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 with starting time or stop time of the EARLINET performed measurements time window within 90 minutes~~.~~ of the ISS overpass, 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 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 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. Regarding solar illumination conditions, low negative biases in CATS backscatter coefficient profiles, of the order of 6.1%, indicate the good nighttime performance of CATS. During daytime, reduced signal-to-noise ratio by solar background illumination prevents retrievals of weakly scattering atmospheric layers that would otherwise be detectable during nighttime, leading to higher negative biases, of the order of 22.3%, in CATS daytime performance.~~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.~~

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 Physics 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 suffered an unrecoverable fault.

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 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 National d'Études Spatiales (CNES) Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission in June, 2006 (Winker et al., 2007). Since 2009 the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument (Winker et al., 2009) onboard CALIPSO operates on the secondary backup laser. The launch of the post-CALIPSO missions, the joint European Space Agency (ESA) and JAXA satellite Earth Cloud Aerosol and Radiation Explorer (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 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 nm). Additional gains of the CATS project 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 performance has been validated against ground-based AErosol RObotic NETwork (AERONET; Holben et al., 1998) measurements and evaluated against satellite-based Atmospheric Optical Depth (AOD) retrievals of Aqua and Terra Moderate Imaging Spectroradiometer (MODIS; Levy et al., 2013) and active CPL (McGill et al., 2002) and CALIPSO CALIOP (Winker et al., 2009) profiles of extinction coefficient and AOD at 1064 nm. Lee et al. (2018) compared daytime quality-assured CATS V2-01 vertically integrated extinction coefficient profiles (1064 nm) and AERONET AOD (1020 nm) values, spatially (within 0.4° Longitude and Latitude) and temporally (±30 minutes) collocated, and found a reasonable agreement with a correlation of 0.64. A comparative analysis of CATS and MODIS C6.1 Dark Target (DT) AOD retrievals, through spectral interpolation between 0.87 and 1.24 μm channels, reported correlation of 0.75 and slope of 0.79, over ocean. In addition, Lee et al., (2019) evaluated AOD and extinction coefficient profiles from CATS through intercomparison with CALIOP. Regarding AOD, analysis of 2681 CATS and CALIOP collocated observation cases (within 0.4° Longitude/Latitude and ±30 minutes ISS and CALIPSO overpass difference), showed correlation of 0.62 and 0.52 over land and ocean respectively during daytime (1342 cases), and 0.84 and 0.81 over land and ocean respectively during nighttime (1339 cases). Comparison of CATS and CALIOP collocated extinction coefficient profiles based on the closest Euclidian distance on the earth's surface shows also good shape agreement, despite an apparent CALIOP underestimation in the lowest 2 km height. CATS and CALIOP observations were used by Rajapakshe et al. (2017) to study the seasonally transported aerosol layers over the SE Atlantic Ocean. The performed comparative analysis reported on similar geographical patterns regarding Above Cloud Aerosols (ACA), Cloud Fraction (CF) and ACA occurrence frequency (ACA_F) between CATS and CALIOP retrievals. However, the authors reported also on differences between CATS and CALIOP vertical aerosol distributions, with ACA bottom height identified by CATS lower than the respective of CALIOP. CATS retrievals were used to document the diurnal cycle and variations of clouds, with CALIOP complementarily used. Noel et al. (2018) showed that both CATS and CALIOP profiles of CF agree well on both the vertical patterns and values at 01:30 and 13:30 LT, over both land and ocean, with minor differences of the order of 2-7% throughout the entire profiles of cloud fraction. CATS depolarization measurements, which are critical in the processing algorithms of aerosol subtype classification, were investigated in the case of desert dust, smoke from biomass burning and cirrus clouds (Yorks et al., 2016), and were found consistent and in good agreement with depolarization measurements from previous studies and historical datasets implementing CPL (Yorks et al., 2011) and CALIOP (Liu et al., 2015).

Overall, CATS retrievals have been evaluated and found in reasonable agreement with ground-based AERONET, airborne CPL and satellite-based MODIS and CALIOP measurements. However, for the quality assessment of CATS backscatter coefficient profiles, a large-scale and dense network of ground-based lidar systems is needed, in order to facilitate high-quality collocated and concurrent measurements. This necessity is largely related

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 (0.5° 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 of a unique infrastructure for assessing the validation needs for spaceborne lidar missions. 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 of 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 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.

2 Data and methodology

2.1 EARLINETCATS

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 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 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.

CATS products and processing algorithms (Pauly et al., 2019) 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 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 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 addition to CATS Level 2 Feature Type (namely: clear air, cloud, aerosol and totally attenuated), the algorithm provides the confidence level of the Feature Type 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.

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

~~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/, 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) 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., 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 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).

2.2 CATSEARLINET

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 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 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.

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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 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 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 CATS Data Release Notes, Quality Statements and Theoretical Basis, available at https://cats.gsfc.nasa.gov/ (last access: 20 December 2018).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. 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 between “active”, “not permanent”, “joining” and “not active”. An EARLINET station is classified as active when on condition of performing regularly and simultaneously measurements with the other stations composing the lidar network, and accordingly, contributing with uploading the performed measurements to the EARLINET database (https://www.earlinet.org/, last access: 20 December 2018). Lidar observations in the framework of EARLINET are 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).

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2.3 EARLINET-CATS correlative measurements

2.3.1 Comparison methodology

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 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 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

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 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 with starting time or stop time of the performed measurements widow within 90 minutes of the ISS station overpass. The EARLINET-CATS cases considered to the assessment of the accuracy and representativeness of CATS backscatter coefficient profiles are provided in Table 2, including the name of the EARLINET station, the EARLINET measurements window, the ISS overpass time and ISS minimum distance between the corresponding EARLINET station and the lidar footprint of CATS and the Daytime/Nighttime information. 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 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. Cases with detected cirrus either at the EARLINET Range-Corrected-Signal quicklooks or at the ISS-CATS backscatter coefficient profiles or the feature type profiles are not considered in the study. Initially, the presence of clouds is 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" 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" $\geq$ -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. CATS requirements applied in the methodology are summarized in Table 3.

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 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-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 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 % (Althausen et al., 2009; Baars et al., 2012; Engelmann et al., 2016; Hänel et al., 2012), thus meeting the quality assurance requirements of EARLINET. None of the lidar systems participateding in the present study, is equipped with a rotational-vibrational Raman channel excited 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:

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

And the corresponding lidar equation at 607 nm by:

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

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

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

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 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 respectivelybackscattering respectively, whereas α_{mol} and α_{par} are the molecular and particle extinction coefficients.

Finally, in order to perform the intercomparison between CATS and EARLINET profiles, the high resolution of EARLINET profiles was lowered to match the vertical resolution of CATS profiles (i.e. 60m). The objective of obtaining profiles of similar vertical resolution was addressed through computing the EARLINET mean backscatter coefficient value from all EARLINET bins within each CATS 60m backscatter coefficient height range. The computed EARLINET profiles of similar vertical resolution with CATS followed with high accuracy the characterizes and tendencies, both qualitative and quantitative, of the initial EARLINET profiles, despite the loss of vertical resolution (Iarlori et al., 2015).

2.3.34 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 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 (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 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 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 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 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.

3 Results and discussion

3.1 EARLINET-CATS Correlative Cases

To illustrate strengths and limitations of CATS products, we discuss in detail~~s~~ three selected cases of collocated and 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~~considered here 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 (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~~ of 50 km, between the Leipzig station and the ISS footprint, and Leipzig measurements within 90 minutes 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 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. Although the case presented and discussed in Figure 3 corresponds to a nighttime ISS overpass, the case is representative for cloud free and relative homogeneous atmospheric scenes in terms of aerosols, for both daytime and nighttime solar background illumination, demonstrating the overall high performance of CATS under such conditions.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 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-laaying 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).

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 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 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 $Mm^{-1}sr^{-1}$ / 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 CATS Level 2 provides the feature classification of the detected layers and associated confidence level of the classification. In addition to the backscatter coefficient, 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.~~ The Cloud-~~aerosol~~ Aerosol 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 ≥ -1) are filtered. The strict cloud screening is applied because of our basic idea to establish the accuracy of CATS aerosol backscatter coefficient 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 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 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 $Mm^{-1}sr^{-1}$). 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 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~~ in the end of 2018) to improve the accuracy of the Feature Type and Feature Type Score, especially during daytime.

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 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 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. The intercomparison statistical values between CATS and EARLINET are summarized in Table 4.

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).

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 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 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., 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 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 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 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).

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, 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.

Another source of ~~discrepancies~~ discrepancy 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 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 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 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 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

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-performance EARLINET stations across Europe and one located in Central Asia. Our analysis is based ~~to~~ on 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, typically with starting time or stop time of the measurements within 90 minutes 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 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 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 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 biases and unrealistic AOD values.

The qualitative and quantitative agreement between CATS and EARLINET reported in this study is encouraging, especially during nighttime, agreement that will hopefully facilitate further studies implementing CATS observations in the future. CATS, for a period of almost three years, provided an unprecedented global dataset of vertical profiles of aerosols and clouds, much like CALIOP, taking though advantage of the unique orbital characteristics of the ISS. ISS enabled CATS to provide for the first time satellite-based lidar measurements of the diurnal evolution of aerosols and clouds over the tropics and midlatitudes, and to be more specific to latitudes below 52o. Since CALIPSO and Aeolus (and in the future also EarthCARE) are polar sun-synchronous satellites of fixed equatorial crossing time (01:30 and 13:30 LT for CALIOP, 06:00 and 18:00 for ALADIN), it is expected that, at least for the near future, CATS dataset will remain the only available satellite-based lidar source of nearly global diurnal measurements of atmospheric aerosols and clouds. In addition, while CALIOP is a two-wavelength lidar system operating at 532 nm and 1064 nm with depolarization capabilities at 532 nm, CATS provided satellite-based aerosol and cloud depolarization profiles at 1064 nm, thus in a different wavelength. This dataset, much like CALIOP dataset, is especially useful for studies of the three-dimensional distribution of non-spherical aerosol particles in the atmosphere (e.g. mineral dust and volcanic ash), and especially since it is an active sensor, over regions of high reflectivity (e.g. deserts, ice). Future studies including the exploitations of CATS unique observations may help the scientific community to shed new light on physical processes of aerosols and clouds in the Earth's atmosphere.

Competing interests. The authors declare that they have no conflict of interest.

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References

Althausen, D., Engelmann, R., Baars, H., Heese, B., Ansmann, A., Müller, D., and Komppula, M.: Portable Raman Lidar PollyXT for Automated Profiling of Aerosol Backscatter, Extinction, and Depolarization, J. Atmos. Ocean. Technol., 26, 2366–2378, 2009.

Amiridis, V., Wandinger, U., Marinou, E., Giannakaki, E., Tsekeri, A., Basart, S., Kazadzis, S., Gkikas, A., Taylor, M., Baldasano, J. and Ansmann, A.: Optimizing CALIPSO Saharan dust retrievals, Atmos. Chem. and Phys., 13(23), 12089–12106, doi:https://doi.org/10.5194/acp-13-12089-2013, 2013.

Amiridis, V., Marinou, E., Tsekeri, A., Wandinger, U., Schwarz, A., Giannakaki, E., Mamouri, R., Kokkalis, P., Binietoglou, I., Solomos, S., Herekakis, T., Kazadzis, S., Gerasopoulos, E., Proestakis, E., Kottas, M., Balis, D., Papayannis, A., Kontoes, C., Kourtidis, K., Papagiannopoulos, N., Mona, L., Pappalardo, G., Le Rille, O. and Ansmann, A.: LIVAS: a 3-D multi-wavelength aerosol/cloud database based on CALIPSO and EARLINET, Atmos. Chem. Phys., 15(13), 7127–7153, doi:10.5194/acp-15-7127-2015, 2015.

Ansmann, A., Bosenberg, J., Chaikovsky, A., Comeron, A., Eckhardt, S., Eixmann, R., Freudenthaler, V., Ginoux, P., Komguem, L., Linne, H., Marquez, M. a. L., Matthias, V., Mattis, I., Mitev, V., Muller, D., Music, S., Nickovic, S., Pelon, J., Sauvage, L., Sobolewsky, P., Srivastava, M. K., Stohl, A., Torres, O., Vaughan, G., Wandinger, U. and Wiegner, M.: Long-range transport of Saharan dust to northern Europe: The 11-16 October 2001 outbreak observed with EARLINET, J. Geophys. Res.-Atmos., 108(D24), 4783, doi:10.1029/2003JD003757, 2003.

Ansmann, A., Riebesell, M., Wandinger, U., Weitkamp, C., Voss, E., Lahmann, W., and Michaelis, W.: Combined Raman elastic backscatter LIDAR for vertical profiling of moisture, aerosol extinction, backscatter, and LIDAR ratio, Appl. Phys., B55, 18–28, https://doi.org/10.1007/BF00348608, 1992.

Ansmann, A., Tesche, M., Gross, S., Freudenthaler, V., Seifert, P., Hiebsch, A., Schmidt, J., Wandinger, U., Mattis, I., Mueller, D. and Wiegner, M.: The 16 April 2010 major volcanic ash plume over central Europe: EARLINET lidar and AERONET photometer observations at Leipzig and Munich, Germany, Geophys. Res. Lett., 37, L13810, doi:10.1029/2010GL043809, 2010.

Ansmann, A., Tesche, M., Seifert, P., Gross, S., Freudenthaler, V., Apituley, A., Wilson, K. M., Serikov, I., Linne, H., Heinold, B., Hiebsch, A., Schnell, F., Schmidt, J., Mattis, I., Wandinger, U. and Wiegner, M.: Ash and fine-mode particle mass profiles from EARLINET-AERONET observations over central Europe after the eruptions of the Eyjafjallajokull volcano in 2010, J. Geophys. Res.-Atmos., 116, D00U02, doi:10.1029/2010JD015567, 2011.

Ansmann, A., Wandinger, U., Le Rille, O., Lajas, D. and Straume, A. G.: Particle backscatter and extinction profiling with the spaceborne high-spectral-resolution Doppler lidar ALADIN: methodology and simulations, Appl. Optics, 46(26), 6606–6622, doi:10.1364/AO.46.006606, 2007.

Baars, H., Ansmann, A., Althausen, D., Engelmann, R., Heese, B., Müller, D., Artaxo, P., Paixao, M., Pauliquevis, T., and Souza, R.: Aerosol profiling with lidar in Amazon Basin during the wet and dry season, J. Geophys. Res., 117, D21201, 2012.

Baars, H., Kanitz, T., Engelmann, R., Althausen, D., Heese, B., Komppula, M., Preissler, J., Tesche, M., Ansmann, A., Wandinger, U., Lim, J.-H., Ahn, J. Y., Stachlewska, I. S., Amiridis, V., Marinou, E., Seifert, P., Hofer, J., Skupin, A., Schneider, F., Bohlmann, S., Foth, A., Bley, S., Pfuller, A., Giannakaki, E., Lihavainen, H., Viisanen, Y., Hooda, R. K., Pereira, S. N., Bortoli, D., Wagner, F., Mattis, I., Janicka, L., Markowicz, K. M., Achtert, P., Artaxo, P., Pauliquevis, T., Souza, R. A. F., Sharma, V. P., van Zyl, P. G., Beukes, J. P., Sun, J., Rohwer, E. G., Deng, R., Mamouri, R.-E. and Zamorano, F.: An overview of the first decade of Polly(NET): an emerging network of automated Raman-polarization lidars for continuous aerosol profiling, Atmos. Chem. Phys., 16(8), 5111–5137, doi:10.5194/acp-16-5111-2016, 2016.

Balis, D., Koukouli, M.-E., Siomos, N., Dimopoulos, S., Mona, L., Pappalardo, G., Marenco, F., Clarisse, L., Ventress, L. J., Carboni, E., Grainger, R. G., Wang, P., Tilstra, G., Ronald van der, A., Theys, N. and Zehner, C.: Validation of ash optical depth and layer height retrieved from passive satellite sensors using EARLINET and airborne lidar data: the case of the Eyjafjallajokull eruption, Atmos. Chem. Phys., 16(9), 5705–5720, doi:10.5194/acp-16-5705-2016, 2016.

Binietoglou, I., Basart, S., Alados-Arboledas, L., Amiridis, V., Argyrouli, A., Baars, H., Baldasano, J. M., Balis, D., Belegante, L., Bravo-Aranda, J. A., Burlizzi, P., Carrasco, V., Chaikovsky, A., Comeron, A., D'Amico, G., Filioglou, M., Granados-Munoz, M. J., Guerrero-Rascado, J. L., Ilic, L., Kokkalis, P., Maurizi, A., Mona, L., Monti, F., Munoz-Porcar, C., Nicolae, D., Papayannis, A., Pappalardo, G., Pejanovic, G., Pereira, S. N., Perrone, M. R., Pietruczuk, A., Posyniak, M., Rocadenbosch, F., Rodriguez-Gomez, A., Sicard, M., Siomos, N., Szkop, A., Terradellas, E., Tsekeri, A., Vukovic, A., Wandinger, U. and Wagner, J.: A methodology for investigating dust model performance using synergistic EARLINET/AERONET dust concentration retrievals, Atmos. Meas. Tech., 8(9), 3577–3600, doi:10.5194/amt-8-3577-2015, 2015.

Bockmann, C., Wandinger, U., Ansmann, A., Bosenberg, J., Amiridis, V., Boselli, A., Delaval, A., De Tomasi, F., Frioud, M., Grigorov, I. V., Hagard, A., Horvat, M., Iarlori, M., Komguem, L., Kreipl, S., Larchevque, G., Matthias, V., Papayannis, A., Pappalardo, G., Rocadenbosch, F., Rodrigues, J. A., Schneider, J., Shcherbakov, V. and Wiegner, M.: Aerosol lidar intercomparison in the framework of the EARLINET project. 2. Aerosol backscatter algorithms, Appl. Optics, 43(4), 977–989, doi:10.1364/AO.43.000977, 2004.

Bosenberg, J., et al. (2001), The German aerosol lidar network: Methodology, data, analysis, MPI Rep. 317, Max-Planck-Inst. fu¨r Meteorol., Hamburg, Germany.

Bosenberg, J., et al. (2003), EARLINET: A European Aerosol Research Lidar Network to establish an aerosol climatology, final report, MPI Rep. 348, Max-Planck-Inst. fu¨r Meteorol., Hamburg, Germany.

Burton, S. P., Ferrare, R. A., Hostetler, C. A., Hair, J. W., Kittaka, C., Vaughan, M. A., Obland, M. D., Rogers, R. R., Cook, A. L., Harper, D. B., and Remer, L. A.: Using airborne high spectral resolution lidar data to evaluate combined active plus passive retrievals of aerosol extinction profiles, J. Geophys. Res.-Atmos., 115, D00H15, doi:10.1029/2009jd012130, 2010.

Burton, S. P., R. A. Ferrare, C. A. Hostetler, J. W. Hair, R. R. Rogers, M. D. Obland, C. F. Butler, A. L. Cook, D. B. Harper, and K. D. Froyd (2012), Aerosol classification using airborne High Spectral Resolution Lidar measurements—Methodology and examples, Atmos. Meas. Tech., 5, 73–98, www.atmos-meas-tech.net/5/73/2012/, doi:10.5194/amt-5-73-2012.

Burton, S. P., R. A. Ferrare, M. A. Vaughan, A. H. Omar, R. R. Rogers, C. A. Hostetler, and J. W. Hair (2013), Aerosol classification from airborne HSRL and comparisons with the 1 CALIPSO vertical feature mask, Atmos. Meas. Tech. Discuss., 6, 1815–1858, doi:10.5194/amtd-6-1815-2013.

Chimot, J., Veefkind, J. P., Vlemmix, T., de Haan, J. F., Amiridis, V., Proestakis, E., Marinou, E. and Levelt, P. F.: An exploratory study on the aerosol height retrieval from OMI measurements of the 477 nm O-2-O-2 spectral band using a neural network approach, Atmos. Meas. Tech., 10(3), 783–809, doi:10.5194/amt-10-783-2017, 2017.

D'Amico, G., Amodeo, A., Baars, H., Binietoglou, I., Freudenthaler, V., Mattis, I., Wandinger, U. and Pappalardo, G.: EARLINET Single Calculus Chain - overview on methodology and strategy, Atmos. Meas. Tech., 8(11), 4891–4916, doi:10.5194/amt-8-4891-2015, 2015.

D'Amico, G., Amodeo, A., Mattis, I., Freudenthaler, V. and Pappalardo, G.: EARLINET Single Calculus Chain - technical - Part 1: Pre-processing of raw lidar data, Atmos. Meas. Tech., 9(2), 491–507, doi:10.5194/amt-9-491-2016, 2016.

Dubovik, O., Smirnov, A., Holben, B., King, M. D., Eck, T. F., Kaufman, Y. J., and Slutsker, I., and Eck, T. F.: Accuracy assessments of aerosol optical properties retrieved from Aerosol Robotic Network (AERONET) Sun and sky radiance measurements, J. Geophys. Res., 105, 9791–9806, 2000.

Digirolamo, P., Gagliardi, R., Pappalardo, G., Spinelli, N., Velotta, R. and Berardi, V.: 2 Wavelength Lidar Analysis of Stratospheric Aerosol-Size Distribution, J. Aerosol. Sci., 26(6), 989–1001, doi:10.1016/0021-8502(95)00025-8, 1995.

Engelmann, R., Kanitz, T., Baars, H., Heese, B., Althausen, D., Skupin, A., Wandinger, U., Komppula, M., Stachlewska, I. S., Amiridis, V., Marinou, E., Mattis, I., Linne, H. and Ansmann, A.: The automated multiwavelength Raman polarization and water-vapor lidar Polly(XT): the neXT generation, Atmos. Meas. Tech., 9(4), 1767–1784, doi:10.5194/amt-9-1767-2016, 2016.

Fernald, F.: Analysis of Atmospheric Lidar Observations - Some Comments, Appl. Optics, 23(5), 652–653, doi:10.1364/AO.23.000652, 1984.

Grigas, T., Hervo, M., Gimmestad, G., Forrister, H., Schneider, P., Preissler, J., Tarrason, L. and O'Dowd, C.: CALIOP near-real-time backscatter products compared to EARLINET data, Atmos. Chem. Phys., 15(21), 12179–12191, doi:10.5194/acp-15-12179-2015, 2015.

Haarig, M., Ansmann, A., Althausen, D., Klepel, A., Gross, S., Freudenthaler, V., Toledano, C., Mamouri, R.-E., Farrell, D. A., Prescod, D. A., Marinou, E., Burton, S. P., Gasteiger, J., Engelmann, R. and Baars, H.: Triple-wavelength depolarization-ratio profiling of Saharan dust over Barbados during SALTRACE in 2013 and 2014, Atmos. Chem. Phys., 17(17), 10767–10794, doi:10.5194/acp-17-10767-2017, 2017.

Hair, J. W., C. A. Hostetler, A. L. Cook, D. B. Harper, R. A. Ferrare, T. L. Mack, W. Welch, L. R. Isquierdo, and F. E. Hovis (2008), Airborne high spectral resolution lidar for profiling aerosol optical properties, Appl. Optics, 47, 6734–6752, doi:10.1364/AO.47.006734.

Hänel, A., Baars, H., Althausen, D., Ansmann, A., Engelmann, R., and Sun, Y. J.: One-year aerosol profiling with EUCAARI Raman lidar at Shangdianzi GAW station: Beijing plume and seasonal variation, J. Geophys. Res., 117, D13201, 2012.

Hlavka, D. L., J. E. Yorks, S. A. Young, M. A. Vaughan, R. E. Kuehn, M. J. McGill, and S. D. Rodier, 2012: Airborne validation of cirrus cloud properties derived from CALIPSO lidar measurements: Optical properties, J. Geophys. Res., 117, D09207, doi:10.1029/2011JD017053.

Hair, J. W., Hostetler, C. A., Cook, A. L., Harper, D. B., Ferrare, R. A., Mack, T. L., Welch, W., Izquierdo, L. R., and Hovis, F. E.: Airborne high spectral resolution lidar for profiling aerosol optical properties, Appl. Optics, 47, 6734–6752, doi:10.1364/AO.47.006734, 2008.

Hofer, J., Althausen, D., Abdullaev, S. F., Makhmudov, A. N., Nazarov, B. I., Schettler, G., Engelmann, R., Baars, H., Fomba, K. W., Müller, K., Heinold, B., Kandler, K., and Ansmann, A.: Long-term profiling of mineral dust and pollution aerosol with multiwavelength polarization Raman lidar at the Central Asian site of Dushanbe, Tajikistan: case studies, Atmos. Chem. Phys., 17, 14559-14577, https://doi.org/10.5194/acp-17-14559-2017, 2017.

Holben, B. N., Eck, T. F., Slutsker, I., Tanre, D., Buis, J. P., Setzer, A., Vermote, E., Reagan, J. A., Kaufman, Y. J., Nakajima, T., Lavenu, F., Jankowiak, I. and Smirnov, A.: AERONET - A federated instrument network and data archive for aerosol characterization, Remote Sens. Environ., 66(1), 1–16, doi:10.1016/S0034-4257(98)00031-5, 1998.

Hughes, E. J., J. E. Yorks, N. A. Krotkov, A. M. da Silva, *and* M. McGill *(*2016*)*, Using CATS Near-Realtime Lidar Observations to Monitor and Constrain Volcanic Sulfur Dioxide (SO_2) Forecasts, Geophys. Res. Lett., 43, *doi:*10.1002/2016GL070119.

Iarlori, M., Madonna, F., Rizi, V., Trickl, T., and Amodeo, A.: Effective resolution concepts for lidar observations, Atmos. Meas. Tech., 8, 5157-5176, https://doi.org/10.5194/amt-8-5157-2015, 2015.

Illingworth, A. J., Barker, H. W., Beljaars, A., Ceccaldi, M., Chepfer, H., Clerbaux, N., Cole, J., Delanoe, J., Domenech, C., Donovan, D. P., Fukuda, S., Hirakata, M., Hogan, R. J., Huenerbein, A., Kollias, P., Kubota, T., Nakajima, T., Nakajima, T. Y., Nishizawa, T., Ohno, Y., Okamoto, H., Oki, R., Sato, K., Satoh, M., Shephard, M. W., Velazquez-Blazquez, A., Wandinger, U., Wehr, T. and van Zadelhoff, G.-J.: THE EARTHCARE SATELLITE The Next Step Forward in Global Measurements of Clouds, Aerosols, Precipitation, and Radiation, Bull. Amer. Meteorol. Soc., 96(8), 1311–1332, doi:10.1175/BAMS-D-12-00227.1, 2015.

Janicka L., Stachlewska I.S., Veselovskii I., Baars H, Temporal variations in optical and microphysical properties of mineral dust and biomass burning aerosol derived from daytime Raman lidar observations over Warsaw, Poland, ATMOSPHERIC ENVIRONMENT Vol.169, 162-174, 2017.

Kacenelenbogen, M., Vaughan, M. A., Redemann, J., Hoff, R. M., Rogers, R. R., Ferrare, R. A., Russell, P. B., Hostetler, C. A., Hair, J. W., and Holben, B. N.: An accuracy assessment of the CALIOP/CALIPSO version

2/version 3 daytime aerosol extinction product based on a detailed multi-sensor, multi-platform case study, Atmos. Chem. Phys., 11, 3981–4000, doi:10.5194/acp-11-3981-2011, 2011.

Kar, J., Vaughan, M. A., Lee, K.-P., Tackett, J. L., Avery, M. A., Garnier, A., Getzewich, B. J., Hunt, W. H., Josset, D., Liu, Z., Lucker, P. L., Magill, B., Omar, A. H., Pelon, J., Rogers, R. R., Toth, T. D., Trepte, C. R., Vernier, J.-P., Winker, D. M., and Young, S. A.: CALIPSO lidar calibration at 532 nm: version 4 nighttime algorithm, Atmos. Meas. Tech., 11, 1459-1479, https://doi.org/10.5194/amt-11-1459-2018, 2018.

Kim, M.-H., Omar, A. H., Tackett, J. L., Vaughan, M. A., Winker, D. M., Trepte, C. R., Hu, Y., Liu, Z., Poole, L. R., Pitts, M. C., Kar, J. and Magill, B. E.: The CALIPSO Version 4 Automated Aerosol Classification and Lidar Ratio Selection Algorithm, Atmospheric Measurement Techniques Discussions, 1–43, doi:https://doi.org/10.5194/amt-2018-166, 2018.

Kittaka, C., Winker, D. M., Vaughan, M. A., Omar, A., and Remer, L. A.: Intercomparison of column aerosol optical depths from CALIPSO and MODIS-Aqua, Atmos. Meas. Tech., 4, 131–141, doi:10.5194/amt-4-131-2011 , 2011.

Klett, J.: Stable Analytical Inversion Solution for Processing Lidar Returns, Appl. Optics, 20(2), 211–220, doi:10.1364/AO.20.000211, 1981.

Lee, L., Zhang, J., Reid, J. S. and Yorks, J. E.: Investigation of CATS aerosol products and application toward global diurnal variation of aerosols, Atmospheric Chemistry and Physics Discussions, 1–47, doi:https://doi.org/10.5194/acp-2018-1298, 2018.

Levy, R. C., Mattoo, S., Munchak, L. A., Remer, L. A., Sayer, A. M., Patadia, F. and Hsu, N. C.: The Collection 6 MODIS aerosol products over land and ocean, Atmos. Meas. Tech., 6(11), 2989–3034, doi:10.5194/amt-6-2989-2013, 2013.

Liu, Z. Y., Vaughan, M. A., Winker, D. M., Hostetler, C. A., Poole, L. R., Hlavka, D., Hart, W. and McGill, M.: Use of probability distribution functions for discriminating between cloud and aerosol in lidar backscatter data, J. Geophys. Res.-Atmos., 109(D15), D15202, doi:10.1029/2004JD004732, 2004.

Liu, Z., Vaughan, M., Winker, D., Kittaka, C., Getzewich, B., Kuehn, R., Omar, A., Powell, K., Trepte, C. and Hostetler, C.: The CALIPSO Lidar Cloud and Aerosol Discrimination: Version 2 Algorithm and Initial Assessment of Performance, J. Atmos. Oceanic Technol., 26(7), 1198–1213, doi:10.1175/2009JTECHA1229.1, 2009.

Mamouri, R. E., Amiridis, V., Papayannis, A., Giannakaki, E., Tsaknakis, G. and Balis, D. S.: Validation of CALIPSO space-borne-derived attenuated backscatter coefficient profiles using a ground-based lidar in Athens, Greece, Atmos. Meas. Tech., 2(2), 513–522, doi:10.5194/amt-2-513-2009, 2009.

Mattis, I., D'Amico, G., Baars, H., Amodeo, A., Madonna, F. and Iarlori, M.: EARLINET Single Calculus Chain - technical - Part 2: Calculation of optical products, Atmos. Meas. Tech., 9(7), 3009–3029, doi:10.5194/amt-9-3009-2016, 2016.

Mccormick, M., Winker, D., Browell, E., Coakley, J., Gardner, C., Hoff, R., Kent, G., Melfi, S., Menzies, R., Platt, C., Randall, D. and Reagan, J.: Scientific Investigations Planned for the Lidar in-Space Technology Experiment (lite), Bull. Amer. Meteorol. Soc., 74(2), 205–214, doi:10.1175/1520-0477(1993)074<0205:SIPFTL>2.0.CO;2, 1993.

McGill, M., Hlavka, D., Hart, W., Scott, V. S., Spinhirne, J. and Schmid, B.: Cloud Physics Lidar: instrument description and initial measurement results, Appl. Optics, 41(18), 3725–3734, doi:10.1364/AO.41.003725, 2002.

McGill, M. J., J. E. Yorks, V. S. Scott, A. W. Kupchock, and P. A. Selmer (2015), The Cloud Aerosol Transport System (CATS): A technology demonstration on the International Space Station, Proc. SPIE 9612, Lidar Remote Sensing for Environmental Monitoring XV, 96120A, doi:10.1117/12.2190841.

McGill, M. J., M. A. Vaughan, C. R. Trepte, W. D. Hart, D. L. Hlavka, D. M. Winker, and R. Kuehn, 2007: Airborne validation of spatial properties measured by the CALIPSO lidar, J. Geophys. Res., 112, D20201, doi:10.1029/2007JD008768.

Mona, L., Pappalardo, G., Amodeo, A., D'Amico, G., Madonna, F., Boselli, A., Giunta, A., Russo, F. and Cuomo, V.: One year of CNR-IMAA multi-wavelength Raman lidar measurements in coincidence with CALIPSO overpasses: Level 1 products comparison, Atmos. Chem. Phys., 9(18), 7213–7228, doi:10.5194/acp-9-7213-2009, 2009.

Noel, V., Chepfer, H., Chiriaco, M. and Yorks, J.: The diurnal cycle of cloud profiles over land and ocean between 51 degrees S and 51 degrees N, seen by the CATS spaceborne lidar from the International Space Station, Atmos. Chem. Phys., 18(13), 9457–9473, doi:10.5194/acp-18-9457-2018, 2018.

Omar, A. H., Winker, D. M., Kittaka, C., Vaughan, M. A., Liu, Z. Y., Hu, Y. X., Trepte, C. R., Rogers, R. R., Ferrare, R. A., Lee, K. P., Kuehn, R. E., and Hostetler, C. A.: The CALIPSO automated aerosol classification and lidar ratio selection algorithm, J. Atmos. Ocean. Tech., 1994–2014, doi:10.1175/2009jtecha1231.1, 2009.Oo, M. and Holz, R.: Improving the CALIOP aerosol optical depth using combined MODISCALIOP observations and CALIOP integrated attenuated total color ratio, J. Geophys. Res., 116, D14201, doi:10.1029/2010jd014894, 2011.

Omar, A. H., Winker, D. M., Tackett, J. L., Giles, D. M., Kar, J., Liu, Z., Vaughan, M. A., Powell, K. A., and Trepte, C. R.: CALIOP and AERONET aerosol optical depth comparisons: One size fits none, J. Geophys. Res.-Atmos., 118, 4748–4766, doi:10.1002/jgrd.50330, 2013.

Ortiz-Amezcua, P., Luis Guerrero-Rascado, J., Jose Granados-Munoz, M., Antonio Benavent-Oltra, J., Boeckmann, C., Samaras, S., Stachlewska, I. S., Janicka, L., Baars, H., Bohlmann, S. and Alados-Arboledas, L.: Microphysical characterization of long-range transported biomass burning particles from North America at three EARLINET stations, Atmos. Chem. Phys., 17(9), 5931–5946, doi:10.5194/acp-17-5931-2017, 2017.

Palm, S., W. Hart, D. Hlavka, E. J. Welton, A. Mahesh, and J. Spinhirne, 2002: GLAS atmospheric data products. NASA Goddard Space Flight Center Geoscience Laser Altimeter System Algorithm Theoretical Basis Document Version 4.2, 141 pp.

Palm, S. P., Hlavka, D. L., Selmer, P., and Pauly, R.: the Cloud Aerosol Transport System (CATS) Data Product Catalog release 3.0, available at: https://cats.gsfc.nasa.gov/media/docs/CATS_ Data_Products_Catalog.pdf (last access: 12 February 2018), 2016.

Papagiannopoulos, N., Mona, L., Alados-Arboledas, L., Amiridis, V., Baars, H., Binietoglou, I., Bortoli, D., D'Amico, G., Giunta, A., Luis Guerrero-Rascado, J., Schwarz, A., Pereira, S., Spinelli, N., Wandinger, U., Wang, X. and Pappalardo, G.: CALIPSO climatological products: evaluation and suggestions from EARLINET, Atmos. Chem. Phys., 16(4), 2341–2357, doi:10.5194/acp-16-2341-2016, 2016.

Pappalardo, G., Amodeo, A., Pandolfi, M., Wandinger, U., Ansmann, A., Bosenberg, J., Matthias, V., Amiridis, V., De Tomasi, F., Frioud, M., Iarlori, M., Komguem, L., Papayannis, A., Rocadenbosch, F. and Wang, X.: Aerosol lidar intercomparison in the framework of the EARLINET project. 3. Raman lidar algorithm for aerosol extinction, backscatter, and lidar ratio, Appl. Optics, 43(28), 5370–5385, doi:10.1364/AO.43.005370, 2004.

Pappalardo, G., Wandinger, U., Mona, L., Hiebsch, A., Mattis, I., Amodeo, A., Ansmann, A., Seifert, P., Linne, H., Apituley, A., Alados Arboledas, L., Balis, D., Chaikovsky, A., D'Amico, G., De Tomasi, F., Freudenthaler, V., Giannakaki, E., Giunta, A., Grigorov, I., Iarlori, M., Madonna, F., Mamouri, R.-E., Nasti, L., Papayannis, A., Pietruczuk, A., Pujadas, M., Rizi, V., Rocadenbosch, F., Russo, F., Schnell, F., Spinelli, N., Wang, X. and Wiegner, M.: EARLINET correlative measurements for CALIPSO: First intercomparison results, J. Geophys. Res.-Atmos., 115, D00H19, doi:10.1029/2009JD012147, 2010.

Pappalardo, G., Mona, L., D'Amico, G., Wandinger, U., Adam, M., Amodeo, A., Ansmann, A., Apituley, A., Alados Arboledas, L., Balis, D., Boselli, A., Bravo-Aranda, J. A., Chaikovsky, A., Comeron, A., Cuesta, J., De Tomasi, F., Freudenthaler, V., Gausa, M., Giannakaki, E., Giehl, H., Giunta, A., Grigorov, I., Gross, S., Haeffelin, M., Hiebsch, A., Iarlori, M., Lange, D., Linne, H., Madonna, F., Mattis, I., Mamouri, R.-E., McAuliffe, M. a. P., Mitev, V., Molero, F., Navas-Guzman, F., Nicolae, D., Papayannis, A., Perrone, M. R., Pietras, C., Pietruczuk, A., Pisani, G., Preissler, J., Pujadas, M., Rizi, V., Ruth, A. A., Schmidt, J., Schnell, F., Seifert, P., Serikov, I., Sicard, M., Simeonov, V., Spinelli, N., Stebel, K., Tesche, M., Trickl, T., Wang, X., Wagner, F., Wiegner, M. and Wilson, K. M.: Four-dimensional distribution of the 2010 Eyjafjallajokull volcanic cloud over Europe observed by EARLINET, Atmos. Chem. Phys., 13(8), 4429–4450, doi:10.5194/acp-13-4429-2013, 2013.

Pappalardo, G., Amodeo, A., Apituley, A., Comeron, A., Freudenthaler, V., Linne, H., Ansmann, A., Boesenberg, J., D'Amico, G., Mattis, I., Mona, L., Wandinger, U., Amiridis, V., Alados-Arboledas, L., Nicolae, D. and Wiegner, M.: EARLINET: towards an advanced sustainable European aerosol lidar network, Atmos. Meas. Tech., 7(8), 2389–2409, doi:10.5194/amt-7-2389-2014, 2014.

Pauly, R. M., Yorks, J. E., Hlavka, D. L., McGill, M. J., Amiridis, V., Palm, S. P., Rodier, S. D., Vaughan, M. A., Selmer, P. A., Kupchock, A. W., Baars, H., and Gialitaki, A.: Cloud Aerosol Transport System (CATS) 1064 nm Calibration and Validation, Atmos. Meas. Tech. Discuss., https://doi.org/10.5194/amt-2019-172, in review, 2019.

Perrone, M. R., De Tomasi, F., Burlizzi, P.: Aerosol Products by CALIOP at 532 nm and by a ground-based Raman lidar at 355 nm: Intercomparison methodology. Atm. Res. 101, 438-449, 2011.

Perrone, M. R., De Tomasi, F., Stohl, A., Kristiansen, N. I.: Integration Of Measurements And Model Simulations To Characterize Eyjafjallajokull Volcanic Aerosols Over South-Eastern Italy", Atmospheric Chemistry And Physics, 12, 10001,10013, 2012.

Powell, K. A., et al. (2009), CALIPSO lidar calibration algorithms: Part INighttime 532-nm parallel channel and 532-nm perpendicular channel, J. Atmos. Oceanic Technol., 26, 2015–2033, doi:10.1175/2009JTECHA1242.1.

Rajapakshe, C., Zhang, Z., Yorks, J. E., Yu, H., Tan, Q., Meyer, K., Platnick, S. and Winker, D. M.: Seasonally transported aerosol layers over southeast Atlantic are closer to underlying clouds than previously reported, Geophys. Res. Lett., 44(11), 5818–5825, doi:10.1002/2017GL073559, 2017.

Redemann, J., Vaughan, M. A., Zhang, Q., Shinozuka, Y., Russell, P. B., Livingston, J. M., Kacenelenbogen, M., and Remer, L. A.: The comparison of MODIS-Aqua (C5) and CALIOP (V2 & V3) aerosol optical depth, Atmos. Chem. Phys., 12, 3025–3043, doi:10.5194/acp-12-3025-2012, 2012.

Remer, L. A., Kaufman, Y. J., Tanre, D., Mattoo, S., Chu, D. A., Martins, J. V., Li, R. R., Ichoku, C., Levy, R. C., Kleidman, R. G., Eck, T. F., Vermote, E., and Holben, B. N.: The MODIS aerosol algorithm, products, and validation, J. Atmos. Sci., 62, 947–973, https://doi.org/10.1175/JAS3385.1, 2005.

Rienecker, M. M. (11). Coauthors, 2008: The GEOS-5 Data Assimilation System—Documentation of versions 5.0. 1, 5.1. 0, and 5.2. 0. NASA Tech. Rep. NASA/TM-2008-104606, 27, 92.

Rodier, S., M. Vaughan, S. Palm, J. Yorks, M. McGill, M. Jensen, T. Murray, K.-P. Lee and C. Trepte, 2015: Laser Remote Sensing from ISS: CATS Cloud and Aerosol Data Products, proceedings of the ILRC 2015, New York, New York.

Rogers, R. R., Hostetler, C. A., Hair, J. W., Ferrare, R. A., Liu, Z., Obland, M. D., Harper, D. B., Cook, A. L., Powell, K. A., Vaughan, M. A., and Winker, D. M.: Assessment of the CALIPSO Lidar 532 nm attenuated backscatter calibration using the NASA LaRC airborne High Spectral Resolution Lidar, Atmos. Chem. Phys., 11, 1295–1311, doi:10.5194/acp-11-1295-2011, 2011.

Rogers, R. R., Vaughan, M. A., Hostetler, C. A., Burton, S. P., Ferrare, R. A., Young, S. A., Hair, J. W., Obland, M. D., Harper, D. B., Cook, A. L., and Winker, D. M.: Looking through the haze: evaluating the CALIPSO level 2 aerosol optical depth using airborne high spectral resolution lidar data, Atmos. Meas. Tech., 7, 4317-4340, https://doi.org/10.5194/amt-7-4317-2014, 2014.

Schuster, G. L., Vaughan, M., MacDonnell, D., Su, W., Winker, D., Dubovik, O., Lapyonok, T., and Trepte, C.: Comparison of CALIPSO aerosol optical depth retrievals to AERONET measurements, and a climatology for the lidar ratio of dust, Atmos. Chem. Phys., 12, 7431–7452, doi:10.5194/acp-12-7431-2012, 2012.

Sicard, M., Guerrero-Rascado, J. L., Navas-Guzman, F., Preissler, J., Molero, F., Tomas, S., Bravo-Aranda, J. A., Comeron, A., Rocadenbosch, F., Wagner, F., Pujadas, M. and Alados-Arboledas, L.: Monitoring of the Eyjafjallajokull volcanic aerosol plume over the Iberian Peninsula by means of four EARLINET lidar stations, Atmos. Chem. Phys., 12(6), 3115–3130, doi:10.5194/acp-12-3115-2012, 2012.

Sicard, M., D'Amico, G., Comeron, A., Mona, L., Alados-Arboledas, L., Amodeo, A., Baars, H., Baldasano, J. M., Belegante, L., Binietoglou, I., Bravo-Aranda, J. A., Fernandez, A. J., Freville, P., Garcia-Vizcaino, D., Giunta, A., Granados-Munoz, M. J., Guerrero-Rascado, J. L., Hadjimitsis, D., Haefele, A., Hervo, M., Iarlori, M., Kokkalis, P., Lange, D., Mamouri, R. E., Mattis, I., Molero, F., Montoux, N., Munoz, A., Munoz Porcar, C., Navas-Guzman, F., Nicolae, D., Nisantzi, A., Papagiannopoulos, N., Papayannis, A., Pereira, S., Preissler, J., Pujadas, M., Rizi, V., Rocadenbosch, F., Sellegri, K., Simeonov, V., Tsaknakis, G., Wagner, F. and Pappalardo, G.: EARLINET: potential operationality of a research network, Atmos. Meas. Tech., 8(11), 4587–4613, doi:10.5194/amt-8-4587-2015, 2015.

Solomos, S., Ansmann, A., Mamouri, R.-E., Binietoglou, I., Patlakas, P., Marinou, E. and Amiridis, V.: Remote sensing and modelling analysis of the extreme dust storm hitting the Middle East and eastern Mediterranean in September 2015, Atmos. Chem. Phys., 17(6), 4063–4079, doi:10.5194/acp-17-4063-2017, 2017.

Solomos, S., Kalivitis, N., Mihalopoulos, N., Amiridis, V., Kouvarakis, G., Gkikas, A., Binietoglou, I., Tsekeri, A., Kazadzis, S., Kottas, M., Pradhan, Y., Proestakis, E., Nastos, P. T. and Marenco, F.: From Tropospheric Folding to Khamsin and Foehn Winds: How Atmospheric Dynamics Advanced a Record-Breaking Dust Episode in Crete, Atmosphere, 9(7), 240, doi:10.3390/atmos9070240, 2018.

Stachlewska I.S., Samson M., Zawadzka O., Harenda K., Janicka L., Poczta P., Szczepanik D., Heese B., Wang D., Borek K., Tetoni E., Proestakis E., Siomos N., Nemuc A., Chojnicki B.H., Markowicz K.M., Pietruczuk A., Szkop A., Althausen D., Stebel K., Schuettemeyer D., Zehner C., Modification of Local Urban Aerosol Properties by Long-Range Transport of Biomass Burning Aerosol, REMOTE SENSING Vol.10 Issue: 3 Article No.412, 2018.

Stoffelen, A., Pailleux, J., Kallen, E., Vaughan, J. M., Isaksen, L., Flamant, P., Wergen, W., Andersson, E., Schyberg, H., Culoma, A., Meynart, R., Endemann, M. and Ingmann, P.: The atmospheric dynamics mission for global wind field measurement, Bull. Amer. Meteorol. Soc., 86(1), 73-+, doi:10.1175/BAMS-86-1-73, 2005.

Tesche, M., Wandinger, U., Ansmann, A., Althausen, D., Müller, D., and Omar, A. H.: Ground-based validation of CALIPSO observations of dust and smoke in the Cape Verde region, J. Geophys. Res., 118, 1–14, doi:10.1002/jgrd.50248, 2013.

Thorsen, T. J., and Q. Fu (2015), CALIPSO-inferred aerosol direct radiative effects: Bias estimates using ground-based Raman lidars, J. Geophys. Res. Atmos., 120, 12,209–12,220, doi:10.1002/2015JD024095.

Thorsen, T. J., Q. Fu, R. K. Newsom, D. D. Turner, and J. M. Comstock (2015), Automated retrieval of cloud and aerosol properties from the ARM Raman lidar. Part I: Feature detection, J. Atmos. Oceanic Technol., 32(11), 1977–1998, doi:10.1175/jtech-d-14-00150.1.

Toth, T. D., Campbell, J. R., Reid, J. S., Tackett, J. L., Vaughan, M. A., Zhang, J. and Marquis, J. W.: Minimum aerosol layer detection sensitivities and their subsequent impacts on aerosol optical thickness retrievals in CALIPSO level 2 data products, Atmos. Meas. Tech., 11(1), 499–514, doi:10.5194/amt-11-499-2018, 2018.

Tsekeri, A., Amiridis, V., Lopatin, A., Marinou, E., Igloffstein, J., Pikridas, M., Sciare, J., Gerasopoulos, E., Liakakou, E., Birgit, W., Baars, H., Kottas, M., Kokkalis, P., Raptis, I.P., Solomos, S., Binietoglou, I., Mihalopoulos, N., Engelmann, R., Wandinger, U., Ansmann, A. and Dubovik, O.: Aerosol absorption profiling from the synergy of lidar and sun-photometry in the framework of the ACTRIS-2 campaigns in Germany, Greece and Cyprus, EPJ Web of Conferences 176, 08005, doi: https://doi.org/10.1051/epjconf/201817608005, {ILRC 28}, 2018.

Vaughan,M.,K. Powell, R.Kuehn, S. Young,D. Winker, C.Hostetler, W. Hunt, Z. Liu, M. McGill, and B. Getzewich (2009), Fully automated detection of cloud and aerosol layers in the CALIPSO lidar measurements, J. Atmos. Oceanic Technol., 26, 2034–2050, doi:10.1175/2009JTECHA1228.1.

Vaughan, M. A., Young, S. A., Winker, D. M., Powell, K. A., Omar, A. H., Liu, Z., Hu, Y. and Hostetler, C. A.: Fully automated analysis of space-based lidar data: an overview of the CALIPSO retrieval algorithms and data products, in Laser Radar Techniques for Atmospheric Sensing, vol. 5575, pp. 16–31, International Society for Optics and Photonics., 2004.

Vaughan, M., Powell, K., Kuehn, R., Young, S., Winker, D., Hostetler, C., Hunt, W., Liu, Z., McGill, M., and Getzewich, B.: Fully automated detection of cloud and aerosol layers in the (CALIPSO) lidar measurements, J. Atmos. Ocean. Tech., 26, 2034–2050, 2009.

Wandinger, U., Freudenthaler, V., Baars, H., Amodeo, A., Engelmann, R., Mattis, I., Groß, S., Pappalardo, G., Giunta, A., D'Amico, G., Chaikovsky, A., Osipenko, F., Slesar, A., Nicolae, D., Belegante, L., Talianu, C., Serikov, I., Linné, H., Jansen, F., Apituley, A., Wilson, K. M., de Graaf, M., Trickl, T., Giehl, H., Adam, M., Comerón, A., Muñoz-Porcar, C., Rocadenbosch, F., Sicard, M., Tomás, S., Lange, D., Kumar, D., Pujadas, M., Molero, F., Fernández, A. J., Alados-Arboledas, L., Bravo-Aranda, J. A., Navas-Guzmán, F., Guerrero-Rascado, J. L., Granados-Muñoz, M. J., Preißler, J., Wagner, F., Gausa, M., Grigorov, I., Stoyanov, D., Iarlori, M., Rizi, V., Spinelli, N., Boselli, A., Wang, X., Lo Feudo, T., Perrone, M. R., De Tomasi, F., and Burlizzi, P.: EARLINET instrument intercomparison campaigns: overview on strategy and results, Atmos. Meas. Tech., 9, 1001-1023, https://doi.org/10.5194/amt-9-1001-2016, 2016.

Wandinger, U. and Ansmann, A.: Experimental determination of the lidar overlap profile with Raman lidar, Appl. Opt., 41, 511–514, doi:10.1364/AO.41.000511, 2002.

Wandinger, U., Hiebsch, A., Mattis, I., Pappalardo, G., Mona, L., and Madonna, F.: Aerosols and Clouds: Long-Term Database from Spaceborne Lidar Measurements, Tech. rep., final report, ESTEC Contract 21487/08/NL/HE, ESA Publications Division, Noordwijk, the Netherlands, 2011.

Wandinger, U., M. Tesche, P. Seifert, A. Ansmann, D. Müller, and D. Althausen (2010), Size matters: Influence of multiple scattering on CALIPSO light-extinction profiling in desert dust, Geophys. Res. Lett., 37, L10801, doi:10.1029/2010GL042815.

Wang, X., Boselli, A., D’Avino, L., Pisani, G., Spinelli, N., Amodeo, A., Chaikovsky, A., Wiegner, M., Nickovic, S., Papayannis, A., Perrone, M. R., Rizi, V., Sauvage, L. and Stohl, A.: Volcanic dust characterization by EARLINET during Etna’s eruptions in 2001-2002, Atmos. Environ., 42(5), 893–905, doi:10.1016/j.atmosenv.2007.10.020, 2008.

Winker, D. M., Hunt, W. H. and McGill, M. J.: Initial performance assessment of CALIOP, Geophys. Res. Lett., 34(19), L19803, doi:10.1029/2007GL030135, 2007.

Winker, D. M., Vaughan, M. A., Omar, A., Hu, Y., Powell, K. A., Liu, Z., Hunt, W. H. and Young, S. A.: Overview of the CALIPSO Mission and CALIOP Data Processing Algorithms, J. Atmos. Ocean. Technol., 26(11), 2310–2323, doi:10.1175/2009JTECHA1281.1, 2009.

Yorks, J. E., D. L. Hlavka, M. A. Vaughan, M. J. McGill, W. D. Hart, S. Rodier, and R. Kuehn, 2011a: Airborne validation of cirrus cloud properties derived from CALIPSO lidar measurements: Spatial properties, J. Geophys. Res., 116, D19207, doi:10.1029/2011JD015942.

Yorks, J. E., McGill, M. J., Scott, V. S., Wake, S. W., Kupchock, A., Hlavka, D. L., Hart, W. D. and Selmer, P. A.: The Airborne Cloud-Aerosol Transport System: Overview and Description of the Instrument and Retrieval Algorithms, J. Atmos. Ocean. Technol., 31(11), 2482–2497, doi:10.1175/JTECH-D-14-00044.1, 2014.

Yorks, J. E., McGill, M. J., Palm, S. P., Hlavka, D. L., Selmer, P. A., Nowottnick, E. P., Vaughan, M. A., Rodier, S. D. and Hart, W. D.: An overview of the CATS level 1 processing algorithms and data products, Geophys. Res. Lett., 43(9), 4632–4639, doi:10.1002/2016GL068006, 2016.

Yorks, J. E., S.D. Rodier, E. Nowottnick, P.A. Selmer, M.J. McGill, S.P. Palm, and M. A. Vaughan (2019), CATS Level 2 Vertical Feature Mask Algorithms and Data Products: An Overview and Initial Assessment, Atmos. Meas. Tech. Discuss., in preparation.

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: ISS-CATS and EARLINET cases considered in the evaluation process of CATS backscatter coefficient profiles at 1064 nm.

Day-Night Flag	Date yyyy/mm/dd	Time hh:mm:ss (UTC)	EARLINET station	min Distance (km)	EARLINET Date (yyyy/mm/dd) | measuring time cloud-free window (UTC)
N	2015/11/25	03:44:09	Athens	40.42	2015/11/25 | 03:30:00 – 04:30:00
N	2016/01/29	01:46:08	Athens	46.84	2016/01/29 | 01:00:00 – 02:30:00
N	2016/02/01	17:23:36	Athens	23.29	2016/02/01 | 17:45:00 – 19:30:00
N	2016/02/01	17:23:39	Athens NTUA	18.58	2016/02/01 | 18:20:51 – 19:57:41
D	2016/05/03	06:45:15	Barcelona	45.93	2016/05/03 | 08:59:00 – 09:59:00
D	2015/08/13	17:29:18	Belsk	2.39	2015/08/13 | 18:02:10 – 18:45:40
N	2016/08/08	17:34:50	Belsk	6.56	2016/08/08 | 17:31:08 – 18:12:05
N	2016/07/28	19:15:24	Bucharest	45.35	2016/07/28 | 17:41:22 – 18:41:22
N	2016/09/14	04:21:09	Cabauw	21.01	2016/09/14 | 05:27:25 – 06:00:03
N	2015/08/03	21:40:39	Dushanbe	42.64	2015/08/03 | 20:00:00 – 22:00:00
N	2016/08/14	15:39:07	Dushanbe	22.08	2016/08/14 | 15:57:00 – 17:19:00
D	2015/06/20	08:38:33	Dushanbe	13.33	2015/06/20 | 08:54:00 – 09:07:00
D	2015/07/12	06:47:07	Dushanbe	33.46	2015/07/12 | 06:25:00 – 07:10:00
D	2016/05/02	07:35:38	Evora	47.27	2016/05/02 | 07:58:50 – 08:00:21
D	2016/05/31	19:43:41	Evora	39.42	2016/05/31 | 19:29:56 – 19:59:35
N	2016/01/30	00:50:16	Hohenpeissenberg	13.36	2016/01/30 | 00:20:00 – 01:20:00
N	2016/03/17	02:12:09	Hohenpeissenberg	43.40	2016/03/17 | 01:42:00 – 02:42:00
D	2015/10/31	12:56:05	Hohenpeissenberg	34.41	2015/10/31 | 12:26:00 – 13:26:00
D	2016/04/12	15:29:18	Hohenpeissenberg	12.77	2016/04/12 | 14:55:00 – 16:05:00
D	2016/08/07	16:49:29	Hohenpeissenberg	31.81	2016/08/07 | 16:19:30 – 17:19:30
D	2016/08/23	10:42:43	Hohenpeissenberg	36.11	2016/08/23 | 10:12:30 – 11:12:30
D	2016/09/14	05:58:59	Hohenpeissenberg	28.37	2016/09/14 | 04:59:00 – 05:59:00
N	2015/07/27	21:14:35	Lecce	34.69	2015/07/27 | 20:42:00 – 21:09:00
N	2016/08/04	22:44:06	Lecce	4.72	2016/08/04 | 20:50:00 – 21:20:00
N	2015/07/30	00:18:19	Leipzig	41.16	2015/07/30 | 00:34:00 – 01:04:00
N	2015/08/03	21:29:44	Leipzig	15.81	2015/08/03 | 21:31:00 – 22:00:00
N	2015/09/24	01:13:34	Leipzig	25.05	2015/09/24 | 01:01:00 – 01:30:00
N	2015/09/29	00:05:33	Leipzig	36.49	2015/09/28 | 22:42:00 – 23:12:00
N	2015/09/29	23:13:24	Leipzig	48.46	2015/09/28 | 22:55:00 – 23:24:00
N	2015/09/30	22:21:13	Leipzig	12.89	2015/09/30 | 21:25:00 – 21:34:00
N	2016/06/05	20:14:01	Leipzig	36.93	2016/06/05 | 20:02:00 – 20:31:00
N	2016/09/13	03:37:49	Leipzig	3.79	2016/06/05 | 00:00:00 – 02:30:00
N	2016/09/12	04:29:46	Leipzig	45.08	2016/09/12 | 00:00:00 – 02:30:00
N	2016/09/15	03:30:25	Leipzig	48.36	2016/09/15 | 00:00:00 – 02:30:00
D	2015/04/21	14:54:35	Leipzig	6.73	2015/04/21 | 16:04:00 – 16:33:00
D	2015/04/21	16:31:00	Leipzig	31.28	2015/04/21 | 16:34:00 – 17:04:00
D	2015/04/24	15:25:13	Leipzig	47.83	2015/04/24 | 14:03:00 – 14:32:00
D	2015/08/13	17:27:54	Leipzig	1.36	2015/08/13 | 19:01:00 – 19:30:00
D	2016/08/24	11:26:39	Leipzig	3.46	2016/08/24 | 10:00:00 – 12:00:00
D	2016/08/24	13:03:12	Leipzig	48.97	2016/08/24 | 10:00:00 – 12:00:00
N	2015/07/21	00:13:26	Potenza	2.01	2015/07/21 | 00:00:00 – 02:52:19
D	2015/11/06	10:54:52	Thessaloniki	19.46	2015/11/06 | 11:57:03 – 12:27:20
N	2016/01/28	19:17:11	Thessaloniki	39.54	2016/01/28 | 20:08:40 – 20:38:57
D	2015/08/13	17:29:20	Warsaw	42.95	2015/08/13 | 17:00:00 – 17:22:00
D	2015/08/19	15:22:30	Warsaw	44.47	2015/08/19 | 15:25:00 – 15:47:00
D	2016/06/07	18:29:46	Warsaw	41.22	2016/06/07 | 18:15:00 – 18:43:00
N	2016/08/08	17:34:53	Warsaw	46.99	2016/08/08 | 17:00:00 – 17:23:00

Table 3: List of CATS quality assurance thresholds applied in the EARLINET comparison.

Mode	7.2
Level	2
Parameter	Backscatter Coefficient
Wavelength	1064nm
Distance	≤ 50km radius from the EARLINET stations
Feature Type Score	≤ -2
Sky Condition	0 – clean skies *and* 1 – clear skies (no clouds)
Backscatter Coefficient	$0 \le b_{1064nm} \le 2$ [$Mm^{-1}sr^{-1}$]
Vertical range window	≤ 10 km (a.s.l.)

Table ~~2~~4: 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
Mean Relative Bias [%]	-24.06	-19.84
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

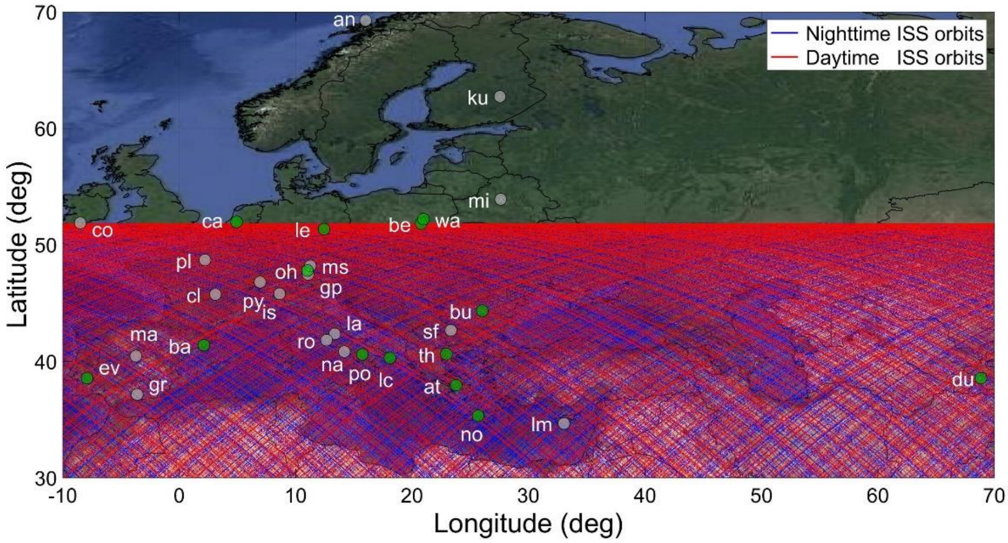

Figure 1: Distribution of EARLINET lidar stations over Europe and West Asia. Green dots: stations used in the inter-comparison. ISS orbits between 02/2015 and 09/2016 are overlaid in red for daytime and in blue for nighttime overpasses.

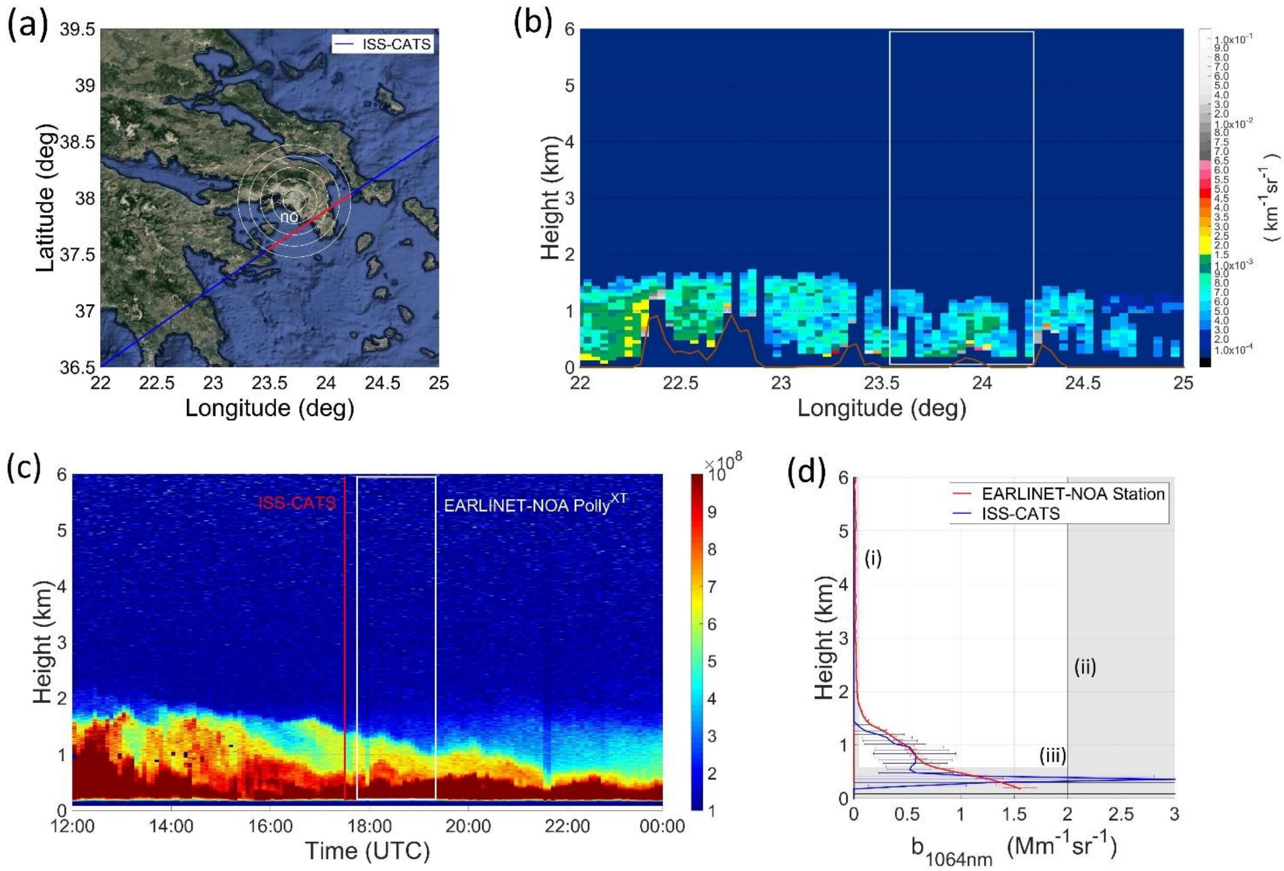

Figure 2: (a) Nighttime ISS orbit over Athens-Greece on the 1st of February 2016 (blue line). The concentric white circles denote regions of 10, 20, 30, 40 and 50 km from the location of PollyXT-NOA lidar system (white dot). Red colour in the ISS footprint indicates CATS observations within 50 km distance 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).

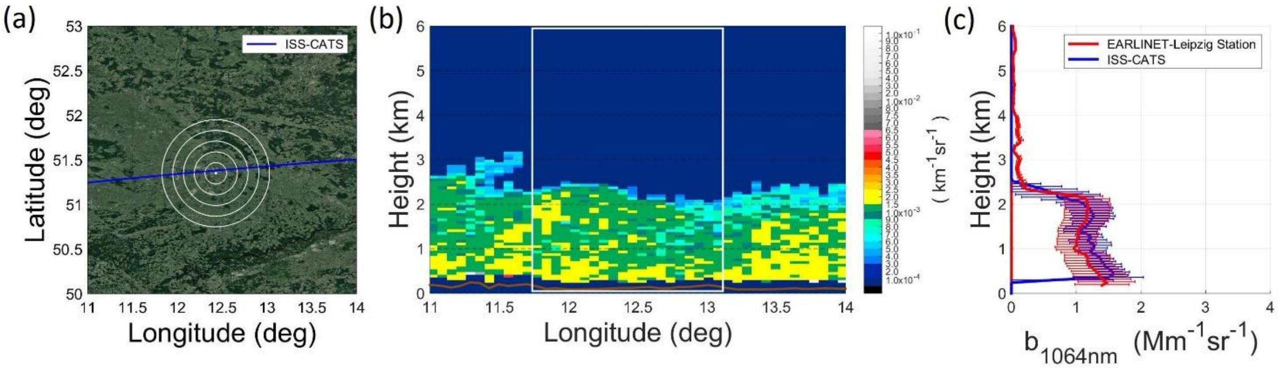

Figure 3: (a) Nighttime ISS orbit over EARLINET Leipzig station on the 13th of September 2016 (blue line). The white ~~circle~~dot denotes the location of Leipzig lidar system, (b) CATS Backscatter Coefficient at 1064 nm and (c) CATS (blue line) and EARLINET-Leipzig (red line) backscatter coefficient profiles (1064 nm).

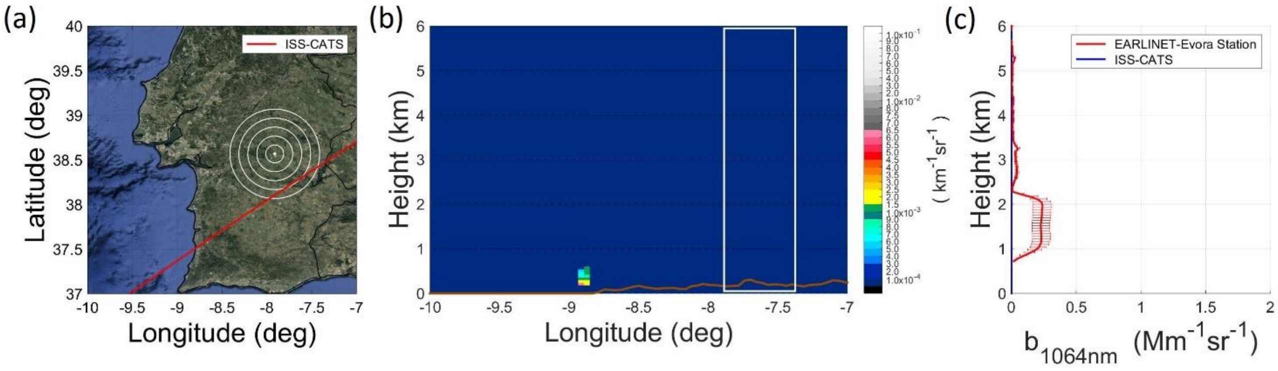

Figure 4: (a) Daytime ISS orbit over Évora EARLINET station on the 31th of May 2016 (red line). The white ~~circle~~dot denotes the location of Évora lidar system, (b) CATS Backscatter Coefficient at 1064 nm and (c) CATS (blue line) and EARLINET-Évora (red line) backscatter coefficient profiles (1064 nm).

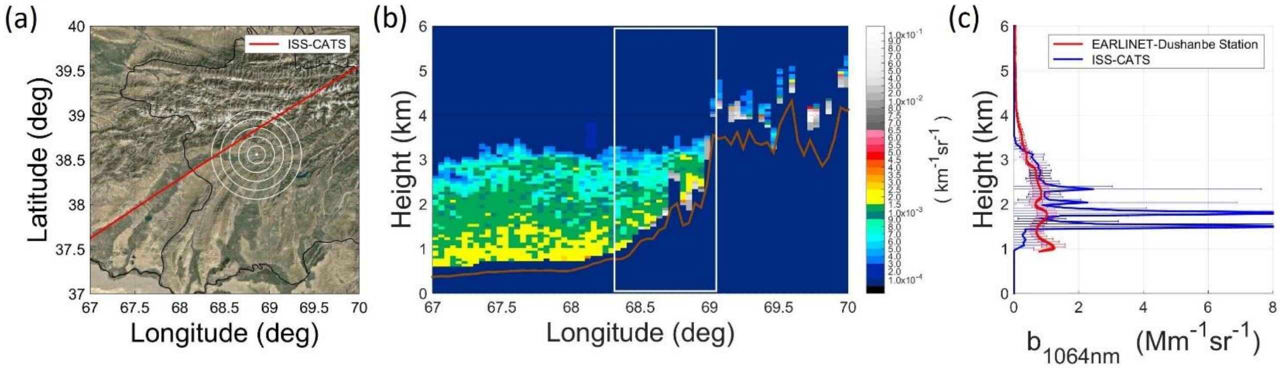

Figure 5: (a) Nighttime ISS orbit over Dushanbe EARLINET station on the 25th of May 2015 (blue line). The white ~~circle~~dot denotes the location of Dushanbe lidar system, (b) CATS Backscatter Coefficient at 1064 nm and (c) CATS (blue line) and EARLINET-Dushanbe (red line) backscatter coefficient profiles (1064 nm).

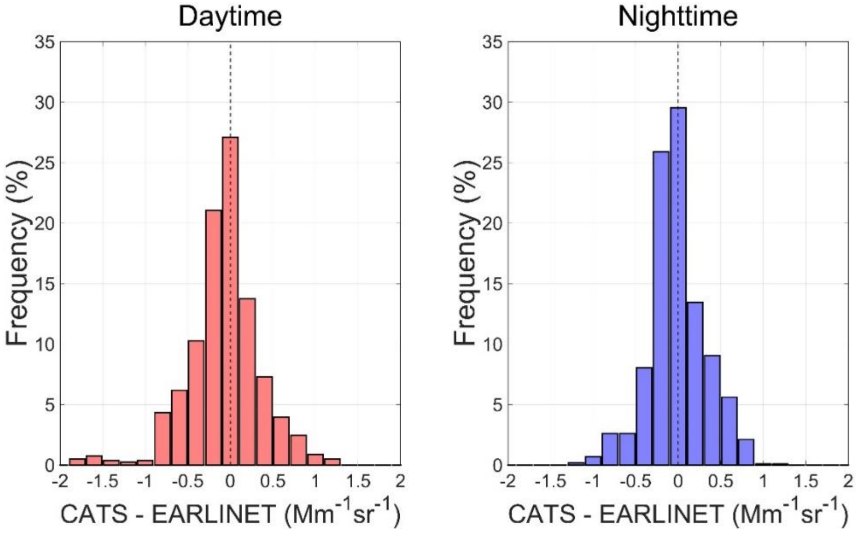

Figure 6. Distributions of the differences between CATS Level 2 and the corresponding EARLINET backscatter coefficient measurements, calculated over (a) daytime (21 collocated cases) and (b) nighttime (26 collocated cases).

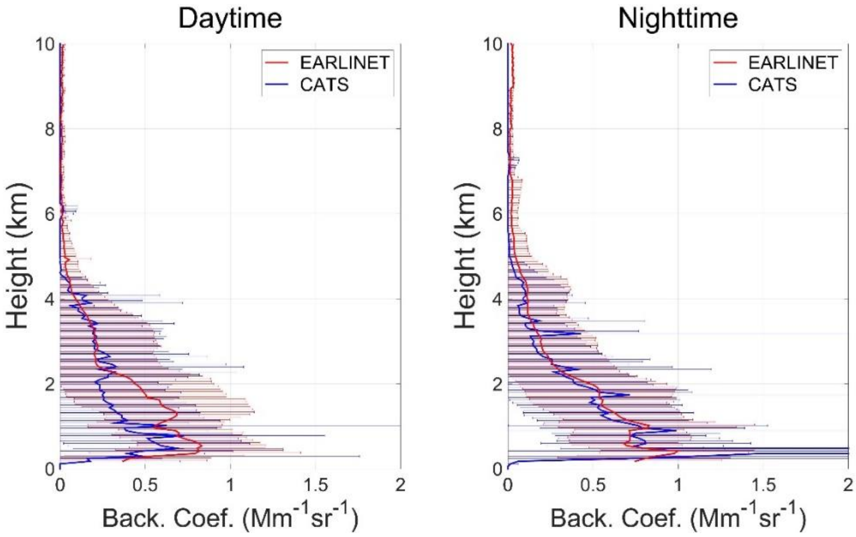

Figure 7. CATS (blue line) and EARLINET (red line) mean profiles of backscatter coefficient at 1064 nm for (left) daytime and (right) nighttime. The horizontal lines represent the SD of CATS (blue colour) and EARLINET (red colour) profiles.

Interactive comment on "EARLINET evaluation of the CATS L2 aerosol backscatter coefficient product" by Emmanouil Proestakis et al.
Anonymous Referee #1
Received and published: 18 March 2019

General Comments: In this study the authors are presenting the coordinated effort of the European Aerosol Research Lidar Network (EARLINET), to evaluate the Level 2 aerosol backscatter coefficient product derived by the space borne backscatter lidar namely Cloud-Aerosol Transport System (CATS). The manuscript is well written and has a scientific merit. Therefore, in my opinion it worth being published under the special issue "EARLINET aerosol profiling: contributions to atmospheric and climate research" of the Atmospheric Chemistry and Physics journal. However, in order to help improving the manuscript, I would kindly suggest the authors to take into account the following specific comments.

The authors would like to thank the reviewer for the interesting and at the same time substantial comments and suggestions. We tried, and did our best, to incorporate the proposed changes and corrections in the revised manuscript, aiming at improving the presented paper. Following, you will find our responses, one by one to the comments addressed.
Kind regards,
Emmanouil Proestakis

Specific Comments:
1. Abstract: Page 2, line 1: "Independently of daytime/nighttime conditions.". Please consider revising this statement. At the end of this paragraph the authors are mentioning an underestimation of 22.3% during day and 6.1% during night time. So there is a significant difference in the comparison based on the sky light conditions something that has to be mentioned clearly in the abstract. Where you can attribute this difference? e.g. SNR issue, significance of your day-night statistical sample?

The authors agree with the statement of the reviewer. Therefore, the sentence was modified from:
"In addition, CATS misclassification 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."
To:
"In addition, CATS misclassification 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. Regarding solar illumination conditions, low negative biases in CATS backscatter coefficient profiles, of the order of 6.1%, indicate the good nighttime performance of CATS. During daytime, reduced signal-to-noise ratio by solar background illumination prevents retrievals of weakly scattering atmospheric layers that would otherwise be detectable during nighttime, leading to higher negative biases, of the order of 22.3%, in CATS daytime performance."

Regarding the comment of the reviewer, where the authors attribute this difference, the effect of SNR is considered the most critical factor, because measurement noise by solar illumination background and layer detection are different during daytime and nighttime, with the effect propagating through the retrieval algorithms to atmospheric layer detection and classifications and eventually to Level 2 and Level 3 products. Example of the critical level of SNR effect is the Minimum Detectable Backscatter (MDB), as reported by McGill et al. (2007), for both CALIOP and CATS and for both daytime and nighttime conditions (Table 1). According to *Table 1* the detection sensitiveness of thin, weakly scattering atmospheric layers at CATS M7.2 1064 nm is two orders of magnitude higher during nighttime that during daytime (MDB two orders of magnitude lower during nighttime than during daytime). In the case of CALIOP, both for 532 and 1064 nm, MDB during nighttime is an order of magnitude lower during nighttime than during daytime.

Table 1: CATS and CALIPSO 532 and 1064 nm Minimum Detectable Backscatter (MDB) with Units in $Km^{-1}sr^{-1}$ (McGill et al., 2007).		
	CATS 7.2	CALIPSO
532 nm night	$1.6x10^{-2} \pm 0.84x10^{-3}$	$1.6x10^{-4} \pm 0.84x10^{-4}$
1064 nm night	$5.0x10^{-5} \pm 0.77x10^{-5}$	$1.6x10^{-4} \pm 0.84x10^{-4}$
532 nm day	$3.8x10^{-2} \pm 1.05x10^{-3}$	$1.7x10^{-3} \pm 0.84x10^{-3}$
1064 nm day	$1.3x10^{-3} \pm 0.24x10^{-3}$	$1.0x10^{-3} \pm 0.30x10^{-3}$

2. Introduction: The Introduction is well written however I am missing the scientific question that this manuscript envisages to answer. Please try to make this clear in this section and consider mentioning the achievements and progress of the scientific community so far towards this topic. Are there any similar activities for CATS? The results presented here are having great difference with similar studies for other space borne lidars? The reader has to reach section 2.1 in order to find some answers on the aforementioned concerns.

The authors agree with the reviewer that the manuscript was characterized by a significant lack of mentioning similar achievements and activities, towards the assessment of CATS performance. The authors agree with the reviewer regarding the necessity of including the findings of the aforementioned studies and have adjusted the manuscript accordingly. To be more specific, the following paragraphs were added to the manuscript (Section 1 - Introduction):

"*CATS performance has been validated against ground-based AErosol RObotic NETwork (AERONET; Holben et al., 1998) measurements and evaluated against satellite-based Atmospheric Optical Depth (AOD) retrievals of Aqua and Terra Moderate Imaging Spectroradiometer (MODIS; Levy et al., 2013) and active CPL (McGill et al., 2002) and CALIPSO CALIOP (Winker et al., 2009) profiles of extinction coefficient and AOD at 1064 nm. Lee et al. (2018) compared daytime quality-assured CATS V2-01 vertically integrated extinction coefficient profiles (1064 nm) and AERONET AOD (1020 nm) values, spatially (within 0.4° Longitude and Latitude) and temporally (±30 minutes) collocated, and found a reasonable agreement with a correlation of 0.64. A comparative analysis of CATS and MODIS C6.1 Dark Target (DT) AOD retrievals, through spectral interpolation between 0.87 and 1.24 μm channels, reported correlation of 0.75 and slope of 0.79, over ocean. In addition, Lee et al., (2019) evaluated AOD and extinction coefficient profiles from CATS through intercomparison with CALIOP. With regard to AOD, analysis a total of 2681 CATS and CALIOP collocated observation cases (within 0.4° Longitude/Latitude and ±30 minutes ISS and CALIPSO overpass difference), showed correlation of 0.62 and 0.52 over land and ocean respectively during daytime (1342 cases), and 0.84 and 0.81 over land and ocean respectively during nighttime (1339 cases). Comparison of CATS and CALIOP collocated extinction coefficient profiles based on the closest Euclidian distance on the earth's surface, shows also good shape agreement, despite an apparent CALIOP underestimation in the lowest 2 km height. CATS and CALIOP observations were used by Rajapakshe et al. (2017) to study the seasonally transported aerosol layers over the SE Atlantic Ocean. The performed comparative analysis reported on similar geographical patterns regarding Above Cloud Aerosols (ACA), Cloud Fraction (CF) and ACA occurrence frequency (ACA_F) between CATS and CALIOP retrievals. However, the authors reported also on differences between CATS and CALIOP vertical aerosol distributions, with ACA bottom height identified by CATS lower than the respective of CALIOP. CATS retrievals were used to document the diurnal cycle and variations of clouds, with CALIOP complementarily used. Noel et al. (2018) showed that both CATS and CALIOP profiles of CF agree well on both the vertical patterns and values at 01:30 and 13:30 LT, over both land and ocean, with minor differences of the order of 2-7% throughout the entire profiles of cloud fraction. CATS depolarization measurements, which are critical in the processing algorithms of aerosol subtype classification, were investigated in the case of desert dust, smoke from biomass burning and cirrus clouds (Yorks et al., 2016), and were found consistent and in good agreement with depolarization measurements from previous studies and historical datasets implementing CPL (Yorks et al., 2011) and CALIOP (Liu et al., 2015).*"

Regarding the question the manuscript envisages to answer, the author have modified/included the following paragraphs to the manuscript (Section 1 - Introduction):

"*Overall, CATS retrievals have been evaluated and found in reasonable agreement with ground-based AERONET, airborne CPL and satellite-based MODIS and CALIOP measurements. However, for the quality assessment of CATS* *backscatter coefficient profiles, a large-scale and dense network of ground-based lidar systems is needed, in order to facilitate high-quality collocated and concurrent measurements. This necessity is largely related to the ISS orbital characteristics, the CATS near-nadir viewing (0.5° 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 of a unique infrastructure for assessing the validation needs for spaceborne lidar missions.*".

3. Section 2.3.1: I think it would be beneficial for the manuscript to include a flowchart showing the methodology of the comparison followed by the authors. The entire process can be summarized there along with the methodology requirements followed by the authors. e.g. the spatial - temporal constraints, cloud screening requirements, etc. The information exists in the manuscript but I feel like it is scattered among the sections.

The authors agree with the reviewer that is would be beneficial to summarize the key parameters and the associated thresholds implemented in the framework of the study. For this reason the following table was included in the manuscript:

Table: List of CATS quality assurance thresholds applied in the EARLINET comparison.

Mode	7.2
Level	2
Parameter	Backscatter Coefficient
Wavelength	1064nm
Distance	≤ 50km radius from the EARLINET stations
Feature Type Score	≤ -2
Sky Condition	0 – clean skies *and* 1 – clear skies (no clouds)
Backscatter Coefficient	$0 \leq b_{1064nm} \leq 2$ [$Mm^{-1}sr^{-1}$]
Vertical range window	≤ 10 km (a.s.l.)

Regarding EARLINET, the authors implement the Single Calculus Chain (SCC) is used D'Amico et al, 2015; D'Amico et al, 2016; Mattis et al., 2016), for the homogenization of the lidar data in a standardized output format. SCC facilitates an automatic algorithm developed to further address the quality assurance of the lidar measurements. The EARLINET implementation is described in "*Section 3.2.3*".

4. Page 7, lines 18-19: "::: is less than 30%, ::: requirements of EARLINET". The authors are kindly requested to provide a reference for this statement.

The text is modified according to the reviewer's recommendation, and the following references were included: "*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 % (Althausen et al., 2009; Baars et al., 2012; Engelmann et al., 2016; Hänel et al., 2012), thus meeting the quality assurance requirements of EARLINET.*" with the following references:

- *Althausen, D., Engelmann, R., Baars, H., Heese, B., Ansmann, A., Müller, D., and Komppula, M.: Portable Raman Lidar PollyXT for Automated Profiling of Aerosol Backscatter, Extinction, and Depolarization, J. Atmos. Ocean. Technol., 26, 2366–2378, 2009.*
- *Baars, H., Ansmann, A., Althausen, D., Engelmann, R., Heese, B., Müller, D., Artaxo, P., Paixao, M., Pauliquevis, T., and Souza, R.: Aerosol profiling with lidar in Amazon Basin during the wet and dry season, J. Geophys. Res., 117, D21201, 2012.*
- *Engelmann, R., Kanitz, T., Baars, H., Heese, B., Althausen, D., Skupin, A., Wandinger, U., Komppula, M., Stachlewska, I. S., Amiridis, V., Marinou, E., Mattis, I., Linne, H. and Ansmann, A.: The automated multiwavelength Raman polarization and water-vapor lidar Polly(XT): the neXT generation, Atmos. Meas. Tech., 9(4), 1767–1784, doi:10.5194/amt-9-1767-2016, 2016.*
- *Hänel, A., Baars, H., Althausen, D., Ansmann, A., Engelmann, R., and Sun, Y. J.: One-year aerosol profiling with EUCAARI Raman lidar at Shangdianzi GAW station: Beijing plume and seasonal variation, J. Geophys. Res., 117, D13201, 2012.*

5. Page 8, line 8: “scattering respectively”-> “backscattering respectively”.

The text is modified according to the reviewer’s recommendation.

6. Section 2.3.3: This section is important for following up the manuscript and has to be highlighted. Therefore, I would kindly suggest to the authors to list it as 2.4.

The text is modified according to the reviewer’s recommendation.

7. Page 9, line 6: “The discussed constraints:::”: How much these constrains affect the final dataset (in terms of number of measurements and overall evaluation)?

Regarding the question of the reviewer on the discussed constrains on the dataset, Figures 1-4 show quantitatively the effects of (i) distance between the EARLINET station and the closest profile of the CATS-ISS overpass for each correlative case, (ii) CATS Feature Type, (iii) number of CATS Level 2 (L2) Aerosol Profiles (APro) used in the CATS horizontal average, and the effect of (iv) topography of EARLINET stations. The comparison exercise examines the effect of one discussed constrain at a time, while keeping all the other parameters in the methodology constant, and considers various evaluation metrics, as discussed in the following sections.

(i) Effect of distance between the EARLINET station and the closest profile of the CATS-ISS overpass

Figure 1 shows the effect of distance between the closest CATS L2 APro and the respective EARLINET station matchup, for different upper Euclidean distance thresholds (i.e.: 5n km, $n \in N=\{1,10\}$). To be more specific, the Mean Bias (MB; [$Mm^{-1}sr^{-1}$]) - (Fig.1a), Root Mean Square Error (RMSE; [$Mm^{-1}sr^{-1}$]) - (Fig.1b), Correlation Coefficient (Fig.1c), and the number of CATS-EARLINET correlative cases per each upper distance threshold are considered. For each upper distance threshold, all the available CATS-EARLINET cases of Euclidean distance lower or equal to the respective upper limit are considered in the computation of the aforementioned evaluation metrics. This cumulative approach is selected due to the limited number of CATS-EARLINET correlative cases, and is applied separately for daytime and nighttime ISS overpasses, due to the different CATS measurement conditions.

Based on the analysis, during nighttime (daytime), the CATS-EARLINET MB is increasing (decreasing) starting from the 5 km upper distance threshold, to reach -0.0300 (-0.123) $Mm^{-1}sr^{-1}$, for the radius threshold of 50km shown in the study. The computed RMSE values are in the range between 0.447 and 0.343 $Mm^{-1}sr^{-1}$ for nighttime and between 0.357 and 0.448 $Mm^{-1}sr^{-1}$ for daytime, for the distance thresholds of 5km and 50km respectively. The minimum RMSE values are observed when considering ISS overpass cases of closer than 40 km distance to the EARLINET stations during nighttime, corresponding to MB of 0.018 $Mm^{-1}sr^{-1}$. The Correlation Coefficient is decreasing with increasing distance between the ISS overpass and the EARLINET stations. Notably, the Correlation Coefficient is not changing considerably for thresholds between 15 and 40 km for nighttime (~0.8) and between 15 and 30 km for daytime (~ 0.7). Sharp decreases in the Correlation Coefficient are observed during daytime (0.547), for distances closer to the EARLINET stations than during nighttime (0.693), for 35 and 40 km distance respectively. The observed tendencies can be explained in terms of the distance thresholds and number of available cases, since the distance thresholds define the number of cases that are used in the analysis and the number of case is critical to assess the performance of CATS. Consequently, the MB, RMSE and Correlation Coefficient are all subject to both the number and the characteristics of the CATS-EARLINET cases used. In the study the authors use the maximum number of available EARLINET cases, to avoid any possible selection effect resulting from a poor sample of correlative cases, when strict collocation filters are applied. Using the maximum number of available correlative cases, i.e. twenty six (26) and twenty one (21) for nighttime and daytime respectively, for ISS overpasses within 50km radius from the EARLINET stations, the authors envisage to quantitatively address the question of CATS performance and the representativeness of the aerosol backscatter coefficient profiles, over various atmospheric, illumination and ISS overpass conditions.

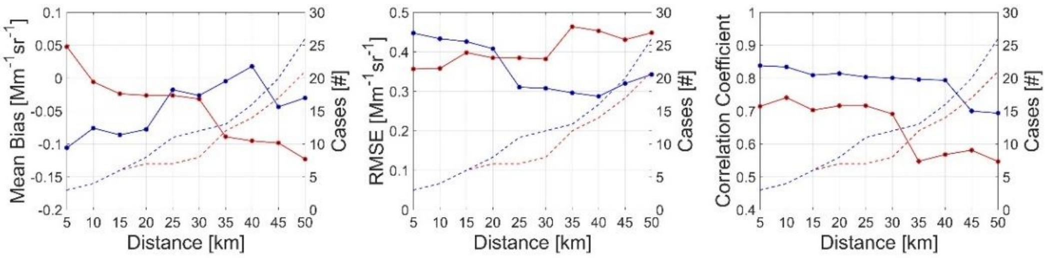

Figure 1: CATS backscatter coefficient at 1064nm with respect to EARLINET ground-based measurements, as a function of distance (km) between the closest CATS Level 2 Aerosol Profile and the respective "collocated" EARLINET station, for daytime (red line) and nighttime (blue line) ISS overpasses. Left: Mean Bias [$Mm^{-1}sr^{-1}$], center: RMSE [$Mm^{-1}sr^{-1}$] and right: Correlation Coefficient. Dashed lines correspond to the number of CATS-EARLINET correlative cases considered per each upper distance threshold between the CATS footprint and the locations of EARLINET stations.

(ii) Effect of Feature Type Score

The main objective of the CATS Cloud Aerosol Discrimination (CAD) score, or Feature Type Score, is to provide to the Feature Type classification a level of confidence. In the case of CATS, the Feature Type score is an integer number ranging between -10 and 10. The values of CATS Feature Type score correspond to classified aerosol atmospheric layers (negative values) and cloud atmospheric layers (positive values), while the magnitude of the Feature Type score corresponds to the confidence level of the classification. A value of -10 indicates complete confidence that the layer is an aerosol layer, while Feature Type score equal to 0, indicates an atmospherics layer with equal probability to be cloud or aerosol.

Figure 2 shows the effect of Feature Type Score, for different values, between -8 and 0 (i.e. for atmospheric layers classified as aerosol layers). The Mean Bias (MB; [$Mm^{-1}sr^{-1}$]) - (Fig.2a), Root Mean Square Error (RMSE; [$Mm^{-1}sr^{-1}$]) - (Fig.2b) and Correlation Coefficient (Fig.2c) are shown per each Feature Type Score. For each Feature Type score, cases of lower classification confidence level are not considered in the assessment of CATS performance and representativity, indicating the effect of the selected Feature Type thresholds.

Based on the MB, RMSE and Correlation Coefficient, a similar tendency is observed for different Feature Type Scores. To be more specific, not considerable changes are observed for different Feature Type Scores, regardless of the selected Feature Type threshold. This effect is due to the atmospheric characteristics of the CATS-EARLINET cases considered in the analysis. In the framework of the study, to account for contamination effects of multiple-scattering and specular reflection in the intercomparison process, only cloud-free atmospheric scenes are used. Furthermore, cases with detected cirrus, either at the EARLINET Range-Corrected-Signal quicklooks or at the ISS-CATS backscatter coefficient profiles or the feature type profiles, are not considered in the study. Initially, the presence of clouds was 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 was not feasible due to the presence of clouds, and/or CATS cases that the presence of clouds propagated into the CATS spatial-averaged profile were discarded from the analysis. Consequently, the lack of dependence shown in Figure 2 (a-c) is the result from the a priory selection of cloud free conditions selected in the analysis. However, a notably characteristic is the nighttime performance of CATS, which as shown from the lower absolute MB and lower RMSE, but in addition from the higher Correlation Coefficient values, due to higher SNR, is more representative than the corresponding daytime performance.

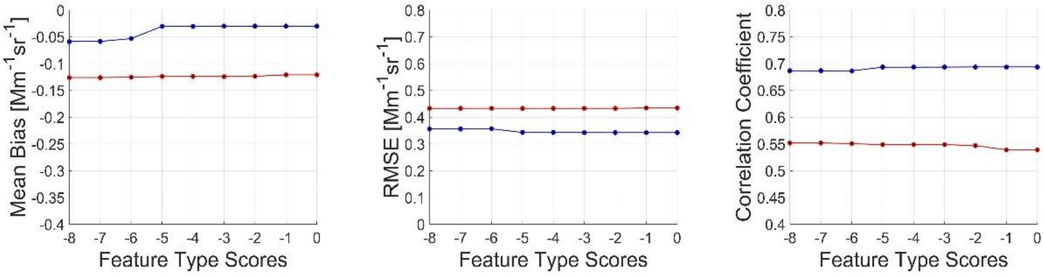

Figure 2: CATS backscatter coefficient at 1064nm with respect to EARLINET ground-based measurements, as a function of Feature Type score, for daytime (red line) and nighttime (blue line) ISS overpasses. Left: Mean Bias [Mm^{-1}sr^{-1}], center: RMSE [Mm^{-1}sr^{-1}] and right: Correlation Coefficient.

(iii) Effect of number of CATS-ISS L2 aerosol profiles used in the spatial averaging

Similarly to the analysis presented and discussed above, Figure 3 shows the effect of different number of aerosol profiles used when spatially averaging to retrieve the CATS aerosol profiles used in the framework of the study. In Figure 3, the acronym "CPro" corresponds to the closest CATS profiles to the corresponding EARLINET station. Accordingly, the Mean Bias (MB; [Mm^{-1}sr^{-1}]) - (Fig.3a), Root Mean Square Error (RMSE; [Mm^{-1}sr^{-1}]) - (Fig.3b), Correlation Coefficient (Fig.3c), are computed for different number of profiles used (i.e. CPro±1Profile, CPro±2Profiles, …).

Based on the MB, RMSE and Correlation Coefficient, the representativeness of CATS spatial profile is increasing with increasing number of aerosol profiles used in the horizontal averaging. To be more specific nighttime MB is almost constant, showing a low dependence on the number of profiles used, while for daytime CATS cases the opposite effect is observed, with improvement of CATS performance though increasing number of profiles used. Regarding RMSE no significant changes are observed, though a slight decreasing tendency in the RMSE is observed for both daytime and nighttime cases. Regarding the Correlation Coefficient, increasing in the values is also observed, with increasing number of profiles used, both for daytime and nighttime cases, denoting the improvement of the representativeness with increasing number of CATS profiles used in the spatial averaging.

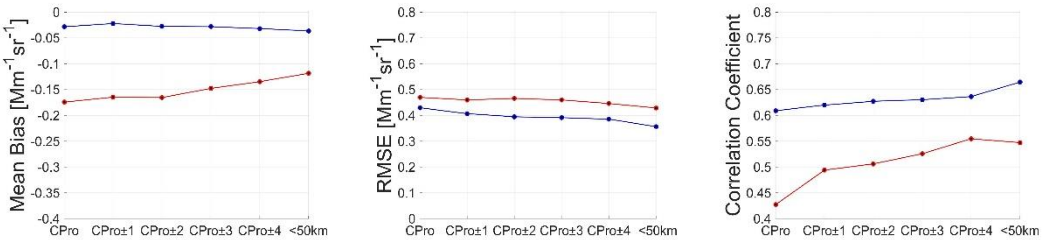

Figure 3: CATS backscatter coefficient at 1064nm with respect to EARLINET ground-based measurements, as a function of the number of L2 Aerosol Profiles used in the CATS spatial averaging, for daytime (red line) and nighttime (blue line) ISS overpasses. Left: Mean Bias [Mm^{-1}sr^{-1}], center: RMSE [Mm^{-1}sr^{-1}] and right: Correlation Coefficient. "CPro" corresponds to the closest CATS profile to the EARLINET station.

(iv) Effect of EARLINET stations topography

In order to study the effect of topography on the CATS profiles the authors separated the participating EARLINET stations into 3 clusters: Continental (Case I – Belsk, Bucharest, Leipzig, and Warsaw), Coastal (Case II – NOA, Athens NTUA, Barcelona, Cabauw, Thessaloniki and Lecce) and Mountainous (Case III – Dushanbe, Evora, Observatory Hohenpeissenberg, Potenza). The three clusters and the characteristics of the stations are given in Table 2. In addition, Figure 4 shows the locations of the participating stations; green circles denote Continental stations, blue circles denote Coastal stations and brown circles denote Mountainous stations. Figure 4 shows, additionally to the geographical distribution of the active EARLINET stations, the daytime/nighttime overpasses of ISS within the evaluation period, between 02/2015 and 09/2016, encompassing the first twenty months of CATS operation. Due to the limited available dataset of CATS-EARLINET cases, the daytime/nighttime approach was not followed in the case of the analysis regarding the effect of topography.

Table 2: Clustering of EARLINET stations with respect to topographical features.

Case I - Continental				
EARLINET Station	Identification Code	Latitude (°N)	Longitude (°E)	Altitude a.s.l. (m)
Belsk	be	51.83	20.78	180
Bucharest	bu	44.35	26.03	93
Leipzig	le	51.35	12.43	90
Warsaw	wa	52.21	20.98	112

Case II - Coastal				
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
Cabauw	ca	51.97	4.93	0
Thessaloniki	th	40.63	22.95	50
Lecce	lc	40.33	18.10	30

Case III - Mountainous				
EARLINET Station	Identification Code	Latitude (°N)	Longitude (°E)	Altitude a.s.l. (m)
Dushanbe	du	38.56	68.86	864
Évora	ev	38.57	-7.91	293
Observatory Hohenpeissenberg	oh	47.8	11.01	974
Potenza	po	40.60	15.72	760

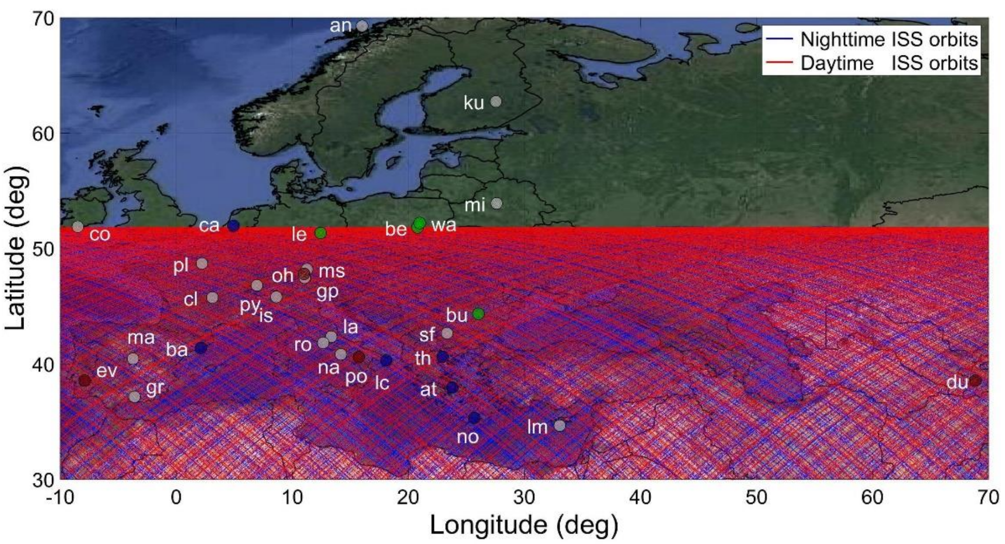

Figure 4: Distribution of EARLINET lidar stations over Europe and West Asia. Green dots: Continental stations used in the inter-comparison. Blue dots: Coastal stations used in the inter-comparison. Brown dots: Mountainous stations used in the inter-comparison. ISS orbits between 02/2015 and 09/2016 are overlaid in red for daytime and in blue for nighttime overpasses.

Figure 5 shows the effect of Topography, for three different clusters of station characteristics, as introduced above (Case I: Continental, Case II: Coastal and Case III: Mountainous). In Figure 5a, the Box and Whisker plot on the $CATS_i$-$EARLINET_i$ residuals is shown, including the lower and upper whiskers which indicate the 10th and 90th percentiles respectively, and the 25th and the 75th quantiles indicated by the lower and upper box boundaries respectively. The horizontal line and the red dot indicate the statistical mean and median values respectively while outliers are indicated by red crosses. According to the results, it is evident that the correlative measurements between the Mountainous EARLINET stations and the ISS overpasses are characterized by higher variability, more extreme differences, higher absolute mean and median biases and higher RMSE than in the Continental and Maritime cases. 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 between the CATS lidar footprint and the ground-based lidar stations and surface returns enhance the discrepancies, especially in the lowermost part of the profiles, resulting in higher differences between the EARLINET profiles and CATS profiles. Due to the lack of the aforementioned effects arising from complex topography, CATS representativeness and performance is higher over the Continental cases, while CATS performance over the Coastal stations is characterized by slightly lower absolute value of mean bias and at the same time by lower Correlation Coefficient than in the case of Continental cases. However, it has to be taken into consideration the important factor related to the presented results that is the number of CATS-EARLIENT correlative cases used in the analysis, 23 for Case I - Continental, 10 for Case II - Coastal and 14 for Case III - Mountainous. Analytical evaluation metrics on the effect of topography are given in Table 3.

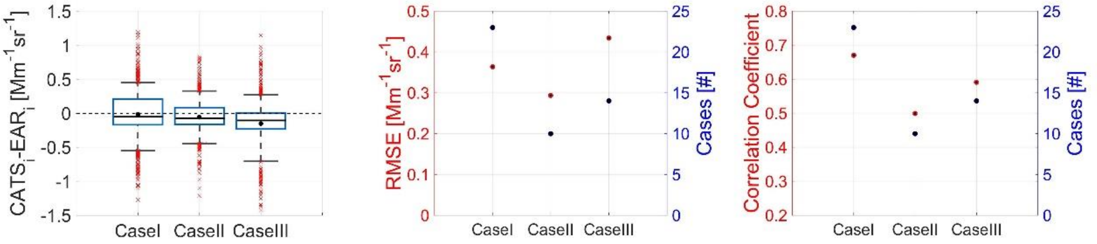

Figure 5: CATS backscatter coefficient at 1064nm with respect to EARLINET ground-based measurements, as a function of different topography of EARLINET stations for three different clusters of station topographical characteristics (Case I: Continental, Case II: Coastal and Case III: Mountainous). In Fig.5a, the Box and Whisker plot on the $CATS_i$-$EARLINET_i$ residuals is shown, including the lower and upper whiskers which indicate the 10th and 90th percentiles respectively, and the 25th and the 75th quantiles indicated by the lower and upper box boundaries respectively. The horizontal line and the red dot indicate the statistical mean and median values respectively while outliers are indicated by red crosses. Fig.5b and Fig.5c show the RMSE and Correlation Coefficient as a function of the different clusters, including the number of available cases per cluster.

Table 3: Clusters of EARLINET stations and CATS evaluation metrics.

	Continental stations	Coastal stations	Mountainous stations
Median	-0.053 [Mm^{-1}sr^{-1}]	-0.076 [Mm^{-1}sr^{-1}]	-0.106 [Mm^{-1}sr^{-1}]
Mean	-0.016 [Mm^{-1}sr^{-1}]	-0.058 [Mm^{-1}sr^{-1}]	-0.151[Mm^{-1}sr^{-1}]
RMSE	0.367 [Mm^{-1}sr^{-1}]	0.293 [Mm^{-1}sr^{-1}]	0.434 [Mm^{-1}sr^{-1}]
Correlation Coefficient	0.673	0.499	0.591
Number of cases	23	10	14

8. Page 9, line 18: “here considered”-> “considered here”.

The text is modified according to the reviewer’s recommendation.

9. Page 9, lines 32-33: I cannot understand this conclusive statement. How "the absence of significant biases, both daytime and nighttime" is obvious from figure 3c.

The reviewer is right, that Figure 3c corresponds to a nighttime atmospheric scene, therefore the statement, referring not only to nighttime but also to daytime conclusions, may be confusing for the reader. The authors, have inspected of all available cases one-by-one, and wanted to provide the information through this section, that when the atmospheric scene is homogeneous and the scattering characteristics of the aerosol layers are above the MDB thresholds of CATS sensor (i.e. sufficient SNR for detection and classification), the overall CATS performance under such homogeneous conditions is good, with absence of significant biases. This conclusion holds both for daytime and nighttime. For this reason the "*representative case*" was used.

However, since the authors agree with the reviewer that the sentence may be confusing, the sentence was reformulated from:

"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."

to:

"Although the case presented and discussed in Figure 3 corresponds to a nighttime ISS overpass, the case is representative for cloud free and relative homogeneous atmospheric scenes in terms of aerosols, for both daytime and nighttime solar background illumination, demonstrating the overall high performance of CATS under such conditions."

10. Page 10, lines 9-10: "due to the different SNR:::": I think that indeed this is the case. But this contradicts to the author statement of no significant bias between day and night conditions stated earlier (page 9, lines 32-33).

The reviewer is right on the high importance and effect of SNR is CATS retrievals and algorithms. Statement of page 9, lines 32-33 has been reformulated to avoid possible confusions, according to the reviewer's comment.

11. Page 10, lines 24-29: I have the feeling that this information should be moved to section 2.2 where the description of CATS data level product is already given. At that section, the authors can present a detailed description of their methodology followed for could screening.

According to reviewer's recommendation the suggested part of the manuscript was moved (and slightly modified to fit better to the paragraph), to Section 2.1 (former Section 2.2 in the ACPD discussion version).

To be more specific, the suggested part was modified from:

"In addition to the backscatter coefficient, 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."

to:

"In addition to CATS Level 2 Feature Type (namely: clear air, cloud, aerosol and totally attenuated), the algorithm provides the confidence level of the Feature Type 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."

12. Page 11, line 23: "end of 2018:::" -> Maybe "end of 2019" ?

The manuscript was modified to:

"*Based on this analysis and comparisons with CALIPSO, the CATS cloud-aerosol discrimination algorithm was updated for the V3-00 Level 2 data products (released in the end of 2018) to improve the accuracy of the Feature Type and Feature Type Score, especially during daytime.*"

13. Section 3.2: I wonder why the authors constrained their study only to the comparison of aerosol backscatter and they did not proceed with comparison of other aerosol related properties as well (e.g. physical and not properties such as integrated backscatter, AOD, lidar ratio, layer center of mass-thickness). I have the feeling that by taking into account more properties in their comparison will improve the manuscript and will enhance the arguments (i.e. argument of tenuous layer, argument of lidar ratio assumption) for the discrepancies shown here. In addition to that the information provided by each station individually is lost in the analysis demonstrated here. For example, a figure showing the differences between CATS-EARLINET for day and night time conditions per station along with the mean value may explain some of the discrepancies shown in this section (e.g. the argument of topography) or it may reveal other discrepancy patterns if any (i.e. latitudinal).

CATS products and processing algorithms are provided in different levels of processing. CATS Level 1B (L1B) data include vertical profiles of total and perpendicular attenuated backscatter signals, range-corrected, calibrated and annotated with ancillary meteorological parameters (McGill et al., 2007; Powell et al., 2009; Vaughan et al., 2010). CATS Level 2 (L2) 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 respectively. In addition, L2 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).
Regarding CATS L1B, the validation is a study led by NASA GSFC Team, and more specific by Dr. Rebecca Pauly (Science Systems and Applications Inc., Lanham, 20706, United States Science Systems and Applications Inc., Lanham, 20706, United States), member of the CATS Team. The study is already submitted on AMT journal: "*Pauly, R. M., Yorks, J. E., Hlavka, D. L., McGill, M. J., Amiridis, V., Palm, S. P., Rodier, S. D., Vaughan, M. A., Selmer, P. A., Kupchock, A. W., Baars, H., and Gialitaki, A.: Cloud Aerosol Transport System (CATS) 1064 nm Calibration and Validation, Atmos. Meas. Tech. Discuss., https://doi.org/10.5194/amt-2019-172, in review, 2019*".
In this study, the EARLINET authors in collaboration with the CATS Team evaluate CATS Level 2 Mode 7.2 v2.01 backscatter profiles at 1064nm (Palm et al., 2016). The reason of focusing to the evaluation of backscatter coefficient is the operation wavelength of CATS, i.e. the 1064nm wavelength. Since EARLINET lidar systems do not provide depolarization ratio measurements at 1064nm the particulate depolarization ratio parameter could not be evaluated, included in the analyssis. In addition, since CATS is a satellite-based elastic backscatter lidar (McGill et al., 2015), in order to provide vertically resolved extinction coefficient profiles (km^{-1}) of aerosols and clouds in the Earth's atmosphere, the computation algorithm implements a number of intermediate parameters (i.e. lidar ratio, feature type classification, aerosol subtype classification, among others). Due to the reason that the profiles of extinction coefficient are a computed product and not included in the direct measurements, extinction coefficient profiles were also not included in the analysis. The authors have focused on particulate backscatter coefficients ($km^{-1}sr^{-1}$), since this is the product directly derived from measurements, the sum of the parallel and perpendicular backscatter measurements (i.e., $\beta_{1064nm\_total} = \beta_{1064nm\_parallel} + \beta_{1064\_perpendicular}$). Future study will include high collocated analysis on the CATS performance and representativeness, including the issues mentioned by the reviewer, based on high temporally and spatially collocated measurements between airborne FAAM Bae-146 research aircraft and ISS measurements, performed in the framework of the AER-D/ICE-Dcampaign, over Cape-Verde (Santiago island), on August 6-25, 2015, as introduced by Marenco et al. (2018) – Figure 5.

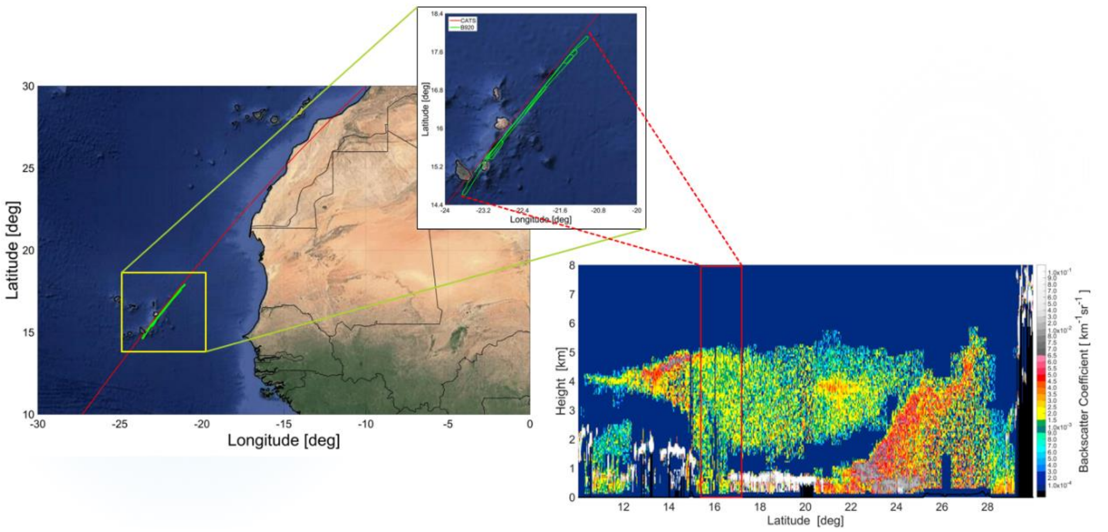

Figure 5: B920 flight on August 7th, 2015 over Cape Verde, high collocated with ISS-CATS overpass. Left: B920 flight and ISS footprint (left), and CATS backscatter coefficient 1064nm scene (right).

Regarding the comment of the reviewer of explicitly addressing the differences between CATS-EARLINET for day and night time conditions per station, along with the mean value to explain some of the discrepancies, it has to be noted that the sample of collocated profiles in many stations does not permit an analysis with strong "per-station" conclusions. For instance, we mention here that Barcelona (ba), Athens_NTUA (at), and Bucharest (bu) stations are participating with only one available case of CATS-EARLINET collocated measurements. In addition, certain number of station happens to contribute with either only nighttime or daytime correlative cases, i.e. Athens_NOA (no) and Lecce (le) with only nighttime cases (three and two cases respectively) and Evora (ev) with only daytime cases (two cases), not allowing to follow the per-station approach.

The undervalue of EARLINET is relying to the approach of the participating community treats EARLINET as a single entity, with the main objective to obtain an extended, coordinated and of continental scale network of sophisticated ground-based Raman lidars and eventually, to foster a quantitative, comprehensive, and statistically significant database of the distribution of aerosol on a continental scale (Bösenberg et al., 2003; Pappalardo et al., 2014). 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).

In order to clarify and demonstrate the sample issue, not allowing to follow a per-station approach, the authors have included here (but also in the manuscript) the following "Table 4", where the cases used in the intercomparison are given.

Table 4: ISS-CATS and EARLINET cases considered in the evaluation process of CATS backscatter coefficient profiles at 1064 nm.

Day-Night Flag	Date yyyy/mm/dd	Time hh:mm:ss (UTC)	EARLINET station	min Distance (km)	EARLINET Date (yyyy/mm/dd) | measuring time cloud-free window (UTC)
N	2015/11/25	03:44:09	Athens	40.42	2015/11/25 | 03:30:00 – 04:30:00
N	2016/01/29	01:46:08	Athens	46.84	2016/01/29 | 01:00:00 – 02:30:00
N	2016/02/01	17:23:36	Athens	23.29	2016/02/01 | 17:45:00 – 19:30:00
N	2016/02/01	17:23:39	Athens_NTUA	18.58	2016/02/01 | 18:20:51 – 19:57:41
D	2016/05/03	06:45:15	Barcelona	45.93	2016/05/03 | 08:59:00 – 09:59:00
D	2015/08/13	17:29:18	Belsk	2.39	2015/08/13 | 18:02:10 – 18:45:40
N	2016/08/08	17:34:50	Belsk	6.56	2016/08/08 | 17:31:08 – 18:12:05
N	2016/07/28	19:15:24	Bucharest	45.35	2016/07/28 | 17:41:22 – 18:41:22

N	2016/09/14	04:21:09	Cabauw	21.01	2016/09/14 | 05:27:25 – 06:00:03
N	2015/08/03	21:40:39	Dushanbe	42.64	2015/08/03 | 20:00:00 – 22:00:00
N	2016/08/14	15:39:07	Dushanbe	22.08	2016/08/14 | 15:57:00 – 17:19:00
D	2015/06/20	08:38:33	Dushanbe	13.33	2015/06/20 | 08:54:00 – 09:07:00
D	2015/07/12	06:47:07	Dushanbe	33.46	2015/07/12 | 06:25:00 – 07:10:00
D	2016/05/02	07:35:38	Evora	47.27	2016/05/02 | 07:58:50 – 08:00:21
D	2016/05/31	19:43:41	Evora	39.42	2016/05/31 | 19:29:56 – 19:59:35
N	2016/01/30	00:50:16	Hohenpeissenberg	13.36	2016/01/30 | 00:20:00 – 01:20:00
N	2016/03/17	02:12:09	Hohenpeissenberg	43.40	2016/03/17 | 01:42:00 – 02:42:00
D	2015/10/31	12:56:05	Hohenpeissenberg	34.41	2015/10/31 | 12:26:00 – 13:26:00
D	2016/04/12	15:29:18	Hohenpeissenberg	12.77	2016/04/12 | 14:55:00 – 16:05:00
D	2016/08/07	16:49:29	Hohenpeissenberg	31.81	2016/08/07 | 16:19:30 – 17:19:30
D	2016/08/23	10:42:43	Hohenpeissenberg	36.11	2016/08/23 | 10:12:30 – 11:12:30
D	2016/09/14	05:58:59	Hohenpeissenberg	28.37	2016/09/14 | 04:59:00 – 05:59:00
N	2015/07/27	21:14:35	Lecce	34.69	2015/07/27 | 20:42:00 – 21:09:00
N	2016/08/04	22:44:06	Lecce	4.72	2016/08/04 | 20:50:00 – 21:20:00
N	2015/07/30	00:18:19	Leipzig	41.16	2015/07/30 | 00:34:00 – 01:04:00
N	2015/08/03	21:29:44	Leipzig	15.81	2015/08/03 | 21:31:00 – 22:00:00
N	2015/09/24	01:13:34	Leipzig	25.05	2015/09/24 | 01:01:00 – 01:30:00
N	2015/09/29	00:05:33	Leipzig	36.49	2015/09/28 | 22:42:00 – 23:12:00
N	2015/09/29	23:13:24	Leipzig	48.46	2015/09/28 | 22:55:00 – 23:24:00
N	2015/09/30	22:21:13	Leipzig	12.89	2015/09/30 | 21:25:00 – 21:34:00
N	2016/06/05	20:14:01	Leipzig	36.93	2016/06/05 | 20:02:00 – 20:31:00
N	2016/09/13	03:37:49	Leipzig	3.79	2016/06/05 | 00:00:00 – 02:30:00
N	2016/09/12	04:29:46	Leipzig	45.08	2016/09/12 | 00:00:00 – 02:30:00
N	2016/09/15	03:30:25	Leipzig	48.36	2016/09/15 | 00:00:00 – 02:30:00
D	2015/04/21	14:54:35	Leipzig	6.73	2015/04/21 | 16:04:00 – 16:33:00
D	2015/04/21	16:31:00	Leipzig	31.28	2015/04/21 | 16:34:00 – 17:04:00
D	2015/04/24	15:25:13	Leipzig	47.83	2015/04/24 | 14:03:00 – 14:32:00
D	2015/08/13	17:27:54	Leipzig	1.36	2015/08/13 | 19:01:00 – 19:30:00
D	2016/08/24	11:26:39	Leipzig	3.46	2016/08/24 | 10:00:00 – 12:00:00
D	2016/08/24	13:03:12	Leipzig	48.97	2016/08/24 | 10:00:00 – 12:00:00
N	2015/07/21	00:13:26	Potenza	2.01	2015/07/21 | 00:00:00 – 02:52:19
D	2015/11/06	10:54:52	Thessaloniki	19.46	2015/11/06 | 11:57:03 – 12:27:20
N	2016/01/28	19:17:11	Thessaloniki	39.54	2016/01/28 | 20:08:40 – 20:38:57
D	2015/08/13	17:29:20	Warsaw	42.95	2015/08/13 | 17:00:00 – 17:22:00
D	2015/08/19	15:22:30	Warsaw	44.47	2015/08/19 | 15:25:00 – 15:47:00
D	2016/06/07	18:29:46	Warsaw	41.22	2016/06/07 | 18:15:00 – 18:43:00
N	2016/08/08	17:34:53	Warsaw	46.99	2016/08/08 | 17:00:00 – 17:23:00

14. The pair of observation "i" refer to the vertical height of each case study or to each case study individually? This a general comment related to the comparison methodology followed by the authors: I speculate that the initial vertical resolution of the two profiles is not the same. For example, the L1 data products obtained by CATS are within 60 m vertical resolution (Yorks et al., 2011). On the other hand, the data products obtained by EARLINET (especially the Raman retrievals) are processed (application of low-pass filter on the signal) leading to range-resolution loss. A concept of effective resolution is already discussed in the literature (e.g. Iarlori et al., 2015). Therefore, it is not so clear to the reader how the authors managed to compare values obtained from different atmospheric heights? Did they interpolate their values or they used mean values in specific vertical height windows? In any case the authors are kindly suggested to comment their approach on this. (Iarlori, M., Madonna, F., Rizi, V., Trickl, T., Amodeo, A., Effective resolution concepts for lidar observations, Atmos. Meas. Tech., 8, 5157–5176, 2015 www.atmos-meas-tech.net/8/5157/2015/ doi:10.5194/amt-8-5157-2015).

The authors agree with the reviewer regarding not properly commenting on the respective aspect. Regarding CATS L2 profiles, the product provides 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 5km and 60m respectively. On the contrary, EARLINET profiles were provided by the EARLINET community with higher vertical resolution. Towards the assessment of CATS performance, for the comparison of CATS against EARLINET, we implemented the $CATS_i$-$EARLINET_i$ residuals for each pair of observations "i", as a statistical indicator of CATS average overestimation or underestimation of the aerosol load, in terms of backscatter coefficient values. Since the vertical resolution of the two profiles was not the same and in order to compute the $CATS_i$-$EARLINET_i$ residuals, the EARLINET profiles were reduced in resolution to obtain 1-1 datasets, characterized by the same vertical resolution. This was achieved by computing the EARLINET mean backscatter coefficient value from all EARLINET bins within each CATS 60m backscatter coefficient range. Thus, indeed the speculation of the reviewer on the methodology, through computing mean values in specific vertical height windows, is right.

The aforementioned approach indeed led to loss of vertical resolution in the EARLINET profiles (Iarlori et al., 2015). For this reason, the authors (in the initial steps of the study) performed an exercise, to investigate the magnitude of the effect of the selected approach and the significance of loss of resolution in the EARLINET profiles, since the opposite approach (i.e. to increase the resolution of CATS profiles to match the EARLINET resolution), was not feasible.

Figure 6 shows an example of the exercise, corresponding to a nighttime ISS orbit, on September 30, 2015 (blue line), at a minimum distance of 12.9km from the EARLINET Leipzig – Germany PollyXT lidar system (indicated by a white dot), at 22:21 UTC (Fig. 3a). CATS particulate backscatter coefficient cross section at 1064 nm (Fig.6-right) shows the presence of aerosols up to 2.2 km (a.s.l.). CATS spatial-averaged and Leipzig temporal-averaged profiles were derived from CATS profiles within horizontal distance below of 50 km, between the Leipzig station and the ISS footprint.

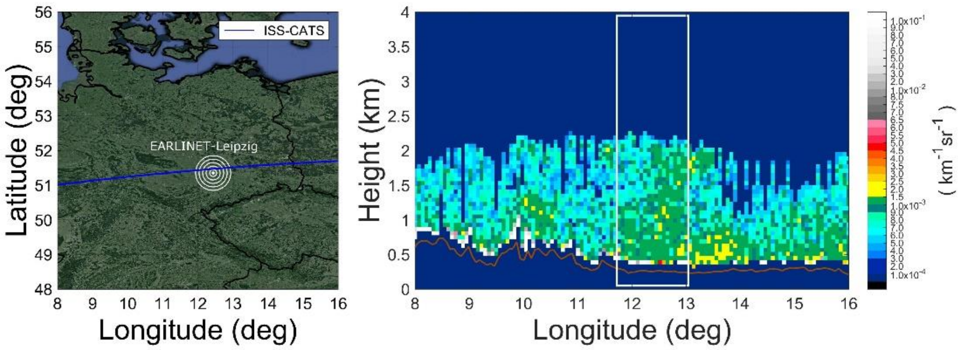

Figure 6: (left) Nighttime ISS orbit over EARLINET Leipzig station on the 30th of September 2015 (blue line). The white dot denotes the location of Leipzig lidar system, (b) CATS Backscatter Coefficient at 1064 nm.

Figure 7 shows the direct comparison between the backscatter coefficient profiles, measured from the EARLINET Leipzig station (red line) and CATS (blue line), along with their standard deviations (horizontal error bars). The profiles indicate 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 adequate agreement, although significant discrepancies were also present, especially to the lowermost part of the profiles, as discussed in the manuscript.

The intercomparison presented in Figure 7 is shown to provide to the reviewer a quantitative response to the specific comment. Figure 7 shows the CATS averaged backscatter coefficient profile in blue color, while with respect to EARLINET both the initial (high resolution) and final (reduced in resolution to match the CATS profile resolution) are provided in black and red colors. As was observed the necessary loss resolution in the EARLINET profiles for achieving vertical match between the two datasets is very low, with final EARLINET profile following with high accuracy the characterizes and tendencies, both qualitative and quantitative, of the initial EARLINET profiles.

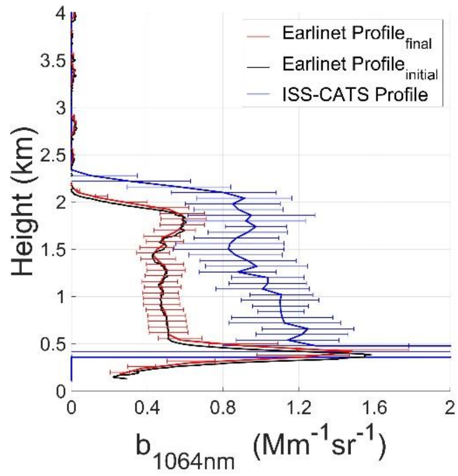

Figure 7: CATS and EARLINET-Leipzig backscatter coefficient profiles (1064 nm) for the nighttime ISS orbit over EARLINET Leipzig station on the 30th of September 2015. CATS backscatter coefficient profile at 1064nm is shown in blue line. EARLINET-Leipzig initial and final profiles, are shown is black and red respectively.

However, the authors agree with the reviewer on the absence of properly addressing the vertical match between the two datasets. For this reason, the following part was added on "*Section 2.3.2 - Particle backscatter coefficient retrievals from ground based lidars at 1064 nm*":
"Finally, in order to perform the intercomparison between CATS and EARLINET profiles, the high resolution of EARLINET profiles was lowered to match the vertical resolution of CATS profiles (i.e. 60m). The objective of obtaining profiles of similar vertical resolution was addressed through computing the EARLINET mean backscatter coefficient value from all EARLINET bins within each CATS 60m backscatter coefficient height range. The computed EARLINET profiles of similar vertical resolution with CATS followed with high accuracy the characterizes and tendencies, both qualitative and quantitative, of the initial EARLINET profiles, despite the loss of vertical resolution (Iarlori et al., 2015). ".

15. Page 13, line 30: "CALIOP" -> Maybe "CATS" instead of CALIOP?

CATS calibration is performed by normalizing the NRB signal in the altitude regime between 23 and 27 km. Although the region is used to normalize the NRB signal to the molecular backscatter, the region between 23 and 27 km is not aerosol free. According to the ATBD, the scattering ratios (e.g. total backscatter to molecular backscatter) at 532 nm are estimated based on CALIPSO CALIOP V4 L1 data. The 532 nm scattering ratios are used to estimate the 1064 nm scattering ratios and accordingly to the calibration of CATS. Consequently, a source of systematic errors in the CATS calibration is related to errors in the stratospheric scattering ratios provided by CALIPSO (ΔR). The scattering ratio values in CATS calibration are determined as outlined in section 3.3.4. of the CATS ATBD (https://cats.gsfc.nasa.gov/media/docs/CATS_ATBD.pdf; last visit: 29/05/2019).

16. Page 15, line 18, lines 24-25: "slight underestimations of the total AOD in climatic studies." "results in large AOD biases and unrealistic AOD values." I agree with these statements. However, in the current state of the manuscript there is no straight forward comparison of AOD but only backscatter coefficient. See also my previous specific comment No. 14.

The authors agree with the reviewer. Although not a CATS extinction coefficient 1064nm and AOD 1064 nm analysis were not included, the authors in order to provide a more detailed overview of CATS capabilities and representativeness have included literature review on studies investigating the performance of CATS. To be more specific, the following paragraph was added to the manuscript (Section 1 - Introduction), in line to the comment of the reviewer and in order to justify the statement mentioned ny the reviewer:

“CATS performance has been validated against ground-based AErosol RObotic NETwork (AERONET; Holben et al., 1998) measurements and evaluated against satellite-based Atmospheric Optical Depth (AOD) retrievals of Aqua and Terra Moderate Imaging Spectroradiometer (MODIS; Levy et al., 2013) and active CPL (McGill et al., 2002) and CALIPSO CALIOP (Winker et al., 2009) profiles of extinction coefficient and AOD at 1064 nm. Lee et al. (2018) compared daytime quality-assured CATS V2-01 vertically integrated extinction coefficient profiles (1064 nm) and AERONET AOD (1020 nm) values, spatially (within 0.4^o Longitude and Latitude) and temporally (±30 minutes) collocated, and found a reasonable agreement with a correlation of 0.64. A comparative analysis of CATS and MODIS C6.1 Dark Target (DT) AOD retrievals, through spectral interpolation between 0.87 and 1.24 μm channels, reported correlation of 0.75 and slope of 0.79, over ocean. In addition, Lee et al., (2019) evaluated AOD and extinction coefficient profiles from CATS through intercomparison with CALIOP. With regard to AOD, analysis a total of 2681 CATS and CALIOP collocated observation cases (within 0.4^o Longitude/Latitude and ±30 minutes ISS and CALIPSO overpass difference), showed correlation of 0.62 and 0.52 over land and ocean respectively during daytime (1342 cases), and 0.84 and 0.81 over land and ocean respectively during nighttime (1339 cases). Comparison of CATS and CALIOP collocated extinction coefficient profiles based on the closest Euclidian distance on the earth’s surface, shows also good shape agreement, despite an apparent CALIOP underestimation in the lowest 2 km height. CATS and CALIOP observations were used by Rajapakshe et al. (2017) to study the seasonally transported aerosol layers over the SE Atlantic Ocean. The performed comparative analysis reported on similar geographical patterns regarding Above Cloud Aerosols (ACA), Cloud Fraction (CF) and ACA occurrence frequency (ACA_F) between CATS and CALIOP retrievals. However, the authors reported also on differences between CATS and CALIOP vertical aerosol distributions, with ACA bottom height identified by CATS lower than the respective of CALIOP. CATS retrievals were used to document the diurnal cycle and variations of clouds, with CALIOP complementarily used. Noel et al. (2018) showed that both CATS and CALIOP profiles of CF agree well on both the vertical patterns and values at 01:30 and 13:30 LT, over both land and ocean, with minor differences of the order of 2-7% throughout the entire profiles of cloud fraction. CATS depolarization measurements, which are critical in the processing algorithms of aerosol subtype classification, were investigated in the case of desert dust, smoke from biomass burning and cirrus clouds (Yorks et al., 2016), and were found consistent and in good agreement with depolarization measurements from previous studies and historical datasets implementing CPL (Yorks et al., 2011) and CALIOP (Liu et al., 2015).

17. Page 29, line 13: “The white circle” -> “The white dot denotes the location”. The white circle refers to points at various distances from the lidar station as stated by the authors in Figure 2. Please consider correcting this minor typo in figures 3, 4, and 5.

The text is modified according to the reviewer’s recommendation.

18. Figure 7: For the night time mean profiles the discrepancies are negligible but for the day time and specifically for the height region from 1-2 km large differences are observed. What is the main reason behind this? The significant influence of the topography? In that case why this difference is not shown also in the nigh-time profiles, considering this as a bias from one or more stations. The low daytime CATS SNR? In that case I would expect to see higher discrepancies than sown inside the PBL (longer atmospheric path), compared to 1-2 km. The calibration region of CATS? In any case, I think that a solid and quantitative explanation on this is missing.

The effect of signal-to-noise ratio (SNR) and the associated Minimum Detection Backscatter (MDB) are the critical factors determining the performance of CATS. However along with the technical capabilities of CATS there are different factors with effect on the final CATS profiles (i.e. topography, as mentioned by the reviewer). Regarding the quantitative and qualitative explanation exercises under different cases are presented and discussed in the reviewer’s question #7.

Interactive comment on "EARLINET evaluation of the CATS L2 aerosol backscatter coefficient product" by Emmanouil Proestakis et al.
Anonymous Referee #2
Received and published: 17 March 2019

The authors would like to thank the reviewer for the interesting and at the same time substantial comments and suggestions. We tried, and did our best, to incorporate the most suitable proposed changes and corrections in the revised manuscript, aiming at improving the presented paper. Following, you will find our responses, one by one to the comments addressed, in the uploaded supplement pdf file.

Kind regards,
Emmanouil Proestakis

General comments:

This manuscript compares EARLINET (ground-based) and CATS (onboard the international spatial station) retrievals of the aerosol backscatter coefficient over 12 European sites and 1 Asian site. The paper is well written, however, I did miss some explanation in the introduction about the importance of CATS product. I believe this could be easily achieved by modifying the order of some paragraphs and including extra information. In particular, I suggest moving the second paragraph of Section 2.2 (page 4, line 30 to page 5, line 12) to the introduction, with the due adjustments.

The authors agree with the reviewer. The science goals of CATS, indeed, were not mentioned in the introduction, leading to issues in the understanding of the scientific importance of the project in the early stages of the manuscript. For this reason the authors have followed the referee's recommendation to rearrange the manuscript, making at the same time all the appropriate modifications to ensure that the adjustments did not have a negative impact to the understanding of the manuscript context. To be more specific, the following section was added to the introduction:

"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 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 National d'Études Spatiales (CNES) Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission in June, 2006 (Winker et al., 2007). Since 2009 the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument (Winker et al., 2009) onboard CALIPSO operates on the secondary backup laser. The launch of the post-CALIPSO missions, the joint European Space Agency (ESA) and JAXA satellite Earth Cloud Aerosol and Radiation Explorer (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 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 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)."

I also suggest comparing some scenes of coincident vertical profiles of CATS and CALIOP. Would that be possible? I believe this would dramatically improve the visibility of the paper. Also, it wasn't clear to me whether CATS should only be used to fill a gap in space-based lidar observations or if it is as reliable as CALIOP. I believe this should be further clarified in the text.

The suggested evaluation study between CATS and CALIOP has been already performed by Lee et al. (2018), Rajapakshe et al. (2017), Noel et al. (2018) and Yorks et al., 2016, reporting also on the good agreement of the intercomparison studies. However, the authors agree with the reviewer regarding the necessity of including the findings of the aforementioned studies and have adjusted the manuscript accordingly. To be more specific, the following paragraph was added to the manuscript (Section 1 - Introduction):

"*CATS performance has been validated against ground-based AErosol RObotic NETwork (AERONET; Holben et al., 1998) measurements and evaluated against satellite-based Atmospheric Optical Depth (AOD) retrievals of Aqua and Terra Moderate Imaging Spectroradiometer (MODIS; Levy et al., 2013) and active CPL (McGill et al., 2002) and CALIPSO CALIOP (Winker et al., 2009) profiles of extinction coefficient and AOD at 1064 nm. Lee et al. (2018) compared daytime quality-assured CATS V2-01 vertically integrated extinction coefficient profiles (1064 nm) and AERONET AOD (1020 nm) values, spatially (within 0.4^o Longitude and Latitude) and temporally (±30 minutes) collocated, and found a reasonable agreement with a correlation of 0.64. A comparative analysis of CATS and MODIS C6.1 Dark Target (DT) AOD retrievals, through spectral interpolation between 0.87 and 1.24 μm channels, reported correlation of 0.75 and slope of 0.79, over ocean. In addition, Lee et al., (2019) evaluated AOD and extinction coefficient profiles from CATS through intercomparison with CALIOP. With regard to AOD, analysis a total of 2681 CATS and CALIOP collocated observation cases (within 0.4^o Longitude/Latitude and ±30 minutes ISS and CALIPSO overpass difference), showed correlation of 0.62 and 0.52 over land and ocean respectively during daytime (1342 cases), and 0.84 and 0.81 over land and ocean respectively during nighttime (1339 cases). Comparison of CATS and CALIOP collocated extinction coefficient profiles based on the closest Euclidian distance on the earth's surface, shows also good shape agreement, despite an apparent CALIOP underestimation in the lowest 2 km height. CATS and CALIOP observations were used by Rajapakshe et al. (2017) to study the seasonally transported aerosol layers over the SE Atlantic Ocean. The performed comparative analysis reported on similar geographical patterns regarding Above Cloud Aerosols (ACA), Cloud Fraction (CF) and ACA occurrence frequency (ACA_F) between CATS and CALIOP retrievals. However, the authors reported also on differences between CATS and CALIOP vertical aerosol distributions, with ACA bottom height identified by CATS lower than the respective of CALIOP. CATS retrievals were used to document the diurnal cycle and variations of clouds, with CALIOP complementarily used. Noel et al. (2018) showed that both CATS and CALIOP profiles of CF agree well on both the vertical patterns and values at 01:30 and 13:30 LT, over both land and ocean, with minor differences of the order of 2-7% throughout the entire profiles of cloud fraction. CATS depolarization measurements, which are critical in the processing algorithms of aerosol subtype classification, were investigated in the case of desert dust, smoke from biomass burning and cirrus clouds (Yorks et al., 2016), and were found consistent and in good agreement with depolarization measurements from previous studies and historical datasets implementing CPL (Yorks et al., 2011) and CALIOP (Liu et al., 2015).*

I also believe a final paragraph stating the main conclusion is needed (that is, what are your suggestions for future studies: should we use CATS or not, under which conditions these retrievals are reliable, what are their advantages and disadvantages and how could future studies benefit - or not - from CATS).

The authors agree with the reviewer and a final paragraph stating suggestions related the use of the unique CAST dataset was included. To be more specific, the following section was added to the "Summary and Conclusions section":

"The qualitative and quantitative agreement between CATS and EARLINET reported in this study is encouraging, especially during nighttime, agreement that will hopefully facilitate further studies implementing CATS observations in the future. CATS, for a period of almost three years, provided an unprecedented global dataset of vertical profiles of aerosols and clouds, much like CALIOP, taking though advantage of the unique orbital characteristics of the ISS. ISS enabled CATS to provide for the first time satellite-based lidar measurements of the diurnal evolution of aerosols and clouds over the tropics and midlatitudes, and to be more specific to latitudes below 52^o. Since CALIPSO and Aeolus (and in the future also EarthCARE) are polar sun-synchronous satellites of fixed equatorial crossing time (01:30 and 13:30 LT for CALIOP, 06:00 and 18:00 for ALADIN), it is expected that, at least for the near future, CATS dataset will remain the only available satellite-based lidar source of nearly global diurnal measurements of atmospheric aerosols and clouds. In addition, while CALIOP is a two-wavelength lidar system operating at 532 nm and 1064 nm with depolarization capabilities at 532 nm, CATS provided satellite-based aerosol and cloud depolarization profiles at 1064 nm, thus in a different wavelength. This dataset, much like CALIOP dataset, is especially useful for studies of the three-dimensional distribution of non-spherical aerosol particles in the atmosphere (e.g. mineral dust and volcanic ash), and especially since it is an active sensor, over regions of high

reflectivity (e.g. deserts, ice). Future studies including the exploitations of CATS unique observations may help the scientific community to shed new light on physical processes of aerosols and clouds in the Earth's atmosphere."

Specific comments:

page 2, line 3 - Please modify "Physic" to "Physics".

The text is modified according to the reviewer's recommendation.

page 2, line 20 - Please reformulate the sentence (suggestion: "Quality assessment of CATS...").

The text is modified according to the reviewer's recommendation.

page 2, line 24 - Please modify "consists" to "consists of".

The text is modified according to the reviewer's recommendation.

page 3, line 15 - What is the difference between capacity and capability?

The text is reformulated according to the reviewer's recommendation:

"Since the beginning of the initiative in 2000, EARLINET has significantly increased its observing and operational capacity"

page 3, line 16 - Please reformulate or remove the sentence "EARLINET stations are classified as active on condition of...".

According to the reviewer's comment, the sentence was reformulated to:

"EARLINET stations are classified between "active", "not permanent", "joining" and "not active". An EARLINET station is classified as active when on condition of performing regularly and simultaneously measurements with the other stations composing the lidar network, and accordingly, contributing with uploading the performed measurements to the EARLINET database (https://www.earlinet.org/, last access: 20 December 2018)."

page 4, line 32 - Please modify "space-borne" to "spaceborne".

The text is modified according to the reviewer's recommendation.

page 6, line 16 - It's not clear to me if observations more than 90 minutes apart were compared or not. Could you clarify this?

The study follows the CALIPSO CALIOP validation methodology developed in the framework of a collaboration between ESA and EARLINET collaboration (Pappalardo et al., 2010). The ESA dedicated program of collocated and concurrent EARLINET observations with CALIOP observations was developed prior to the launch of CALIPSO and is planned with a duration until the end-of-mission of the mission. On the contrary of the well-established CALIPSO-EARLINET validation activity, but also to the ESA-Aeolus and to the upcoming ESA-EarthCARE satellite missions, a similar CATS-EARLINET validation strategy was not established.
The participating EARLIENT stations in the study contributed to the evaluation of CATS through measurements performed during the fixed-scheduled program of EARLINET operation. As described in Pappalardo et al (2014), the EARLINET scheduled program of measurements includes 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, EARLIENT operates a small number of lidar systems capable for 24/7 continuous measurements (Engelmann et al., 2016).
The absence of an established dedicated validation activity between NASA and EARLINET prior to the operation of CATS, in combination with the fixed measurements schedule of EARLINET, the high variable overpass-time of CATS (bounded by the orbital characteristics of ISS) and the frequently cloud-contaminated cases led to a low

number of collocated and concurrent EARLINET-CATS cases to be available for the study. Eventually, this obstacle was tackled through the cooperative effort of a large number of EARLINET stations, contributing through the already performed measurements. The increasing number of EARLINET stations showing interest to contribute to the study led to an overall of forty-seven (47) available cloud-free EARLINET-CATS collocated cases to implement for the evaluation of CATS.
The EARLINET-CATS correlative study considers the collocation criteria established in the validation plan of CALIPSO. Regarding the spatial collocation, EARLINET participating stations contributed with measurements when the ISS overpass was within 50 km horizontal radius from their location.

Regarding the temporal collocation, the study implemented ground-based measurements with a temporal window of EARLINET performed measurements with starting time, or stop time as close in time as possible to the ISS overpass. Accordingly, all the identified EARLINET cases where studied, through case-by-case inspection of the Range-Corrected-Signal quicklooks, for atmospheric homogeneity was of high importance, and additionally for other constrains (e.g. cirrus-clouds). During the first twenty months of CATS operation, based on thirteen EARLINET contributing stations, only 47 cases were found suitable to be used in the comparison. From the total of 47 cases, 44 where performed with "*starting time*", or "*stop time*" within 90 minutes of the ISS overpass. For this reason why the phrase *"typically within 90 minutes of the ISS overpass"* was used in the manuscript. In addition, it has to be mentioned that in the majority of the EARLINET cases encompasses the ISS overpass. The length of the temporal window was variable, based-on the expertise of the EARLINET teams, the homogeneity of the atmospheric scenes and the unique cloud constrains of each case, in order to allow retrievals of high-quality EARLINET backscatter coefficient profiles.

The authors agree though with the reviewer that this part of the manuscript was not clear, therefore the manuscript was revised in the 2.3.1 section referring to the "Comparison methodology", and in addition the manuscript was updated with the following table (*"Table 2"* in the manuscript) that includes information on the correlative cases used in the study. The table provides the "Day-Night Flag" of the study case, "Date" and "Time" of the ISS overpass, the corresponding EARLINET station and the minimum distance between the ISS orbit-track and the station location, and finally the EARLINET temporal window of measurements.

In Section 2.3.1, the following part of the manuscript was reformulated according to the reviewer's recommendation, from:
"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."
to:
"EARLINET contributed with performed measurements as close in time as possible, typically with starting time or stop time of the performed measurements widow within 90 min of the ISS station overpass. The EARLINET-CATS cases considered to the assessment of the accuracy and representativeness of CATS backscatter coefficient profiles are provided in Table 2, including the name of the EARLINET station, the EARLINET measurements window, the ISS overpass time, the ISS minimum distance between the corresponding EARLINET station and the lidar footprint of CATS and the Daytime/Nighttime information."

Table 2: ISS-CATS and EARLINET cases considered in the evaluation process of CATS backscatter coefficient profiles at 1064 nm.

Day-Night Flag	Date yyyy/mm/dd	Time hh:mm:ss (UTC)	EARLINET station	min Distance (km)	EARLINET Date (yyyy/mm/dd) | measuring time cloud-free window (UTC)
N	2015/11/25	03:44:09	Athens	40.42	2015/11/25 | 03:30:00 – 04:30:00
N	2016/01/29	01:46:08	Athens	46.84	2016/01/29 | 01:00:00 – 02:30:00
N	2016/02/01	17:23:36	Athens	23.29	2016/02/01 | 17:45:00 – 19:30:00
N	2016/02/01	17:23:39	Athens_NTUA	18.58	2016/02/01 | 18:20:51 – 19:57:41
D	2016/05/03	06:45:15	Barcelona	45.93	2016/05/03 | 08:59:00 – 09:59:00
D	2015/08/13	17:29:18	Belsk	2.39	2015/08/13 | 18:02:10 – 18:45:40
N	2016/08/08	17:34:50	Belsk	6.56	2016/08/08 | 17:31:08 – 18:12:05
N	2016/07/28	19:15:24	Bucharest	45.35	2016/07/28 | 17:41:22 – 18:41:22

N	2016/09/14	04:21:09	Cabauw	21.01	2016/09/14 | 05:27:25 – 06:00:03
N	2015/08/03	21:40:39	Dushanbe	42.64	2015/08/03 | 20:00:00 – 22:00:00
N	2016/08/14	15:39:07	Dushanbe	22.08	2016/08/14 | 15:57:00 – 17:19:00
D	2015/06/20	08:38:33	Dushanbe	13.33	2015/06/20 | 08:54:00 – 09:07:00
D	2015/07/12	06:47:07	Dushanbe	33.46	2015/07/12 | 06:25:00 – 07:10:00
D	2016/05/02	07:35:38	Evora	47.27	2016/05/02 | 07:58:50 – 08:00:21
D	2016/05/31	19:43:41	Evora	39.42	2016/05/31 | 19:29:56 – 19:59:35
N	2016/01/30	00:50:16	Hohenpeissenberg	13.36	2016/01/30 | 00:20:00 – 01:20:00
N	2016/03/17	02:12:09	Hohenpeissenberg	43.40	2016/03/17 | 01:42:00 – 02:42:00
D	2015/10/31	12:56:05	Hohenpeissenberg	34.41	2015/10/31 | 12:26:00 – 13:26:00
D	2016/04/12	15:29:18	Hohenpeissenberg	12.77	2016/04/12 | 14:55:00 – 16:05:00
D	2016/08/07	16:49:29	Hohenpeissenberg	31.81	2016/08/07 | 16:19:30 – 17:19:30
D	2016/08/23	10:42:43	Hohenpeissenberg	36.11	2016/08/23 | 10:12:30 – 11:12:30
D	2016/09/14	05:58:59	Hohenpeissenberg	28.37	2016/09/14 | 04:59:00 – 05:59:00
N	2015/07/27	21:14:35	Lecce	34.69	2015/07/27 | 20:42:00 – 21:09:00
N	2016/08/04	22:44:06	Lecce	4.72	2016/08/04 | 20:50:00 – 21:20:00
N	2015/07/30	00:18:19	Leipzig	41.16	2015/07/30 | 00:34:00 – 01:04:00
N	2015/08/03	21:29:44	Leipzig	15.81	2015/08/03 | 21:31:00 – 22:00:00
N	2015/09/24	01:13:34	Leipzig	25.05	2015/09/24 | 01:01:00 – 01:30:00
N	2015/09/29	00:05:33	Leipzig	36.49	2015/09/28 | 22:42:00 – 23:12:00
N	2015/09/29	23:13:24	Leipzig	48.46	2015/09/28 | 22:55:00 – 23:24:00
N	2015/09/30	22:21:13	Leipzig	12.89	2015/09/30 | 21:25:00 – 21:34:00
N	2016/06/05	20:14:01	Leipzig	36.93	2016/06/05 | 20:02:00 – 20:31:00
N	2016/09/13	03:37:49	Leipzig	3.79	2016/06/05 | 00:00:00 – 02:30:00
N	2016/09/12	04:29:46	Leipzig	45.08	2016/09/12 | 00:00:00 – 02:30:00
N	2016/09/15	03:30:25	Leipzig	48.36	2016/09/15 | 00:00:00 – 02:30:00
D	2015/04/21	14:54:35	Leipzig	6.73	2015/04/21 | 16:04:00 – 16:33:00
D	2015/04/21	16:31:00	Leipzig	31.28	2015/04/21 | 16:34:00 – 17:04:00
D	2015/04/24	15:25:13	Leipzig	47.83	2015/04/24 | 14:03:00 – 14:32:00
D	2015/08/13	17:27:54	Leipzig	1.36	2015/08/13 | 19:01:00 – 19:30:00
D	2016/08/24	11:26:39	Leipzig	3.46	2016/08/24 | 10:00:00 – 12:00:00
D	2016/08/24	13:03:12	Leipzig	48.97	2016/08/24 | 10:00:00 – 12:00:00
N	2015/07/21	00:13:26	Potenza	2.01	2015/07/21 | 00:00:00 – 02:52:19
D	2015/11/06	10:54:52	Thessaloniki	19.46	2015/11/06 | 11:57:03 – 12:27:20
N	2016/01/28	19:17:11	Thessaloniki	39.54	2016/01/28 | 20:08:40 – 20:38:57
D	2015/08/13	17:29:20	Warsaw	42.95	2015/08/13 | 17:00:00 – 17:22:00
D	2015/08/19	15:22:30	Warsaw	44.47	2015/08/19 | 15:25:00 – 15:47:00
D	2016/06/07	18:29:46	Warsaw	41.22	2016/06/07 | 18:15:00 – 18:43:00
N	2016/08/08	17:34:53	Warsaw	46.99	2016/08/08 | 17:00:00 – 17:23:00

page 6, line 24 - What does "including cirrus clouds" mean? Cirrus clouds scenes were used or not?

The authors acknowledge that the sentence was not clearly written, thus the sentence was reformulated from:
"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."
to:
"In addition, to account for contamination effects of multiple-scattering and specular reflection in the intercomparison process, only cloud-free atmospheric scenes are used. Cases with detected cirrus either at the EARLINET Range-Corrected-Signal quicklooks or at the ISS-CATS backscatter coefficient profiles or the feature type profiles are not considered in the study."

page 7, line 19 - Please modify "participated" to "participating".

The text is modified according to the reviewer's recommendation.

page 7, line 20 - "exited". Did you mean "excited"?

The reviewer is correct, the text is modified according to the reviewer's comment.

page 9, line 14 – Please modify "in details" to "in detail".

The text is modified according to the reviewer's recommendation.

page 9, line 24 - Please modify "below" to "of".

The text is modified according to the reviewer's recommendation.

Page 9, line 37 - Please modify "over-lying" to "overlaying".

The text is modified according to the reviewer's recommendation.

page 11, line 22 - Has the new product already been released? How does the new algorithm differ from the previous one? What kind of improvements does it present?

CATS V3-00 replaced CATS V2-05 on October 1st, 2018. Initially, the changes in CATS Level 1 and Level 2 algorithms corresponding to CATS Version 3-00 data was planned to be the final algorithm release for the CATS project, though observed issues in the CATS products led to the modifications of V3-00 and the release of the V3-01 later on in the beginning of 2019. Since CATS products are provided in different levels of processing, the made changes in the algorithms correspond to both L1B and L2O products.
To be more specific, the changes in the L1B algorithms include:
(1) improvement of the nighttime attenuated total backscatter (ATB) profiles due to improvements in the calibration of CATS, thus improvement also in the daytime ATB profiles, since nighttime ATB is implemented in the calculations of the daytime calibration.
(2) changes to the "Depolarization_Quality_Flag", and
(3) implementation of MERRA-2 Reanalysis data instead of GMAO forecasts, for the meteorology in V3-00 and V3-01.
The changes made in the algorithms of CATS L1B reflect on improvements on CATS L2O products. Though additional changes in CATS L2O algorithms include also:
(1) updates in number of profiles in the L2O datasets
(2) improvements in the calculations of uncertainties in the L2O layer-integrated parameters
(3) changes to the "Depolarization_Quality_Flag"
(4) improvements of the Cloud Aerosol Discrimination (CAD) through the implementation of an additional parameter, namely the "Cloud_350m_Fraction_XXX_FOV", to report of the number of 350 L1B profiles within each 5 km L2O bin of the L2O layer product with attenuated total backscatter values greater than 0.03 $km^{-1}sr^{-1}$, thus atmospheric features of high probability of being a cloud. In addition, the parameter "Num_Profs_Avg_LRatio_XXX_FOV" was added to the L2O Layer data product.
(5) improvements in CATS Feature Type and Feature Type Score variables, but also in the Aerosol Subtype classification (replace of "volcanic" with "UTLS Aerosol") and addition of the parameters "Opaque_Feature_Optical_Depth_1064_XXX_FOV" and "Opaque_Feature_Optical_Depth_Uncertainty_1064_XXX_FOV" in Mode 7.2 L2O datasets.
(6) Updates in the Lidar Ratio (LR) values for cirrus clouds
(7) update of the effective multiple scattering factor for ice clouds values to 0.52.
The above changes in the CATS V3-00 and V3-01 algorithms and the respective products are extensively presented and in-depth discussed in the CATS official website (; last visit on: 22/05/2019), in the "Publications" section.

pages 11 and 12, Section 3.2 and Table 2: It would be interesting to show the mean relative bias (that is bias over mean value).

According to the referee's comment we have computed and included in the table of comparison statistics between CATS and EARLINET the Mean Relative Bias (MRB), calculated as follows:

$$MRB = \left(\frac{1}{n}\sum_{1}^{n}\frac{(b_{CATS} - b_{EAR})}{b_{EAR}}\right) * 100$$

The MRB were found equal to -24.06% and -19.84% for daytime and nighttime CATS observations respectively, and the results were included to the table.

page 14, line 10, Please modify "discrepancies" to "discrepancy".

The text is modified according to the reviewer's recommendation.

page 15, line 1, Please modify "based to" to "based on".

The text is modified according to the reviewer's recommendation.

Figs. 3 to 5: Please use "b) CATS backscatter coefficient at 1064 nm", or "(1064 nm)".

The text is modified according to the reviewer's recommendation.

Fig. 5: I would guess topography influence CATS coefficient quite significantly. Could it be causing the spykes shown in this figure? Could you provide a quantitative estimate of the contributing effect of topography on the discrepancy observed in this figure? What about an estimate of the other contributing effects?

Regarding the question of the reviewer on the discussed constrains on the dataset, Figures 1-4 show quantitatively the effects of (i) distance between the EARLINET station and the closest profile of the CATS-ISS overpass for each correlative case, (ii) CATS Feature Type, (iii) number of CATS Level 2 (L2) Aerosol Profiles (APro) used in the CATS horizontal average, and the effect of (iv) topography of EARLINET stations. The comparison exercise examines the effect of one discussed constrain at a time, while keeping all the other parameters in the methodology constant, and considers various evaluation metrics, as discussed in the following sections.

(i) Effect of distance between the EARLINET station and the closest profile of the CATS-ISS overpass

Figure 1 shows the effect of distance between the closest CATS L2 APro and the respective EARLINET station matchup, for different upper Euclidean distance thresholds (i.e.: 5n km, n∈N={1,10}). To be more specific, the Mean Bias (MB; [$Mm^{-1}sr^{-1}$]) - (Fig.1a), Root Mean Square Error (RMSE; [$Mm^{-1}sr^{-1}$]) - (Fig.1b), Correlation Coefficient (Fig.1c), and the number of CATS-EARLINET correlative cases per each upper distance threshold are considered. For each upper distance threshold, all the available CATS-EARLINET cases of Euclidean distance lower or equal to the respective upper limit are considered in the computation of the aforementioned evaluation metrics. This cumulative approach is selected due to the limited number of CATS-EARLINET correlative cases, and is applied separately for daytime and nighttime ISS overpasses, due to the different CATS measurement conditions.
Based on the analysis, during nighttime (daytime), the CATS-EARLINET MB is increasing (decreasing) starting from the 5 km upper distance threshold, to reach -0.0300 (-0.123) $Mm^{-1}sr^{-1}$, for the radius threshold of 50km shown in the study. The computed RMSE values are in the range between 0.447 and 0.343 $Mm^{-1}sr^{-1}$ for nighttime and between 0.357 and 0.448 $Mm^{-1}sr^{-1}$ for daytime, for the distance thresholds of 5km and 50km respectively. The minimum RMSE values are observed when considering ISS overpass cases of closer than 40 km distance to the EARLINET stations during nighttime, corresponding to MB of 0.018 $Mm^{-1}sr^{-1}$. The Correlation Coefficient is decreasing with increasing distance between the ISS overpass and the EARLINET stations. Notably, the Correlation Coefficient is not changing considerably for thresholds between 15 and 40 km for nighttime (~0.8) and between 15 and 30 km for daytime (~ 0.7). Sharp decreases in the Correlation Coefficient are observed during daytime (0.547), for distances closer to the EARLINET stations than during nighttime (0.693), for 35 and 40 km distance respectively. The observed tendencies can be explained in terms of the distance thresholds and number of available cases, since the distance thresholds define the number of cases that are used in the analysis and the number of case is critical to assess the performance of CATS. Consequently, the MB, RMSE and Correlation Coefficient are all subject to both

the number and the characteristics of the CATS-EARLINET cases used. In the study the authors use the maximum number of available EARLINET cases, to avoid any possible selection effect resulting from a poor sample of correlative cases, when strict collocation filters are applied. Using the maximum number of available correlative cases, i.e. twenty six (26) and twenty one (21) for nighttime and daytime respectively, for ISS overpasses within 50km radius from the EARLINET stations, the authors envisage to quantitatively address the question of CATS performance and the representativeness of the aerosol backscatter coefficient profiles, over various atmospheric, illumination and ISS overpass conditions.

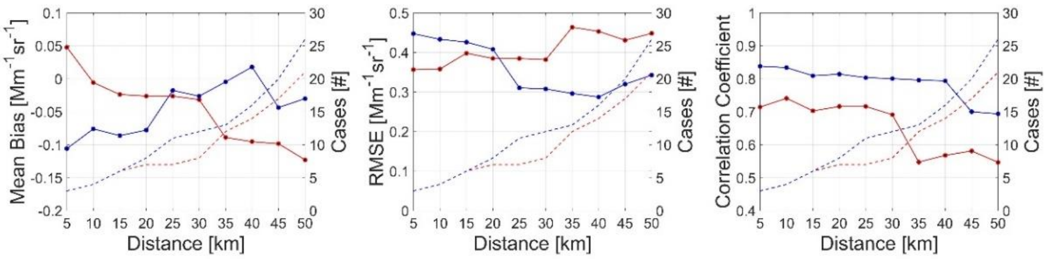

Figure 1: CATS backscatter coefficient at 1064nm with respect to EARLINET ground-based measurements, as a function of distance (km) between the closest CATS Level 2 Aerosol Profile and the respective "collocated" EARLINET station, for daytime (red line) and nighttime (blue line) ISS overpasses. Left: Mean Bias [$Mm^{-1}sr^{-1}$], center: RMSE [$Mm^{-1}sr^{-1}$] and right: Correlation Coefficient. Dashed lines correspond to the number of CATS-EARLINET correlative cases considered per each upper distance threshold between the CATS footprint and the locations of EARLINET stations.

(ii) Effect of Feature Type Score

The main objective of the CATS Cloud Aerosol Discrimination (CAD) score, or Feature Type Score, is to provide to the Feature Type classification a level of confidence. In the case of CATS, the Feature Type score is an integer number ranging between -10 and 10. The values of CATS Feature Type score correspond to classified aerosol atmospheric layers (negative values) and cloud atmospheric layers (positive values), while the magnitude of the Feature Type score corresponds to the confidence level of the classification. A value of -10 indicates complete confidence that the layer is an aerosol layer, while Feature Type score equal to 0, indicates an atmospherics layer with equal probability to be cloud or aerosol.

Figure 2 shows the effect of Feature Type Score, for different values, between -8 and 0 (i.e. for atmospheric layers classified as aerosol layers). The Mean Bias (MB; [$Mm^{-1}sr^{-1}$]) - (Fig.2a), Root Mean Square Error (RMSE; [$Mm^{-1}sr^{-1}$]) - (Fig.2b) and Correlation Coefficient (Fig.2c) are shown per each Feature Type Score. For each Feature Type score, cases of lower classification confidence level are not considered in the assessment of CATS performance and representativity, indicating the effect of the selected Feature Type thresholds.

Based on the MB, RMSE and Correlation Coefficient, a similar tendency is observed for different Feature Type Scores. To be more specific, not considerable changes are observed for different Feature Type Scores, regardless of the selected Feature Type threshold. This effect is due to the atmospheric characteristics of the CATS-EARLINET cases considered in the analysis. In the framework of the study, to account for contamination effects of multiple-scattering and specular reflection in the intercomparison process, only cloud-free atmospheric scenes are used. Furthermore, cases with detected cirrus, either at the EARLINET Range-Corrected-Signal quicklooks or at the ISS-CATS backscatter coefficient profiles or the feature type profiles, are not considered in the study. Initially, the presence of clouds was 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 was not feasible due to the presence of clouds, and/or CATS cases that the presence of clouds propagated into the CATS spatial-averaged profile were discarded from the analysis. Consequently, the lack of dependence shown in Figure 2 (a-c) is the result from the a priory selection of cloud free conditions selected in the analysis. However, a notably characteristic is the nighttime performance of CATS, which as shown from the lower absolute MB and lower RMSE, but in addition from the higher Correlation Coefficient values, due to higher SNR, is more representative than the corresponding daytime performance.

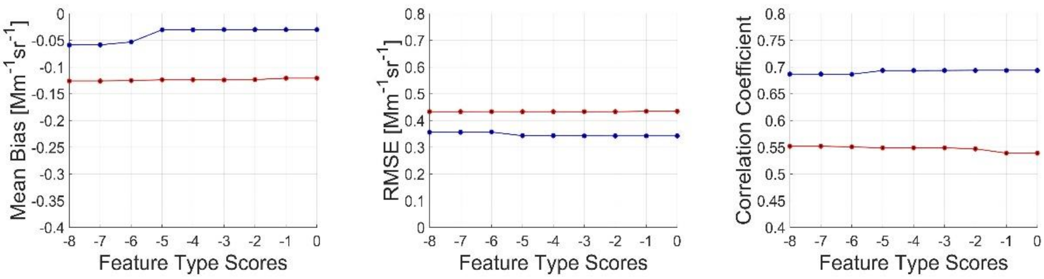

Figure 2: CATS backscatter coefficient at 1064nm with respect to EARLINET ground-based measurements, as a function of Feature Type score, for daytime (red line) and nighttime (blue line) ISS overpasses. Left: Mean Bias [$Mm^{-1}sr^{-1}$], center: RMSE [$Mm^{-1}sr^{-1}$] and right: Correlation Coefficient.

(iii) Effect of number of CATS-ISS L2 aerosol profiles used in the spatial averaging

Similarly to the analysis presented and discussed above, Figure 3 shows the effect of different number of aerosol profiles used when spatially averaging to retrieve the CATS aerosol profiles used in the framework of the study. In Figure 3, the acronym "CPro" corresponds to the closest CATS profiles to the corresponding EARLINET station. Accordingly, the Mean Bias (MB; [$Mm^{-1}sr^{-1}$]) - (Fig.3a), Root Mean Square Error (RMSE; [$Mm^{-1}sr^{-1}$]) - (Fig.3b), Correlation Coefficient (Fig.3c), are computed for different number of profiles used (i.e. CPro±1Profile, CPro±2Profiles, …).

Based on the MB, RMSE and Correlation Coefficient, the representativeness of CATS spatial profile is increasing with increasing number of aerosol profiles used in the horizontal averaging. To be more specific nighttime MB is almost constant, showing a low dependence on the number of profiles used, while for daytime CATS cases the opposite effect is observed, with improvement of CATS performance though increasing number of profiles used. Regarding RMSE no significant changes are observed, though a slight decreasing tendency in the RMSE is observed for both daytime and nighttime cases. Regarding the Correlation Coefficient, increasing in the values is also observed, with increasing number of profiles used, both for daytime and nighttime cases, denoting the improvement of the representativeness with increasing number of CATS profiles used in the spatial averaging.

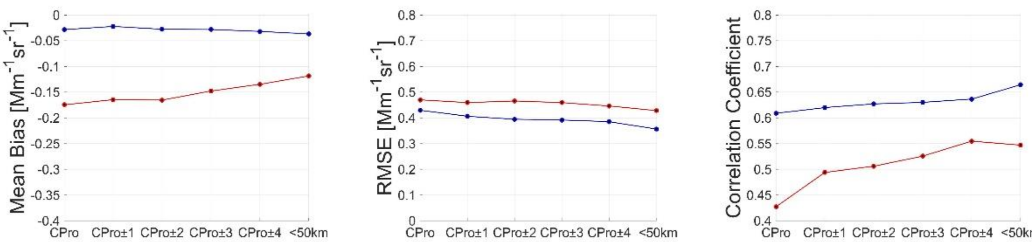

Figure 3: CATS backscatter coefficient at 1064nm with respect to EARLINET ground-based measurements, as a function of the number of L2 Aerosol Profiles used in the CATS spatial averaging, for daytime (red line) and nighttime (blue line) ISS overpasses. Left: Mean Bias [$Mm^{-1}sr^{-1}$], center: RMSE [$Mm^{-1}sr^{-1}$] and right: Correlation Coefficient. "CPro" corresponds to the closest CATS profile to the EARLINET station.

(iv) Effect of EARLINET stations topography

In order to study the effect of topography on the CATS profiles the authors separated the participating EARLINET stations into 3 clusters: Continental (Case I – Belsk, Bucharest, Leipzig, and Warsaw), Coastal (Case II – NOA, Athens NTUA, Barcelona, Cabauw, Thessaloniki and Lecce) and Mountainous (Case III – Dushanbe, Evora, Observatory Hohenpeissenberg, Potenza). The three clusters and the characteristics of the stations are given in Table 1. In addition, Figure 4 shows the locations of the participating stations; green circles denote Continental stations, blue circles denote Coastal stations and brown circles denote Mountainous stations. Figure 4 shows, additionally to the geographical distribution of the active EARLINET stations, the daytime/nighttime overpasses of ISS within the evaluation period, between 02/2015 and 09/2016, encompassing the first twenty months of CATS operation. Due to the limited available dataset of CATS-EARLINET cases, the daytime/nighttime approach was not followed in the case of the analysis regarding the effect of topography.

Table 1: Clustering of EARLINET stations with respect to topographical features.

Case I - Continental

EARLINET Station	Identification Code	Latitude (°N)	Longitude (°E)	Altitude a.s.l. (m)
Belsk	be	51.83	20.78	180
Bucharest	bu	44.35	26.03	93
Leipzig	le	51.35	12.43	90
Warsaw	wa	52.21	20.98	112

Case II - Coastal

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
Cabauw	ca	51.97	4.93	0
Thessaloniki	th	40.63	22.95	50
Lecce	lc	40.33	18.10	30

Case III - Mountainous

EARLINET Station	Identification Code	Latitude (°N)	Longitude (°E)	Altitude a.s.l. (m)
Dushanbe	du	38.56	68.86	864
Évora	ev	38.57	-7.91	293
Observatory Hohenpeissenberg	oh	47.8	11.01	974
Potenza	po	40.60	15.72	760

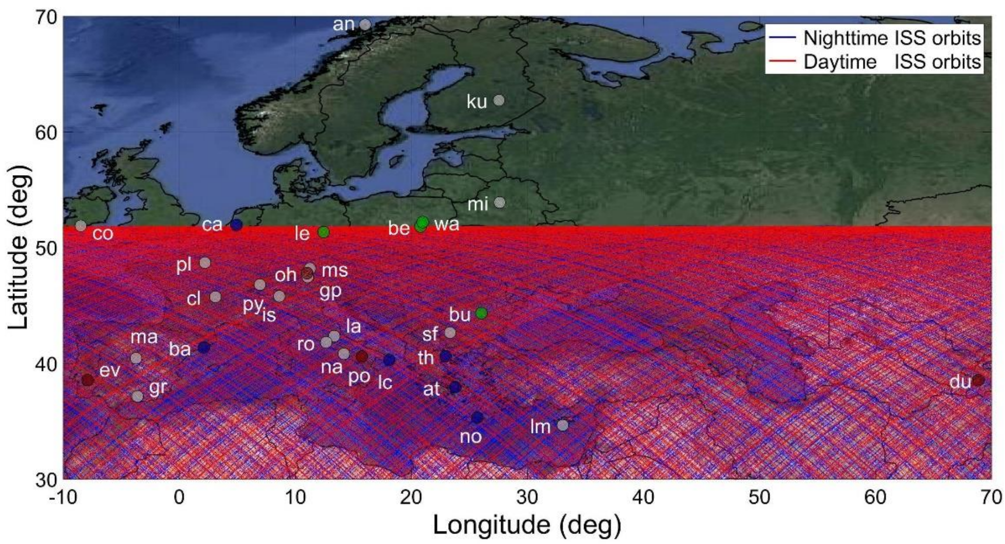

Figure 4: Distribution of EARLINET lidar stations over Europe and West Asia. Green dots: Continental stations used in the inter-comparison. Blue dots: Coastal stations used in the inter-comparison. Brown dots: Mountainous stations used in the inter-comparison. ISS orbits between 02/2015 and 09/2016 are overlaid in red for daytime and in blue for nighttime overpasses.

Figure 5 shows the effect of Topography, for three different clusters of station characteristics, as introduced above (Case I: Continental, Case II: Coastal and Case III: Mountainous). In Figure 5a, the Box and Whisker plot on the $CATS_i$-$EARLINET_i$ residuals is shown, including the lower and upper whiskers which indicate the 10^{th} and 90^{th} percentiles respectively, and the 25^{th} and the 75^{th} quantiles indicated by the lower and upper box boundaries respectively. The horizontal line and the red dot indicate the statistical mean and median values respectively while outliers are indicated by red crosses. According to the results, it is evident that the correlative measurements between the Mountainous EARLINET stations and the ISS overpasses are characterized by higher variability, more extreme differences, higher absolute mean and median biases and higher RMSE than in the Continental and Maritime cases. 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 between the CATS lidar footprint and the ground-based lidar stations and surface returns enhance the discrepancies, especially in the lowermost part of the profiles, resulting in higher differences between the EARLINET profiles and CATS profiles. Due to the lack of the aforementioned effects arising from complex topography, CATS representativeness and performance is higher over the Continental cases, while CATS performance over the Coastal stations is characterized by slightly lower absolute value of mean bias and at the same time by lower Correlation Coefficient than in the case of Continental cases. However, it has to be taken into consideration the important factor related to the presented resultsm that is the number of CATS-EARLIENT correlative cases used in the analysis, 23 for Case I - Continental, 10 for Case II - Coastal and 14 for Case III - Mountainous. Analytical evaluation metrics on the effect of topography are given in Table 2.

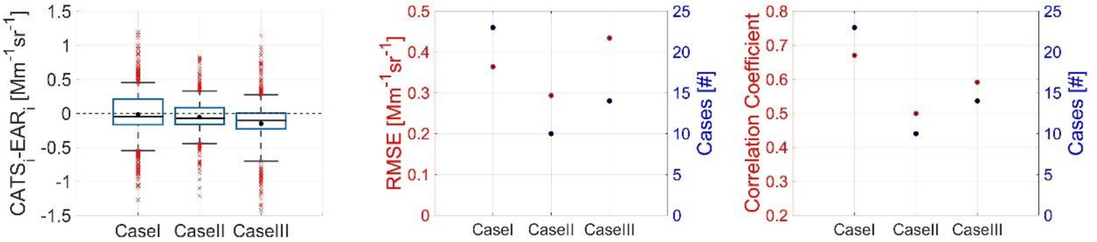

Figure 5: CATS backscatter coefficient at 1064nm with respect to EARLINET ground-based measurements, as a function of different topography of EARLINET stations for three different clusters of station topographical characteristics (Case I: Continental, Case II: Coastal and Case III: Mountainous). In Fig.5a, the Box and Whisker plot on the $CATS_i$-$EARLINET_i$ residuals is shown, including the lower and upper whiskers which indicate the 10^{th} and 90^{th} percentiles respectively, and the 25^{th} and the 75^{th} quantiles indicated by the lower and upper box boundaries respectively. The horizontal line and the red dot indicate the statistical mean and median values respectively while outliers are indicated by red crosses. Fig.5b and Fig.5c show the RMSE and Correlation Coefficient as a function of the different clusters, including the number of available cases per cluster.

Table 2: Clusters of EARLINET stations and CATS evaluation metrics.

	Continental stations	Coastal stations	Mountainous stations
Median	-0.053 [$Mm^{-1}sr^{-1}$]	-0.076 [$Mm^{-1}sr^{-1}$]	-0.106 [$Mm^{-1}sr^{-1}$]
Mean	-0.016 [$Mm^{-1}sr^{-1}$]	-0.058 [$Mm^{-1}sr^{-1}$]	-0.151[$Mm^{-1}sr^{-1}$]
RMSE	0.367 [$Mm^{-1}sr^{-1}$]	0.293 [$Mm^{-1}sr^{-1}$]	0.434 [$Mm^{-1}sr^{-1}$]
Correlation Coefficient	0.673	0.499	0.591
Number of cases	23	10	14