLINET

EARLINET (EARLINET; https://www.earlinet.org/index.php?id=earlinet_homepage, last access: 20 December
2018) was founded by the European Commission (Bösenberg et al., 2001) as a research project within the framework
of the Fifth Framework Programme (FP5). Currently the network activity is integrated and constitutes a major
component of the ACTRIS research infrastructure (ACTRIS; https://www.actris.eu/, last access: 20 December 2018).
The main objective of EARLINET is to establish an extended, coordinated and continental wide network of
sophisticated ground-based Raman lidar systems. The vertical distribution of aerosols in the atmosphere, as well as
their temporal evolution, are provided by high-resolution EARLINET measurements over Europe. The long-term
continuous operation of EARLINET infrastructure has fostered a quantitative, comprehensive, and statistically
significant database of the distribution of aerosol on a continental scale (Bösenberg et al., 2003; Pappalardo et al.,
2014).

Since the beginning of the initiative in 2000, EARLINET has significantly increased its observing and operational
capacity and capability. Currently, EARLINET is composed of twenty-nine operating lidar stations distributed over
Europe (Fig. 1), including seven admitted or joining stations. EARLINET stations are classified as active on condition
of contributing regularly aerosol backscatter/extinction coefficient profiles to the EARLINET database
(https://www.earlinet.org/index.php?id=125, last access: 20 December 2018). Lidar observations in the framework
of EARLINET are regularly and simultaneously performed according to a common schedule - on preselected dates.
The schedule involves three measurements per week, one during daytime around local noon (Monday, 14:00 ± 1h)
and two during nighttime (Monday/Thursday, sunset + 2/3h), to enable Raman extinction retrievals. In addition to
the preselected dates of the operation schedule, dedicated measurements are performed to monitor special events
such as major volcanic activity (Ansmann et al., 2010; Ansmann et al., 2011; Pappalardo et al., 2013; Perrone et al.,
2012; Sicard et al., 2012; Wang et al., 2008), long-range transport of Saharan dust (Ansmann et al., 2003, Solomos
et al., 2017, 2018) and smoke particles (Ortiz-Amezcua et al., 2017, Janicka et al. 2017, Stachlewska et al. 2018).
Some of the EARLINET systems perform meanwhile 24/7 continuous measurements as for example the PollyXT
systems (Engelmann et al., 2016, Baars et al., 2016). The quality assurance and improvement of the performance of
the EARLINET systems is tested through the intercomparison of both the infrastructure (Wandinger et al., 2015) and
the optical products (Böckmann et al., 2004; Pappalardo et al., 2004). In addition, the homogenization of the lidar
data in a standardized output format is facilitated and an automatic algorithm is developed to further address the
quality assurance of the lidar measurements (the Single Calculus Chain (SCC), D'Amico et al, 2015; D'Amico et al,
2016; Mattis et al., 2016). The SCC has been used in near-real time to shown the potential operationality of the
network in a 72-hr continuous measurement exercise in 2012 (Sicard et al., 2015).

Due to its implicit characteristics, EARLINET is an optimum tool to support satellite-based lidar missions with
extensive experience to satellite calibration and validation activities. EARLINET and Cloud-Aerosol Lidar and
Infrared Pathfinder Satellite Observation (CALIPSO; Winker et al., 2009) correlative measurements are regularly
performed in order to investigate the quality of the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)

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observations, to test the presence of possible biases, and to assess the aspects of spaceborne lidar measurements (e.g. Pappalardo et al., 2010; Mamouri et al., 2009, Mona et al., 2009; Perrone et al., 2011; Wandinger et al., 2011; Amiridis et al., 2013; Grigas et al., 2015; Papagiannopoulos et al., 2016). Similarly, the validation programs of the European Space Agency (ESA) Atmospheric Laser Doppler Instrument (ALADIN) onboard Aeolus (Stoffelen et al.,

5   2005; Ansmann et al., 2007) and the ESA-JAXA ATmospheric LIDar (ATLID) onboard the Earth Cloud Aerosol and Radiation Explorer (EarthCARE; Illingworth et al., 2015) are highly-dependent on ground-based EARLINET correlative measurements. In addition, EARLINET supports the homogenization of the different satellite missions. CALIOP, is a two-wavelength polarization-sensitive lidar that operates at 532 and 1064 nm, while the ESA's ALADIN onboard Aeolus and the ESA-JAXA ATLID onboard EarthCARE operate at 355 nm and NASA's CATS

10   lidar at 532 and 1064 nm in Mode 1 and 1064 nm in Mode 2 (Yorks et al., 2014). EARLINET supports the continuity of satellite lidar missions through the calculation of aerosol-dependent spectral conversion factors between different wavelengths, to homogenize different missions at different operating wavelengths in order to provide a long-term 3D climatic record from space (Amiridis et al., 2015).

15   **2.2 CATS**

The CATS elastic backscatter lidar was designed to provide near-real-time measurements of the vertical profiles of aerosol and cloud optical properties at three wavelengths (355, 532 and 1064 nm). As a payload of the JEM-EF on the ISS, CATS was designed to operate two high repetition rate lasers in three different Modes and at four

20   instantaneous fields of view (iFOV). Mode 1 was designed as multi-beam backscatter and depolarization configuration at 532 and 1064 nm, where a beam-splitter would produce two footprints of 14.38 m diameter on the Earth's surface, to the left side FOV (LSFOV) and the right side FOV (RSFOV) of the ISS orbit track, separated by approximately a distance of 7 km. Mode 2 was designed as a demonstration of HSRL, to provide backscatter profiles at 532 nm and backscatter and depolarization ratio profiles at 1064 nm (Forward FOV). Mode 3 was designed to

25   operate and provide backscatter at 355, 532 and 1064 nm, and depolarization ratio at 532 and 1064 nm. CATS was a technology demonstration designed to operate on-orbit for a minimum of six months and up to three years. Due to a failure in the CATS optics at the 355 nm wavelength, CATS did not operate in Mode 3, while the use of Mode 1 was limited between 10/02/2015 and 21/03/2015 due to a failure in the electronics of laser 1. Nevertheless, the successful long-term operation of Mode 2, between 02/2015 and 10/2017, allowed CATS to fulfil its science objectives.

30   CATS was developed to meet three main science goals. The primary objective was to measure and characterize aerosols and clouds on a global scale. The space-borne lidar orbited the Earth at an altitude of approximately 405 km and 51-degree inclination. The use of the ISS as an observation platform facilitated for the first time global lidar-based climatic studies of aerosols and clouds at various local times (Noel et al., 2018, Lee et al., 2018). In addition, near-real-time data acquisition of the CATS observations was developed towards the improvement of aerosol forecast

35   models (Hughes et al, 2016). A secondary objective was related to the need of long-term and continuous satellite-based lidar observations to be available for climatic studies. The first spaceborne lidar mission, the Lidar In-space Technology Experiment (LITE; McCormick et al., 1993) in 1994, was succeeded by the joint NASA and Centre

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National d'Études Spatiales (CNES) CALIPSO mission in June, 2006 (Winker et al., 2007). Since 2009 the CALIOP instrument (Winker et al., 2009) onboard CALIPSO operates on the secondary backup laser. The launch of the post-CALIPSO missions, the joint ESA/JAXA satellite EarthCARE (Illingworth et al., 2015) and the NASA's Aerosols, Clouds, and Ecosystems (ACE) are planned for 2021 and post-2020 respectively. The CATS project was partially

5   intended to fill a potential gap on global lidar observations of vertical aerosols and clouds profiling. The third scientific objective of CATS was to serve as a low-cost technological demonstration for future satellite lidar missions (McGill et al., 2015). Its science goal to explore different technologies was fulfilled through the use of photon-counting detectors and of two low energy (1-2 mJ) and high repetition rate (4-5 kHz) Nd:YVO4 lasers (Multi-Beam and HSRL - UV demonstrations), aiming to provide simultaneous multiwavelength observations (355, 532 and 1064

10   nm). Additional gains of the CATS were related to the exploitation and risk reduction of newly applied laser technologies, to pave the way for future spaceborne lidar missions (high repetition rate, injection seeding, wavelength tripling at 355 nm).

CATS products and processing algorithms rely heavily on the processing algorithms developed in the framework of the CPL, ACATS and CALIPSO lidar systems (Palm et al., 2002; Yorks et al., 2011; Hlavka et al., 2012) and provided

15   in different levels of processing. CATS Level 1B data include vertical profiles of total and perpendicular attenuated backscatter signals, range-corrected, calibrated and annotated with ancillary meteorological parameters based on previous work using CPL and CALIPSO (McGill et al., 2007; Powell et al., 2009; Vaughan et al., 2010). Level 2 products provide the vertical distribution of aerosol and cloud properties (depolarization ratio, backscatter and extinction coefficient profiles at 1064 nm – FFOV), with a horizontal and vertical resolution of 5 km and 60 m

20   respectively. In addition, Level 2 data include geophysical parameters of the identified atmospheric layers (vertical feature mask - feature type, aerosol subtype), the required horizontal averaging and information on the feature type classification confidence (Yorks et al., 2019). In this study, we used CATS Level 2 v2.01 profiles (Palm et al., 2016). A comprehensive overview of the CATS instrument and CATS science goals is given by McGill et al. (2015) and Yorks et al. (2016), while detailed information about CATS datasets and an images browser can be found in the

25   CATS Data Release Notes, Quality Statements and Theoretical Basis, available at https://cats.gsfc.nasa.gov/ (last access: 20 December 2018).

2.3 EARLINET-CATS correlative measurements

2.3.1 Comparison methodology

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To obtain a significant number of collocated and concurrent EARLINET-CATS cases, a large number of EARLINET stations contributed to the CATS evaluation activity. Figure 1 shows the geographical distribution of the active EARLINET stations during the study over Europe and Asia, including the daytime/nighttime overpasses of ISS within the evaluation period, between 02/2015 and 09/2016, encompassing the first twenty months of CATS

35   operation. The green circles denote the stations participating in the EARLINET-CATS inter-comparison activity (namely - in alphabetical order: Athens-NOA, Athens-NTUA, Barcelona, Belsk, Bucharest, Cabauw, Dushanbe, Évora, Lecce, Leipzig, Potenza, Thessaloniki and Warsaw). All participating stations operate high performance

multiwavelength lidar systems. Six of the contributing stations (Athens-NOA, Cabauw, Dushanbe, Évora, Leipzig and Warsaw) are part of the PollyNET subnetwork (http://polly.tropos.de/), operating 24/7 portable, remote-controlled multiwavelength-polarization-Raman lidar systems (PollyXT; Baars et al., 2016; Engelmann et al., 2016). Due to the geographical distribution of EARLINET stations, the evaluation activity accounts for a large variety of
5   aerosol types (marine, urban, desert dust, smoke). Table 1 provides the locations of the EARLINET stations contributing to this analysis along with the surface elevation and the respective identification codes.

In order to quantitatively address the accuracy and representativeness of CATS retrievals, we follow the methodology introduced by EARLINET for CALIOP validation, which is based on correlative independent measurements (Pappalardo et al., 2010). For the validation of spaceborne lidar observations, of fundamental significance is the
10   spatial and temporal variability of the atmospheric scene. The effect of distance between ground-based lidar measurements and space-based lidar measurements was investigated in the framework of the CALIPSO validation. In particular, EARLINET-based studies attribute an introduced discrepancy of the order of 5 % to the intercompared signal analysis, when the horizontal distance between the EARLINET stations and the spaceborne lidar footprint is below 100 km (Mamouri et al., 2009; Mona et al., 2009; Pappalardo et al., 2010; Papagiannopoulos et al., 2016). In
15   the context of the applied validation criteria, we selected CATS measurements within 50 km horizontal distance between the EARLINET stations and the ISS subsatellite overpass position. In addition, the correlative measurements should be as close in time as possible. EARLINET contributed with performed measurements as close in time as possible, typically within 90 min of the ISS station overpass.

The number of available cases for the intercomparison is subject to a certain number of constraints. First and
20   foremost, the orbital inclination of the ISS does not allow to overpass close to EARLINET stations northern of 52.2° latitude. Second, the ISS crossing-time and ground-track over an area is highly variable, enhancing the probability of the overpass time to fall outside the predefined common and fixed schedule of EARLINET measurements. In addition, to account for contamination effects of multiple-scattering and specular reflection in the intercomparison process, only cloud-free (including cirrus clouds) atmospheric scenes are used. Initially, the presence of clouds is
25   investigated through the implementation of CATS backscatter coefficient and depolarization time-height images and EARLINET range-corrected-signal. Cases for which the retrieval of EARLINET temporally-averaged profile is not feasible due to the presence of clouds, and/or CATS cases that the presence of clouds propagated into the CATS spatial-averaged profile are discarded from the analysis. Regarding CATS, the "Sky_Condition" flag is used to screen cloudy (no aerosols) and hazy/cloudy (both clouds/aerosols) profiles from the analysis. The "Feature_Type_Score"
30   parameter stored in the Level 2 data was additionally used to remove aerosol cases of medium/low confidence in the comparison process ("Feature_Type_Score" ≥ -1). Applying all match-up selection criteria resulted in a total of 47 correlative EARLINET-CATS cases suitable to quantitatively address the accuracy and representativeness of CATS Level 2 backscatter coefficient product at 1064 nm.

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2.3.2 Particle backscatter coefficient retrievals from ground based lidars at 1064 nm

In order to evaluate the CATS Level 2 aerosol backscatter product at 1064 nm we utilized backscatter coefficient profiles calculated either with the SCC algorithm or, in case of PollyXT lidar systems, with independently developed user assisted retrieval algorithms (Baars 2016). The EARLINET backscatter coefficient profiles used in this study

5   are calculated with the SCC version 4 algorithm (for the stations that are not part of PollyNET) and with the methodology described in Haarig et al., 2017 (for the stations that are part of PollyNET). The SCC algorithm (D'Amico et al., 2015; D'Amico et al., 2016; Mattis et al., 2016) is developed in the concept of sustaining the homogeneity of aerosol products derived from different EARLINET lidar systems while satisfying the need for coordinated, quality assured measurements. It consists of five different modules, including one for handling the pre-

10   processing of raw lidar data by applying all the necessary instrumental corrections to the signal and a module for providing the final aerosol optical products, namely the particle backscatter and extinction coefficient. In particular, SCC algorithm calculates the backscatter coefficient with the iterative method (Di Girolamo et al., 1995), using only the elastic lidar channels. To calculate the b_{1064nm} with these methods, an assumption of the lidar ratio value is required (as a profile or a height independent value, representative of the corresponding atmospheric scene) and the

15   selection/determination of a reference height (R_0), usually chosen at an altitude range with the minimum aerosol contribution. All methods applied within the SCC, have been tested against synthetic (Mattis et al., 2016) and real lidar data (D'Amico et al., 2015). The comparison showed that by using only the signal from the elastic channels, the mean relative deviation in the calculation of the aerosol backscatter coefficient at 1064 nm is less than 30 %, thus meeting the quality assurance requirements of EARLINET. None of the lidar systems participated in the present

20   study, is equipped with a rotational-vibrational Raman channel exited by the 1064 nm as for example recently reported by Haarig et al (2017). In the case of PollyXT lidars, for the daytime backscatter coefficient calculations, the Fernald-Klett method (Klett, 1981; Fernald, 1984) is implemented assuming a height independent lidar ratio. For the nighttime calculations, the Raman channel at 607 nm is additionally used (Baars et al., 2016). Specifically, the basic lidar equation at 1064 nm can be described by:

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$$P^{1064}(R) = C^{1064} \frac{O(R)}{R^2} (\beta_{par}{}^{1064}(R) + \beta_{mol}{}^{1064}(R)) \exp(-2\int_0^R [a_{mol}{}^{1064}(r) + a_{par}{}^{1064}(r)]dr) \tag{1}$$

And the corresponding lidar equation at 607 nm by:

30    $$P^{607}(R) = C^{607} \frac{O(R)}{R^2} (\beta_{mol}{}^{607}(R)) \exp(-\int_0^R [a_{mol}{}^{532}(r) + a_{par}{}^{532}(r) + a_{mol}{}^{607}(r) + a_{par}{}^{607}(r)]dr) \tag{2}$$

a solution for the particle backscatter coefficient at 1064 nm is obtained, using the ratio:

$$\frac{P^{607}(R_0)P^{1064}(R)}{P^{1064}(R_0)P_{607}(R)} \tag{3}$$

where P^{607} and P^{1064} stand for the power received from a distance R, with respect to the lidar system, at 607 nm and 1064 nm respectively. The constant C at 607 or 1064 nm contains all range independent system parameters. The

5   overlap function $O(R)$, which is less than unity for the altitude range where the laser beam is not completely inside the receiving telescope field of view (Wandinger et al., 2002), is assumed identical between the two channels, which is the case for PollyXT systems which use one beam expander for all three emitted wavelengths. β_{mol} and β_{par} represent molecular and particle scattering respectively, whereas α_{mol} and α_{par} are the molecular and particle extinction coefficients.

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2.3.3 Demonstration of the comparison methodology for a case study over Athens

To illustrate the evaluation methodology for the CATS Level 2 aerosol backscatter coefficient at 1064 nm, a pair of collocated and concurrent CATS and EARLINET lidar observations is shown in Figure 2. The example refers to a

15   nighttime ISS overpass of the coastal city of Athens-Greece on the 1st of February, 2016. During that period, the PollyXT-NOA system was operating in a 24/7 mode in Athens to fulfill the needs of an ACTRIS Joint Research Activity (JRA) for aerosol absorption (Tsekeri et al., 2018). The closest distance between the CATS footprint of the ISS overpass and the location of the EARLINET-NOA station was approximately 23.3 km at 17:24 UTC (Fig. 2a). The vertical distribution of aerosols and clouds is shown in the CATS 1064 nm backscatter coefficient quicklook

20   (Fig. 2b) and the PollyXT-NOA lidar range-corrected signal at 1064 nm, between 01/02/2016 at 12:00 UTC and 02/02/2016 00:00 UTC (Fig. 2c). The temporal averaging window of the ground-based lidar signal is shifted a few minutes after the ISS overpass (17:45-19:30 UTC), due to routinely/automatic depolarization calibration measurements conducted with PollyXT-NOA system at the exact time of the overpass (Engelmann et al. 2016). Both CATS and PollyXT-NOA quicklooks advocate the horizontal and vertical homogeneity of the scene. For the

25   comparison of CATS and EARLINET observations, the latest are regridded to the CATS Level 2 vertical resolution (60 m). Accordingly, CATS spatial averaged and EARLINET-NOA temporal averaged backscatter coefficient profiles (in this example PollyXT-NOA observations) are qualitative compared (Fig. 2d). The horizontal-bars in the CATS profile (Fig. 2d) correspond to the standard deviation of the spatially averaged backscatter coefficient profiles. The comparison of CATS and EARLINET PollyXT-NOA mean backscatter coefficient profiles for the example

30   presented in Figure 2 is an initial demonstration of the good agreement between the two products. The CATS instrument reproduces the observed aerosol features, in terms of aerosol load as well as their vertical distribution (Fig. 2d). The assessment of CATS backscatter coefficient is performed in the region between 0.5 km above ground-level of the EARLINET sites, to account for overlap effects between the laser beam and the telescope (Wandinger and Ansmann, 2002), topographic effects, surface returns, and differences of atmospheric samples within the

35   Planetary Boundary Layer (Fig. 2d - shaded area iii), and 10 km height (a.s.l.). An upper limit of 2 Mm^{-1}sr^{-1} is applied

to the aerosol backscatter coefficient values, in order to account for cloud features possible misclassified as aerosols (Fig. 2d - shaded area ii). Finally, cases of EARLINET backscatter coefficient values below the CATS minimum detectable backscatter limit at 1064 nm are not included in the comparison, when the corresponding CATS backscatter coefficient is reported to be zero (Fig. 2d - shaded area i). The latter constrain is applied to account for

5   very thin detected layers from ground-based Lidar systems with backscatter values below the CATS minimum detection limit due to the low Signal-to-Noise Ratio values (SNR). The discussed constrains are employed because of our basic idea to quantitatively assess the representativeness and accuracy of the detected by CATS aerosol features, while preventing possible contaminations (e.g. presence of clouds) to propagate into the CATS-EARLINET dataset.

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3 Results and discussion
3.1 EARLINET-CATS Correlative Cases

To illustrate strengths and limitations of CATS products, we discuss in details three selected cases of collocated and
15   concurrent CATS-EARLINET observations close to the (EARLINET) stations of Leipzig, Évora and Dushanbe. The three study cases represent different atmospheric conditions with increasing degree of difficulty in the detection of representative aerosol layers by CATS.

The first overpass here considered shows a representative case study of a nighttime ISS orbit, on September 13, 2016 (blue line), at a minimum distance of 3.78 km from the EARLINET Leipzig – Germany PollyXT lidar system
20   (indicated by a white dot), at 03:37 UTC (Fig. 3a). CATS particulate backscatter coefficient cross section at 1064 nm (Fig. 3b) shows the presence of aerosols up to 2.6 km (a.s.l.). CATS feature mask algorithm classifies all of the detected layers as aerosols (not shown). The ground based lidar measurements at Leipzig station between 00:00 and 12:00 UTC did not report any cloud features either, including cirrus clouds. CATS spatial-averaged and Leipzig temporal-averaged profiles were derived from CATS profiles within horizontal distance below 50 km, between the
25   Leipzig station and the ISS footprint, and Leipzig measurements within 90 min of the ISS overpass, respectively (Fig. 3c). The direct comparison of the backscatter coefficient profiles, measured from the EARLINET Leipzig station (red line) and CATS (blue line), along with their standard deviations (horizontal error bars), indicate also the presence of aerosol up to 2.6 km height (a.s.l.). The intercompared profiles between ISS-CATS and EARLINET-Leipzig station are characterized by high agreement, although discrepancies are also present. To the uppermost part
30   of the profiles, between 2.5 and 3 km (a.s.l.), due to the higher SNR, Leipzig lidar is capable to detect tenuous atmospheric features of low backscatter coefficient values. The intercomparison presented in Figure 3c is a representative case, indicating the overall high performance of CATS and the absence of significant biases, during both daytime and nighttime, under relative homogeneous and cloud free conditions.

Small biases between EARLINET and CATS backscatter coefficient are also identified in specific cases. CATS
35   particulate backscatter coefficient profiles are available for the identified atmospheric features and not as full profiles as in the case of the attenuated backscatter profiles. The feature classification algorithm, assuming no cloud or aerosol layers are detected and no over-lying opaque layers are present, classifies the atmospheric layers as clear-air. Clear-

air segments though are not pristine and aerosol-free, as they frequently contain tenuous particulate layers (Kim et al., 2018). Layers of atmospheric features that are not detected, contain either fill values (0.0 km^{-1}sr^{-1}), or are marked as invalid in cases when the calculation of the particulate backscatter coefficients was not possible (-999.9).

5   This scheme of assigning appropriate backscatter coefficients to the detected atmospheric features (e.g., aerosol and clouds) propagates through many of the Level 2 products in the comparison of CATS Level 2 data, thus in the assessment of the representativeness of CATS observations. Consequently, the comparison of CATS Level 2 backscatter coefficient profiles against EARLINET observations is only possible over the detected atmospheric features. In addition, the identification of the atmospheric features strongly depends on the calibrations of CATS lidar system and to the level of the background signal - solar illumination conditions, due to the different SNR between

10   daytime and nighttime.

    Figure 4 shows a daytime ISS match-up, on May 31, 2016 (red line), at a minimum distance of 39.4 km from the EARLINET station of Évora - Portugal (indicated by a white dot), at 19:43:41 UTC, during a time window of cloud free atmospheric conditions (Fig. 4a). CATS particulate backscatter coefficient cross section at 1064 nm (Fig. 4b) shows the absence of aerosol and/or cloud features, while the Évora temporal-averaged profile during the cloud free

15   window (Fig. 4c) indicates the presence of thin aerosol layers in the altitude range between 1 and 2.5 km height (a.s.l.). The aerosol layer detected by the Évora PollyXT lidar system is characterized by backscatter coefficient values lower than 0.3 Mm^{-1}sr^{-1}. Although CATS is characterized by relatively low Minimum Detection Thresholds (Yorks et al., 2016), CATS capabilities are limited in terms of detecting similarly tenuous aerosol layers at levels that lie below the detection thresholds (e.g. CATS 7.2 Minimum Detectable Backscatter 1064 nm: Night: 0.05 ± 0.0077

20   Mm^{-1}sr^{-1} / Day: 1.3 ± 0.24 Mm^{-1}sr^{-1} - for cirrus clouds; Yorks et al., 2016). The detection limitation of CATS may propagate in scientific studies implementing CATS through introduced underestimations and possible biases.

    The assessment of accuracy of CATS Level 2 against EARLINET collocated and concurrent observations is performed on the basis of backscatter coefficient profiles, because this product constitutes the CATS Level 2 parameter with the lowest influence of a-priori assumptions (e.g. lidar ratio). In addition to the backscatter coefficient,

25   CATS Level 2 data provide the feature classification of the detected layers (namely: clear air, cloud, aerosol and totally attenuated) and the numerical confidence level of the classification, similar to the CALIOP Cloud-Aerosol-Discrimination (CAD) algorithm (Liu et al., 2004; Liu et al., 2009). CATS Feature Type Score is a multidimensional probability density function (PDF) developed based on multiyear CPL observations, that discriminates cloud and aerosol features, assigning an integer between -10 and 10 for each detected atmospheric layer. Cloud-aerosol

30   discrimination though is not performed perfectly. Thus misclassified aerosol layers may be classified as clouds, and vice versa. In the framework of the study, for the assessment process of the CATS Level 2 aerosol quality, strict cloud-filtering is applied. In particular, cloud contaminated profiles (Sky Condition 2, 3) and aerosol layers characterized by medium/low classification confidence (Feature_Type_Score $\geq$ -1) are filtered. The strict cloud screening is applied because of our basic idea to establish the accuracy of CATS aerosol backscatter coefficient

35   profiles based on intercomparison against EARLINET, preventing any contamination of cloud features to propagate into the dataset.

As discussed in the case of Leipzig overpass, on average, the agreement between CATS Level 2 backscatter coefficient profiles and EARLINET is good, especially under relative homogeneous cloud-free atmospheric conditions. Under complex atmospheric conditions though, of coexistent and adjacent aerosol and cloud features, the impact of the CATS Feature Type Score on the CATS aerosol retrievals becomes significant. Figure 5 shows the

5   CATS footprint for the nighttime ISS orbit, on May 25, 2015 (blue line), at a minimum distance of 24.3 km from the EARLINET Dushanbe - Tajikistan station (Hofer et al., 2017), at 18:53:19 UTC (Fig. 5a). This EARLINET station is located in a natural basin surrounded by mountain ridges of variable height, between 0.7 and 4 km height (a.s.l.). CATS particulate backscatter coefficient cross section at 1064 nm (Fig. 5b) shows the predominant presence of aerosols, up to 3.6 km height (a.s.l.), adjust to broken thin clouds. These cloud characteristics though are not

10   consistent with the observations performed at Dushanbe station between 13:00 and 23:00 UTC on May 25, 2015 that reported the absence of cloud features below 6 km. CATS lidar profile and the EARLINET-Dushanbe profile yield different behavior in terms of backscatter coefficient (Fig. 5c). The Dushanbe lidar reports a weak presence of aerosols, up to approximately 4 km height (a.s.l.). The backscatter comparison against CATS profile reveals enhanced discrepancies in segments of the CATS profile, denoted by the high backscatter coefficient values (> 2 Mm^{-1}sr^{-1}).

15   The cloud features that cause the observed discrepancies are classified by CATS CAD algorithm as aerosol layers, contaminating the CATS profile, despite the strict cloud screening. Features with invalid CATS CAD Score, although not frequently observed, may impact the quality of the column aerosol optical depth (AOD) and related climatological studies. In addition, complex topography in terms of geographical characteristics, erroneous mean backscatter coefficient profiles due to the high variability of aerosol load in the Planetary Boundary Layer, the horizontal distance

20   between the CATS lidar footprint and the ground-based lidar stations and surface returns enhance further these discrepancies, especially in the lowermost part of the profiles. Based on this analysis and comparisons with CALIPSO, the CATS cloud-aerosol discrimination algorithm was updated for the V3-00 Level 2 data products (to be released by the end of 2018) to improve the accuracy of the Feature Type and Feature Type Score, especially during daytime.

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3.2 EARLINET-CATS comparison statistics

In this section an overall assessment of the CATS backscatter coefficient product at 1064 nm is given, using the entire dataset of CATS-EARLINET collocated profiles. To address quantitatively the accuracy and

30   representativeness of the satellite-based lidar retrievals the estimation of possible biases in the CATS backscatter coefficient is performed. Towards this assessment, in the comparison of CATS against EARLINET we implement the CATS$_i$-EARLINET$_i$ residuals for each pair of observations "i", as statistical indicator of CATS average overestimation or underestimation of the aerosol load, in terms of backscatter coefficient values.

Figure 6 shows the distributions of CATS$_i$-EARLINET$_i$ backscatter coefficient differences. On average, the

35   agreement is good demonstrating the high performance of CATS, with mean and median residual values close to zero and typically within 0.4 Mm^{-1}sr^{-1}. The intercomparison between CATS satellite-based and EARLINET ground-based lidar retrievals reveals the presence of negative biases in the CATS 1064 nm backscatter coefficient profiles.

The CATS$_i$-EARLINET$_i$ differences, for all the available 21 daytime (Fig. 6a) and 26 nighttime (Fig. 6b) cases of paired correlative observations show an underestimation of the CATS retrievals, more pronounced during daytime than nighttime. In the case of daytime observations, the calculated mean (median) CATS difference from EARLINET is -0.123 Mm^{-1}sr^{-1} (-0.095 Mm^{-1}sr^{-1}). In the case of nighttime observations, the corresponding mean (median) difference from EARLINET is -0.031 Mm^{-1}sr^{-1} (-0.065 Mm^{-1}sr^{-1}). The observed standard deviation (SD) is 0.431 Mm^{-1}sr^{-1} over daytime and 0.342 Mm^{-1}sr^{-1} during nighttime. During daytime, minimum and maximum CATS-EARLINET residual values of -1.802 Mm^{-1}sr^{-1} and 1.189 Mm^{-1}sr^{-1} are observed, while the corresponding minimum and maximum values for nighttime are -1.348 Mm^{-1}sr^{-1} and 1.149 Mm^{-1}sr^{-1}. The CATS$_i$-EARLINET$_i$ daytime mean absolute bias and root mean square error (RMSE) statistical indicators (Binietoglou et al., 2015) of daytime observations are 0.323 Mm^{-1}sr^{-1} and 0.448 Mm^{-1}sr^{-1}, while the respective statistical indicators for the nighttime cases are 0.249 Mm^{-1}sr^{-1} and 0.343 Mm^{-1}sr^{-1}. CATS performance is also quantified through the linear correlation coefficient between the CATS and EARLINET backscatter coefficient distributions, with correlation coefficient of 0.54 and 0.69, during daytime and nighttime respectively. The correlations between CATS and EARLINET distributions are not very good, as expected due to the significant influence of the topography, the high inhomogeneities within the local Planetary Boundary Layer (PBL), and the effect of the horizontal distance and temporal measurement differences. The fractional bias values for daytime and nighttime are -0.676 and -0.773 respectively, while the fractional gross error ranges between 1.061 for daytime and 0.999 for nighttime cases. Overall, the agreement between CATS and EARLINET is good. On average though, slight underestimations of CATS compared to EARLINET are observed, 6.3 % during nighttime and 22.3 % during daytime.

Figure 7 reports the mean aerosol backscatter coefficient profiles at 1064 nm as provided by CATS and EARLINET daytime (Fig. 7a) and nighttime (Fig. 7b) lidar observations. On average, the mean aerosol backscatter coefficient profiles reveal similar characteristics between CATS and EARLINET, although the comparisons are subject to the different number of available cases, 21 and 26 for daytime and nighttime respectively. Both CATS and EARLINET daytime and nighttime backscatter coefficient profiles yield higher values close to the surface level, gradually decreasing with altitude. Especially in the range between the full overlap region of the laser beam and the telescope of the EARLINET systems (approximately 1 km) and the middle free-troposphere (~6 km a.s.l.), the mean backscatter coefficient profile of CATS is well within the standard deviation of the EARLINET provided scenes. Nonetheless, discrepancies are also evident. CATS, as a result of the high spatial atmospheric variability, yields usually higher values of standard deviation than EARLINET. In addition, at altitudes higher than 6 km (a.s.l.), CATS mean backscatter coefficient profile yields zero or close-to-zero values, while EARLINET shows the presence of elevated aerosols, with rather low mean backscatter values, lower than 0.2 Mm^{-1}sr^{-1}.

The CATS Level 2 backscatter coefficient product evaluation study shows that CATS agrees reasonably well with ground-based EARLINET measurements, although generally biased low. To assess the ability of CATS lidar to detect aerosol features and optical properties and to shed light on the origin of observed CATS-EARLINET discrepancies the conducted CALIOP validation studies offer an unprecedented basis. This is due to the similar viewing geometry between CATS and CALIOP and to the similarities between Level 1B and Level 2 processing algorithms (McGill et al., 2015; Yorks et al., 2016; 2019).

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Since CALIPSO joined the A-Train constellation of Earth observation satellites in June 2006 (Winker et al., 2007), several studies have been conducted to validate and evaluate CALIOP Level 1B, Level 2 and Level 3 products, against ground-based, airborne, and spaceborne measurements. Airborne NASA Langley HSRL (Hair et al., 2008) and CPL (McGill et al., 2002) flights, of close spatial and temporal coincidence with the CALIPSO satellite

5   documented on the high performance of CALIOP, although with the presence of low negative biases (Burton et al., 2010; 2013; McGill et al., 2007; Rogers et al., 2011; 2014). Kacenelenbogen et al. (2014) reports on the detection of aerosols-above-cloud (AAC) in only 151 of 668 CALIOP-HSRL coincident airborne cases (23 %). The use of ground-based Raman lidar observations also reports that CALIOP Level 1B and Level 2 products are biased low (Mamouri et al. 2009; Mona et al., 2009; Pappalardo et al., 2010; Tesche et al., 2013). In terms of columnar

10   measurements, the conducted validation activities based on collocated observations between CALIOP and AErosol RObotic NETwork (AERONET; Dubovik et al., 2000) showed CALIPSO AOD underestimations (Amiridis et al., 2013; Omar et al., 2013; Schuster et al., 2012). In addition, evaluation studies of AOD observations from the passive spaceborne MODerate resolution Imaging Spectroradiometer (MODIS; Remer et al., 2005) show that CALIOP provides reasonably well known climatic features, although with apparent AOD underestimations (Amiridis et al.,

15   2013; Kittaka et al., 2011; Oo and Holz, 2011; Redemann et al., 2012). The magnitude of the documented agreements and biases in the detection of aerosol features vary from study to study, with respect to the different CALIOP versions. Substantially improvement in the detection of aerosol features is expected in the latest CALIPSO Version 4 (AMT CALIPSO special issue).

Overall, CATS, much like CALIOP, observes reasonably well the vertical distribution of atmospheric aerosol

20   backscatter coefficient, although with slight underestimations. The observed discrepancies in the compared CATS-EARLINET profiles are attributed to several sources.

First, the retrieval accuracy of CATS Level 2 data products, such as the aerosol and cloud backscatter and extinction coefficient profiles, the vertical feature mask and the integrated parameters (e.g. AOD), depends crucially on the calibration of the lidar system and the calibration region (Kar et al., 2018). CATS total attenuated backscatter from

25   molecules and particles in the atmosphere is performed in the calibration region between 22 and 26 km starting with V2-08 of the L1B data (Russell et al., 1979; Del Guasta 1998; McGill et al., 2007; Powell et al., 2009). Uncertainties in the CATS Level 1B backscatter calibration are attributed to random and systematic errors (CATS ATBD). Random errors result mainly from normalizing the 1064 nm lidar signal to modeled molecular signal and are dominated by lidar noise. On the contrary, systematic errors result from a number of different sources, including uncertainties in

30   the CALIOP stratospheric scattering ratios and molecular backscatter coefficient values generated from the Goddard Earth Observing System (GEOS) atmospheric general circulation model and assimilation system used to calculate molecular and ozone atmospheric transmission (Rienecker et al., 2008), and from the non-ideal performance of CATS. The total uncertainty due to the CATS calibration constants is estimated between 5 % and 10 % (CATS ATBD).

35   Secondly, CATS detection and classification schemes, similar to CALIOP, provide Level 2 aerosol products only in regions where aerosol features are detected and identified. This implies that optically thin aerosol layers can go undetected by CATS, due to weak backscattering intensities below the CATS detection thresholds (Kacenelenbogen

et al., 2014; Thorsen et al., 2015). To increase the detection of tenuous aerosol layers CATS incorporates an iterated horizontal averaging scheme (5 and 60 km; Yorks et al., 2019). Failures of space-borne lidar instruments and algorithms to detect tenuous aerosol layers (Toth et al., 2018) result in range bin backscatter coefficient assignments to 0.0 Mm^{-1}sr^{-1}. The faint undetected aerosol layers do not contribute to the CATS aerosol backscatter profiles,

5 consequently neither to extinction coefficient profiles, nor to estimates of CATS AOD, similar to CALIOP AOD (Kim et al., 2013; Rogers et al., 2014; Thorsen and Fu, 2015). The detection sensitivity is attributed to the solar background and sunlight illumination conditions, due to the significantly lower CATS SNR during daytime than nighttime (Rogers et al., 2014). The undetected aerosol layers, although of low aerosol load, introduce negative biases in the CATS-EARLINET comparison.

10 Another source of discrepancies between CATS and EARLINET is attributed to the effect of horizontal distance between the ground-based lidar systems and the space-based lidar footprint. Studies performed in the framework of EARLINET attribute an introduced discrepancy of the order of 5 % to the intercompared profiles, when the horizontal distance is below 100 km (Mamouri et al., 2009; Pappalardo et al., 2010; Papagiannopoulos et al., 2016). The different - opposite viewing geometry (upward for EARLINET/downward for CATS/CALIPSO) and the different

15 transmittance terms are further sources of discrepancies (Mona et al., 2009). In addition, enhanced disagreements observed between CATS and EARLINET in the lowermost part of the mean backscatter coefficient profiles are attributed to the high spatial and temporal variability of the aerosol content within the PBL, to the complexity of the local topography and to surface returns.

Finally, regarding the utility of CATS for climatic studies, another common reason of satellite-based lidar

20 overestimations or underestimations is attributed to the absence of detailed aerosol properties in the classification of the detected aerosol layers. The aerosol-subtype classification scheme frequently results in aerosol layer misclassifications, as has been shown in the case of coincident HSRL-CALIPSO under-flights (Burton et al., 2012). Misclassified aerosol layers incorporate erroneous values of lidar ratio. Possible underestimation or overestimation of aerosol backscatter coefficient profiles, considered with erroneous aerosol-subtype classification, introduce biases

25 in corresponding extinction coefficient profiles and eventually in total columnar AOD retrievals. The CATS V3-0 Level 2 data products improve errors in cloud-aerosol typing identified in these CATS-EARLINET comparisons. Furthermore, Wandinger et al. (2010), based on CALIOP extinction coefficient profiles in case of dust aerosol layers and collocated ground-based Raman lidar measurements, showed that multiple scattering effects can result in negative biases if not considered in the algorithm inversions schemes. Data users should be aware of these multiple

30 scattering effects and cloud-aerosol typing errors when using the CATS data for climate studies, utilizing the CATS Feature Type Scores to reduce uncertainties in the analysis.

4. Summary and conclusions

35 This study implements independent retrievals carried out at several EARLINET stations, to qualitatively and quantitatively assess the performance of the NASA's CATS lidar operating onboard the ISS from February 2015 to October 2017. We compared satellite-based CATS and ground-based independent measurements over twelve high-

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performance EARLINET stations across Europe and one located in Central Asia. Our analysis is based to the first twenty months of CATS operation (02/2015-09/2016). Comparison of CATS Level 2 and EARLINET backscatter coefficient profiles at 1064 nm is allowed only in cases of maximum distance between the ISS overpass and the EARLINET stations below 50 km. EARLINET contributed with observations as close in time as possible, within 90

5   min of the ISS overpass. The analysis was restricted to cloud-free profiles to avoid possible cloud-contamination of the intercompared aerosol backscatter coefficient profiles.

In the quantitative assessment of the performance of CATS, 47 collocated, concurrent and cloud-free measurements of CATS the EARLINET were identified (21 daytime and 26 nighttime), offering a unique opportunity for the evaluation of the space-borne lidar system. The results of the generic comparison are encouraging, demonstrating the

10   overall good performance of CATS, although with negative biases. The agreement, as expected due to higher SNR, is better during nighttime operation, with observed underestimation of 22.3 %, during daytime and 6.1 % during nighttime respectively.

In addition to the generic comparison, three CATS-EARLINET comparison cases were examined to demonstrate the system's performance, under different study conditions. The comparison showed that under cloud-free, relative

15   homogeneous atmospheric aerosol conditions, the spatial averaged CATS backscatter coefficient profiles are in good agreement with EARLINET, independently of light conditions. The deficiency of CATS though to detect tenuous aerosol layers, due to the inherent limitations of space-based lidar systems, may lead to systematic deviations and slight underestimations of the total AOD in climatic studies. In addition, the CATS V2-01 Feature Type Score misclassification of aerosol layers as clouds, and vice versa, in cases of coexistent and/or adjacent aerosol and cloud

20   features, may lead to non-representative, unrealistic and cloud contaminated aerosol profiles. While CATS feature identification will improve in V3-00 data products, the most crucial reason for the observed discrepancies between CATS and EARLINET in the lowermost part of the profiles is related to the complexity of the topography and the geographical characteristics. Especially in the case of large elevation/slope differences, the effects of both inadequate sampling lower than the maximum elevation and of the different atmospheric sampling volumes, result in large AOD

25   biases and unrealistic AOD values.

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Acknowledgements

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5. **Tables and Figures**

Table 1: Contributing EARLINET Lidar Stations, including Identification Codes, Geographical Coordinates and elevation.

EARLINET Station	Identification Code	Latitude (°N)	Longitude (°E)	Altitude a.s.l. (m)
Athens-NOA	no	37.97	23.72	86
Athens-NTUA	at	37.96	23.78	212
Barcelona	ba	41.39	2.12	115
Belsk	be	51.83	20.78	180
Bucharest	bu	44.35	26.03	93
Cabauw	ca	51.97	4.93	0
Dushanbe	du	38.56	68.86	864
Évora	ev	38.57	-7.91	293
Observatory Hohenpeissenberg	oh	47.8	11.01	974
Lecce	lc	40.33	18.10	30
Leipzig	le	51.35	12.43	90
Potenza	po	40.60	15.72	760
Thessaloniki	th	40.63	22.95	50
Warsaw	wa	52.21	20.98	112

Table 2: CATS-EARLINET comparison statistics on mean bias, median, mean absolute bias, standard deviation, root mean
square error (RMSE), minimum/maximum values on the observed backscatter coefficient profiles at 1064 nm ($Mm^{-1}sr^{-1}$) for
daytime and nighttime correlative cases.

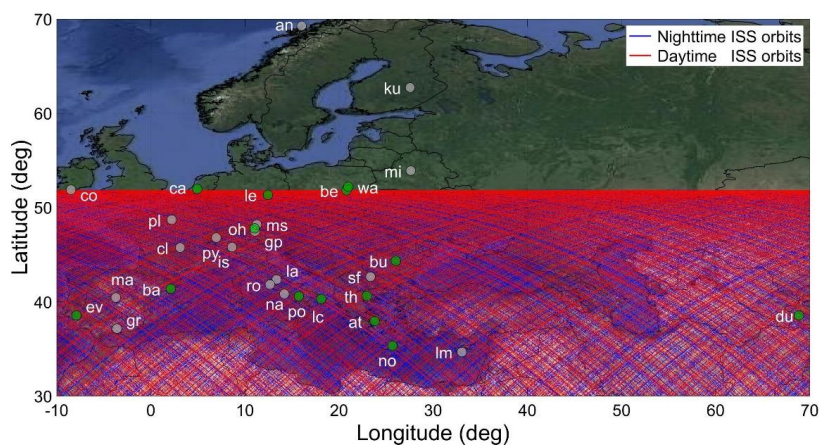| Metric	Daytime	Nighttime
Mean Bias [$Mm^{-1}sr^{-1}$]	-0.123	-0.031
Median Differences [$Mm^{-1}sr^{-1}$]	-0.094	-0.065
Mean Absolute Bias [$Mm^{-1}sr^{-1}$]	0.323	0.249
SD [$Mm^{-1}sr^{-1}$]	0.431	0.342
(min / max Differences) [$Mm^{-1}sr^{-1}$]	(-1.802 / 1.189)	(-1.348 / 1.149)
RMSE [$Mm^{-1}sr^{-1}$]	0.448	0.343
Correlation Coefficient	0.55	0.69
Fractional Bias	-0.773	-0.676
Fractional Gross Error	0.999	1.061
Number of Cases (#)	21	26

Figure 1: Distribution of EARLINET lidar stations over Europe and West Asia. Green dots: stations used in the inter-comparison. ISS orbits between 02/2015 and 09/2016 are overlaid in red for daytime and in blue for nighttime overpasses.

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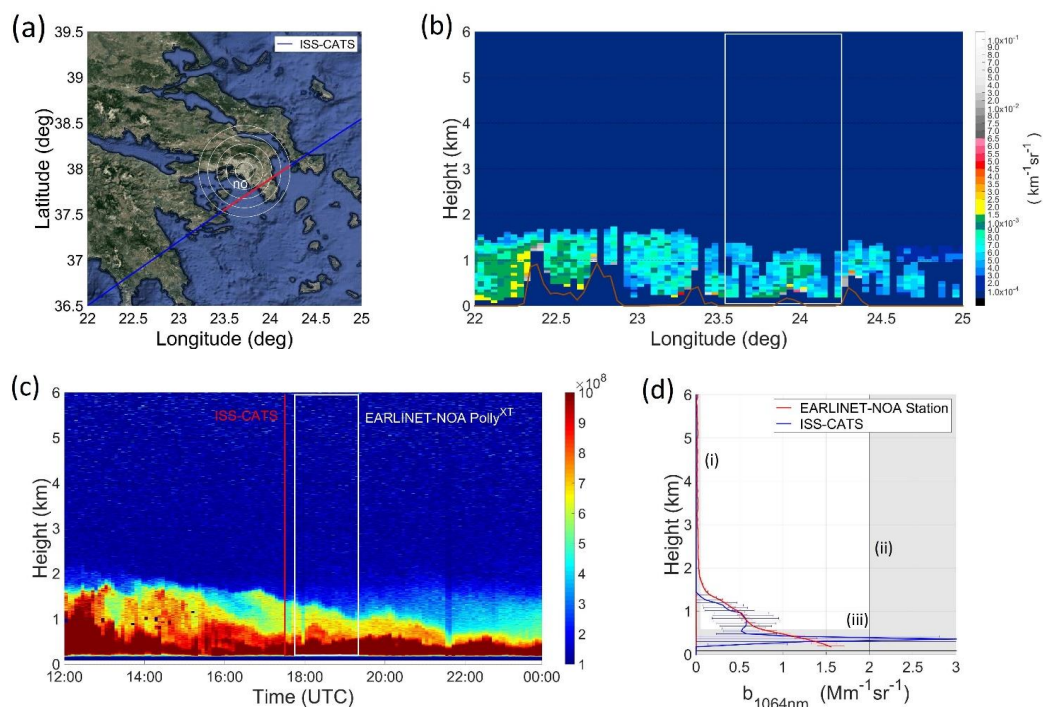10

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Figure 2: (a) Nighttime ISS orbit over Athens-Greece on the 1st of February 2016 (blue line). The concentric white circles denote regions of 10, 20, 30, 40 and 50 km from the location of PollyXT-NOA lidar system (white dot). Red colour in the ISS footprint indicates CATS observations within 50 km distance from the NOA PollyXT lidar system. (b) CATS Backscatter Coefficient at 1064 nm on 2016-02-01, 17:24 UTC. The white box depicts CATS observations used for the profile intercomparison. (c) PollyXT-NOA range-corrected signal time-series at 1064 nm. The white box delineates the temporal averaging of the lidar signals (17:45-19:30 UTC) while the red line denotes the ISS overpass at 2016-02-01, 17:24 UTC - closest distance time. (d) CATS (blue line) and PollyXT-NOA (red line) mean profiles and standard deviations of backscatter coefficient at 1064 nm (0-6 km).
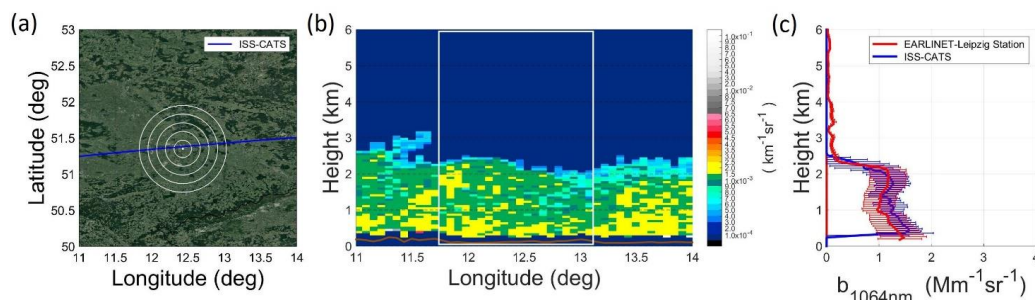
Figure 3: (a) Nighttime ISS orbit over EARLINET Leipzig station on the 13th of September 2016 (blue line). The white circle denotes the location of Leipzig lidar system, (b) CATS Backscatter Coefficient 1064nm and (c) CATS (blue line) and EARLINET-Leipzig (red line) backscatter coefficient profiles (1064 nm).
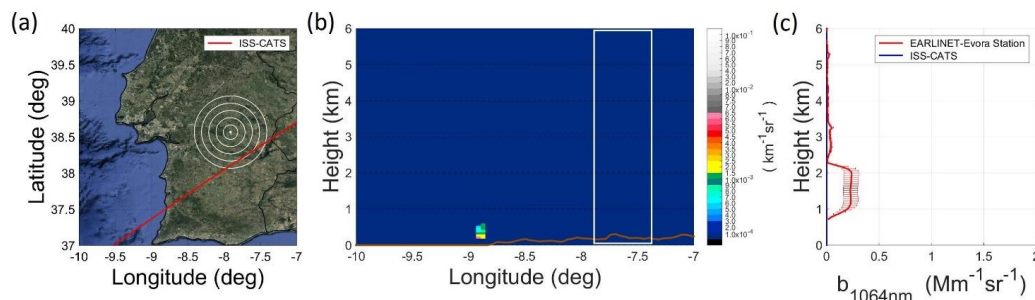
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Figure 4: (a) Daytime ISS orbit over Évora EARLINET station on the 31th of May 2016 (red line). The white circle denotes the location of Évora lidar system, (b) CATS Backscatter Coefficient 1064nm and (c) CATS (blue line) and EARLINET-Évora (red line) backscatter coefficient profiles (1064 nm).
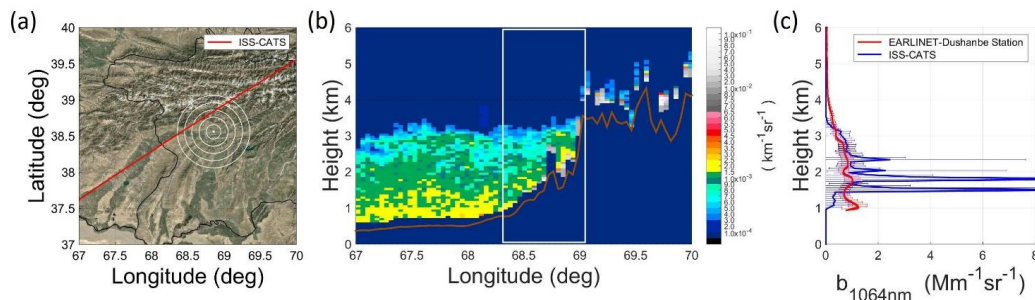
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Figure 5: (a) Nighttime ISS orbit over Dushanbe EARLINET station on the 25th of May 2015 (blue line). The white circle denotes the location of Dushanbe lidar system, (b) CATS Backscatter Coefficient 1064nm and (c) CATS (blue line) and EARLINET-Dushanbe (red line) backscatter coefficient profiles (1064 nm).
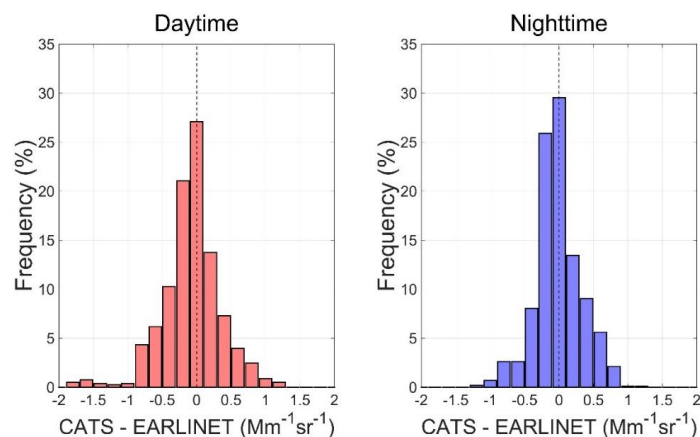
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Figure 6. Distributions of the differences between CATS Level 2 and the corresponding EARLINET backscatter coefficient measurements, calculated over (a) daytime (21 collocated cases) and (b) nighttime (26 collocated cases).
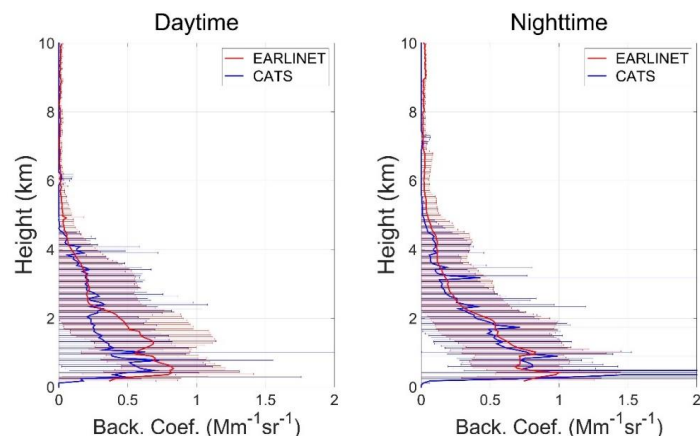

Figure 7. CATS (blue line) and EARLINET (red line) mean profiles of backscatter coefficient at 1064 nm for (left) daytime and (right) nighttime. The horizontal lines represent the SD of CATS (blue colour) and EARLINET (red colour) profiles.