Performance of the laser transmitters and receiver signal evolution during the Aeolus mission from 2018 to 2023

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Abstract: The wind mission Aeolus of the European Space Agency was a seminal achievement in Earth observation and space laser technology. During its nearly five-year lifetime, the space-borne Doppler wind lidar instrument ALADIN onboard the Aeolus satellite employed two switchable ultraviolet laser transmitters to measure atmospheric wind profiles with global coverage, contributing to improving the accuracy of numerical weather prediction. Despite the excellent performance of the nominal and redundant laser which was optimized during the mission through thermal adjustments, the atmospheric return signal levels declined between 2019 and 2022 due to decreasing transmission of the optics between the redundant laser and the telescope. The root cause analysis of the signal loss was supported by the Pierre Auger Observatory in Argentina whose fluorescence detector registered the ultraviolet laser pulses emitted from the instrument in space, thereby offering an independent measurement of the laser energy.

1. Introduction

The European Space Agency's (ESA) Aeolus mission was launched on August 22, 2018, and pioneered global wind profile monitoring through its single payload – the Atmospheric Laser Doppler Instrument (ALADIN) – the world’s first Doppler wind lidar in space. The mission concluded successfully on April 30, 2023, exceeding its planned mission lifetime by 18 months, before the satellite reentered the Earth's atmosphere on July 28, 2023. Initially considered a technology demonstrator, Aeolus’ wind observations evolved to an integral part of several numerical weather prediction (NWP) models worldwide, including those of major weather services like the German Weather Service, Météo France, and the European Centre for Medium-Range Weather Forecasts. Moreover, the wind observations have become relevant for a variety of scientific studies, such as examining global-scale tropical waves or analyzing dynamical events in the stratosphere.

Key part of ALADIN was the single-frequency, ultraviolet (UV) laser that emitted nanosecond pulses in the atmosphere. Over the last three decades, different types of space-borne lidars were deployed (LITE, GLAS, CALIOP, ATLAS, CATS, ACDL, etc.) with most of them using lasers emitting in the visible and/or infrared spectral regions. Major challenges for the operation of UV lasers in space have been the development of UV-resistant optics with high laser-induced damage (LID) threshold and the mitigation of laser-induced contamination (LIC) in vacuum, where organic materials within the instrument interact with the UV laser, forming highly absorbing deposits on optics. These challenges were successfully overcome during the implementation of ALADIN through extensive test campaigns to identify suitable high-power laser optics with reliable coatings, and by developing an in-situ cleaning system (ICS) to maintain an ultra-clean environment with low-pressure molecular oxygen inside the laser and the instrument emit path.

2. ALADIN design

ALADIN was equipped with two fully redundant laser transmitters, denoted as flight models (FM) A and B, which were switchable by means of a flip-flop mechanism (FFM). Both transmitters were realized as diode-pumped Nd:YAG lasers in master oscillator power amplifier configuration that were frequency-tripled to 354.8 nm emission wavelength [1,2]. In the first stage of the laser, the narrowband seed radiation generated from a non-planar Nd:YAG ring laser was fiber-coupled into the folded cavity of the ~80 cm long Q-switched master oscillator (MO). Active stabilization of the MO cavity length was achieved via a piezo actuator and a ramp-hold-fire technique to ensure single mode operation for each laser pulse. The output pulses from the MO were then amplified in a two-stage amplifier, comprising pre-amplifier (PreAMP) and power amplifier (AMP), both realized by side-pumped and conductively-cooled Nd:YAG zigzag slabs. The amplified IR beam (≈250 mJ) then passed through a harmonic generation stage to produce UV output pulses with a conversion efficiency of approximately 30%, yielding pulse energies in excess of 60 mJ. The main parameters of the two ALADIN lasers obtained in-orbit are summarized in Table 1.

The UV pulses from one of two switchable laser transmitters passed through transmit-receive optics (TRO), expanding the beam diameter from 6.2 mm to about 21 mm by means of a beam expander. A small portion (0.5%) of the beam, separated within the TRO, served as the internal reference path signal for frequency determination and calibration of the receiver spectrometers. The main laser output was further expanded to 0.9 m and transmitted into the atmosphere by a 1.5 m-diameter telescope, which also collected the atmospheric return signal. The laser divergence ranged from 18 to 20 µrad, encompassing 86% of the energy, resulting in a footprint on the Earth's surface of about 8 m. Both the internal (INT) and the atmospheric (ATM) signal were guided through a field stop with a diameter of 88 µm before being incident onto the receiver spectrometers. While the broadband backscatter return signals from molecules were analyzed by the Rayleigh channel, the narrowband backscatter from particles like clouds and aerosols was detected by the Mie channel to determine the Doppler frequency shift, and hence the wind speed.

Table 1. Selected in-orbit parameters of the two ALADIN laser transmitters.

Parameter	**Value**
Type	Frequency-tripled Nd:YAG
Cooling	Conductively via cold plate
Laser wavelength	354.8 nm (vacuum)
Pulse repetition rate	50.5 Hz
Pulse energy	FM-A: 40 to 70 mJ; FM-B: 60 to 100 mJ (182 mJ over 1 day)
Frequency stability (rms over 540 pulses)	< 12 MHz (< 7 MHz at optimized cavity control setting)
Beam diameter	< 6.2 mm
Beam divergence (full angle)	< 600 µrad
Operation time in space	FM-A: 15 months; FM-B: 41 months
Total number of laser pulses	FM-A: 1.9 Gshots; FM-B: 5.3 Gshots

3. Laser performance

Soon after the beginning of laser operation in space in September 2018, a decreasing trend in the first flight model laser (FM-A) energies was observed from internal photodiodes placed at different stages inside the laser. The UV energy dropped by about -1 mJ/week to only 41 mJ by June 2019, leading to the decision to switch to the second flight laser (FM-B) which, from on-ground tests, was known to be the better performing laser. The switch between the two lasers was realized by the FFM and the relay optics to direct FM-B onto the emit path of ALADIN, initially reserved for FM-A.

FM-B exhibited higher energy (67 mJ) and a much slower decrease rate than FM-A (Fig. 1). However, similar to FM-A, the energy of FM-B was found to be very sensitive to temperature changes of the laser bench’s cold-plate (CP), which housed all active laser components (MO, PreAMP, AMP), and to the commanded laser frequency. Tackling the temperature sensitivity and its relationship to laser frequency offered a method to enhance and stabilize the laser performance of FM-B. By optimizing the temperature and frequency conditions, the UV energy decrease rate was limited to the expected ageing (mainly pump diode degradation) of about -25% over 3 years of operation.

4. Instrument signal evolution

Over the course of FM-B operations, the INT and ATM path signal levels from the Rayleigh channel decreased by more than 70% between the switchover in June 2019 and October 2022. Consequently, in order to compensate for the signal loss, the laser energy was increased several times up to more than 100 mJ, mostly by increasing the amplifier pump currents and/or by reducing the delay between the MO pulse emission and the amplifier pumping phase while shortening the MO Q-switch duration (enhanced population inversion of the active material). Moreover, the alignment of the FM-B laser beam with the instrument reception path, which was worse compared to that of the FM-A, was optimized by multiple laser adjustments where the heating currents of the PreAMP and AMP were oppositely changed ("unbalancing") which, to some extent, allowed to steer the laser beam along the horizontal axis. However, this procedure affected the CP temperatures, especially since the MO arrangement was located between the two amplifier blocks on the laser bench, thus necessitating subsequent CP temperature adjustments to maximize the laser energy at the given laser frequency.

Due to the persistent signal loss on the emit path behind the laser output, it was decided to switch back to the FM-A laser in November 2022. Despite the lower output energy compared to FM-B at the end of its operation (101 mJ), the switchover increased the atmospheric signal by a factor of 2.2, suggesting that the loss occurred along the optical path that is unique to FM-B, most likely within the relay optics including the FFM. Based on the knowledge gained during the FM-B period, particularly with regard to the interplay of cold-plate temperatures, frequency and laser energy, the FM-A laser performance was successfully optimized according to the procedures developed in the preceding years. This approach resulted in a stable performance of FM-A at around 50 mJ until the end of the operational mission on April 30, 2023.

The successful optimization of the FM-A laser demonstrated that both UV transmitters were capable of delivering remarkably stable energy output when being operated at their respective working points optimized in-orbit. Moreover, both lasers showed excellent frequency stability of <7 MHz (rms over 540 pulses) despite the detrimental impact of micro-vibrations introduced by the satellite's reaction wheels [3].

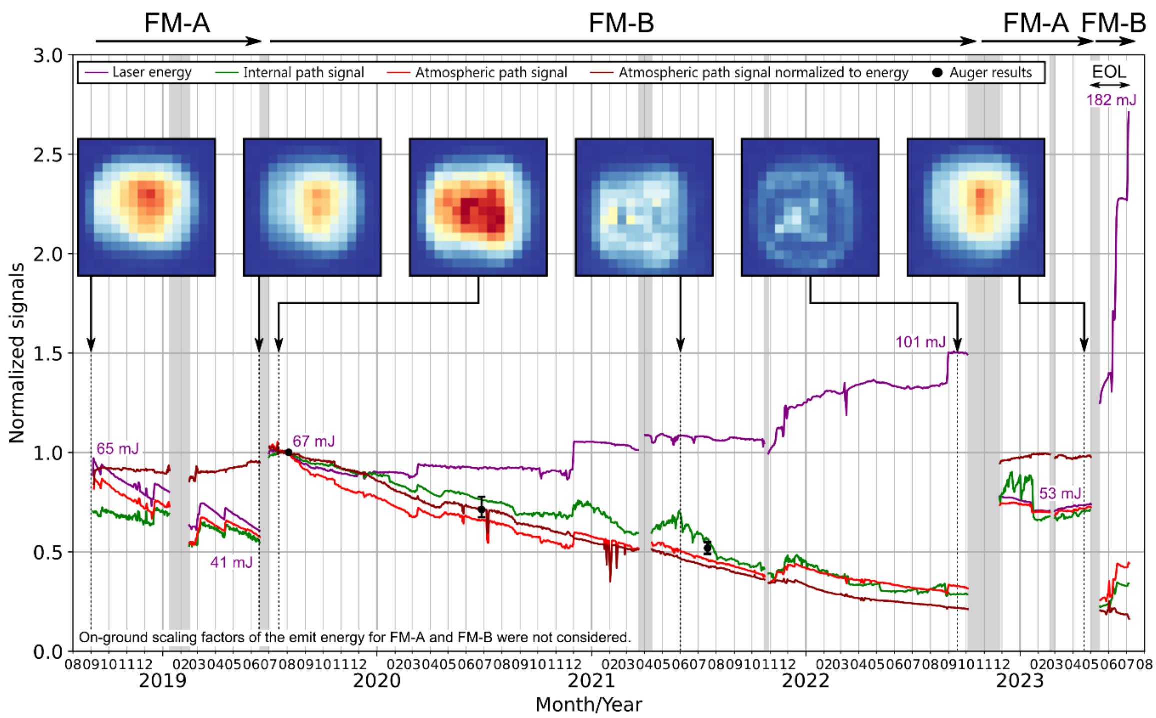

Figure 1. Timeline of the ALADIN signal levels measured at different locations in the instrument over the Aeolus mission period (energy from the laser-internal photodiode). The signal levels are normalized to the respective value from July 26, 2019. Periods when the instrument was temporarily switched off are indicated by grey-shaded areas. The energy measurements from the Pierre Auger Observatory (black dots) are normalized to the value from August 3, 2019 with the error bars indicating the statistical error. The insets represent laser beam monitoring images derived from internal path data of the Mie channel.

5. Ground measurements at the Pierre Auger Observatory

The Pierre Auger Observatory in Argentina detects ultra-high energy cosmic radiation in the Earth's atmosphere using, amongst other techniques, fluorescence detection in the wavelength range between 280 nm and 430 nm. The observatory was hence capable to detect the ALADIN laser beam at times when Aeolus passed the observatory whose four fluorescence detector sites cover an area of around 3000 km², albeit accurate geometric reconstruction of the beam was limited to certain conditions during southern-hemisphere winters.

Precise modelling of the scattering of molecules and aerosols as well as of the optical losses along the path through the atmosphere made it possible to determine the laser energy at the exit of the instrument in space during the FM-B period. As shown by the black dots with error bars in Fig. 1, the Auger measurements confirmed that the signal loss observed between 2019 and 2021 already occurred on the emit path between the laser output and the telescope, thereby driving the efforts to switch back to the FM-A laser. The fact that the energy decrease observed by Auger in 2020 (-28%) and 2021 (-48%) with respect to mid-2019 was smaller than the loss on the detector (-34% and -53%), points to an additional loss mechanism on the receive path, most likely clipping of the return signal on the instrument field stop [4].

6. End-of-life laser activities

Following the end of nominal operations of ALADIN on April 30, 2023, a series of special tests, referred to as end-of-life (EOL) activities, was performed between May and July 2023 to address a number of instrument-related and scientific questions. After a final switchover to the more powerful FM-B laser in mid-May 2023, its output energy was successively increased by boosting the MO and amplifier pump currents, by reducing the amplifier phasings and Q-switch duration as well as by optimizing the heating currents while adapting the CP temperatures, as described above. During its final 33.3 hours before the planned final switch-off on July 5, 2023, the FM-B laser delivered more than 182 mJ of output energy (Fig. 1) without any sign of degradation inside the laser which set a new record for a UV laser ever operated in space.

7. Summary and outlook

The two UV lasers onboard Aeolus operated over 15 and 41 months, respectively, together producing more than 7 billion laser pulses. The successful operation and optimization of both transmitters during the mission ensured a sufficiently high signal-to-noise ratio of the backscatter return and, hence, an acceptable random error of the wind observations to provide positive impact on NWP models. Furthermore, it was demonstrated that high-power UV lasers can be operated in space for multiple years without significant degradation. This signifies a remarkable advancement in the field of space laser technology and holds considerable implications for missions deploying similar UV laser transmitters like EarthCARE, to be launched in May 2024, as well as for Aeolus-2, anticipated in the 2030s.

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9. References

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