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ABSTRACT

First atmospheric measurements with a diode pumped alexandrite ring laser in a ground-based general-purpose Doppler lidar demonstrates high-resolution spectral measurements with minimum hardware requirements. Two decades of Doppler measurements by flash lamp pumped alexandrite ring laser within the worldwide only existing mobile Doppler resonance lidar have shown the capability of such scanning lidar to measure any spectrum from the troposphere to the thermosphere without a frequency reference at the wavelength of desire. An improved second-generation system with a size of 1 m³, including a 50 cm telescope, is currently under development for ground-based automatic observations at harsh environments, such as Antarctica. Minimizing the size, complexity, maintenance time and improving the optical setup pave the way of this technology for future space missions. As an example for a possible future space mission, we discuss a mesospheric potassium resonance Doppler lidar by extrapolating the signal from ground-based measurements.

Keywords: tunable laser, alexandrite, diode-pumped, Doppler-lidar, Faraday filter, frequency reference

1. INTRODUCTION

For more than two decades, flash lamp pumped alexandrite ring laser has performed spectral measurements at different wavelength such as sodium (589 nm), potassium (770 nm) and iron (386 nm). The first ever build alexandrite ring laser is still in operation within the mobile Doppler resonance lidar of the Institute of atmospheric physics, Kühlungsborn, Germany (IAP). So far, this system is worldwide the only transportable resonance lidar for mesospheric Doppler measurements. Even though since more than 20 years in continuous operation around the world, many technologies, such as reference free Doppler temperature measurements or the patent pending spectrum analyzer or Doppler Rayleigh measurements with Faraday filter, are still unique and not considered by other Doppler lidar. The noncommercial alexandrite ring laser within this system was originally developed especially for Doppler measurements at the sodium line at 589 nm. Since this technology has the disadvantage of two additional nonlinear processes, switching to potassium (770 nm) has the advantage of direct access to the atomic line¹. Nonlinear conversion is not required anymore and the laser operates close to the maximum gain of alexandrite. Doppler temperature measurements in 1996 at the potassium line on board of the ice breaker “MS-Polarstern” in Antarctica² shows, that high resolution Doppler temperature measurements with less than 1 MHz spectral resolution is achieved on a strongly vibrating and moving platform by controlling the cavity length of the ring laser with a ramp&fire technology. A modified delay ramp&fire technology has been overtaken for the breadboard demonstrator of the Aeolus Nd:Yag laser³ for space.

Different to single frequency lidar, a Doppler resonance measurement requires numerous frequencies and tuning the laser from pulse to pulse to obtain temperature and wind. Besides the scanning Doppler lidar of the IAP, 3-frequency lidar measure mesospheric temperature and wind on mathematical idealized ‘single frequencies’, ignoring the variability of the atmosphere and applying a steady state theory in the analysis for a highly variable atmosphere. In contrast, the scanning lidar of the IAP are not limited to a few idealized frequencies and the theoretical concept of scanning treat the atmosphere as time depended target allowing the determination of complete spectra, laser properties and instrumental parameters by the measurements itself. Moreover, the 20-year-old mobile scanning lidar perform Doppler measurements of all kind without the need of a reference frequency at the measured wavelength. Spectral measurements of the concentration and Doppler width (temperature) require only a stable instrument for a given measurement interval.

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Doppler shift (wind) measurements require typically a laboratory reference. A stable scanning lidar, however, can obtain this information from the atmosphere itself, by measuring repeatedly vertical profiles for longer times and a larger altitude range. This technology is already sufficient for horizontal wind measurements since the Doppler shift is much larger compared to vertical winds. Scanning lidar make therefore use of the “vapor reference cell” atmosphere and integrate about tides and gravity waves for an accurate determination of the average atomic line center, which correspond to zero wind condition. This approach does not require any laboratory reference system and has allowed the discovery of the two level mesopause in 1996. We note that the average vertical motion of the atmosphere is in the order of a few mm/s in the mesosphere, corresponding to roughly 10 KHz absolute frequency reference in the determination of the line center. A lidar measuring also vertical, need therefore no laboratory reference for Doppler shift measurements if switching fast enough between various positions in the sky. The analysis later on replaces the reference frequency.

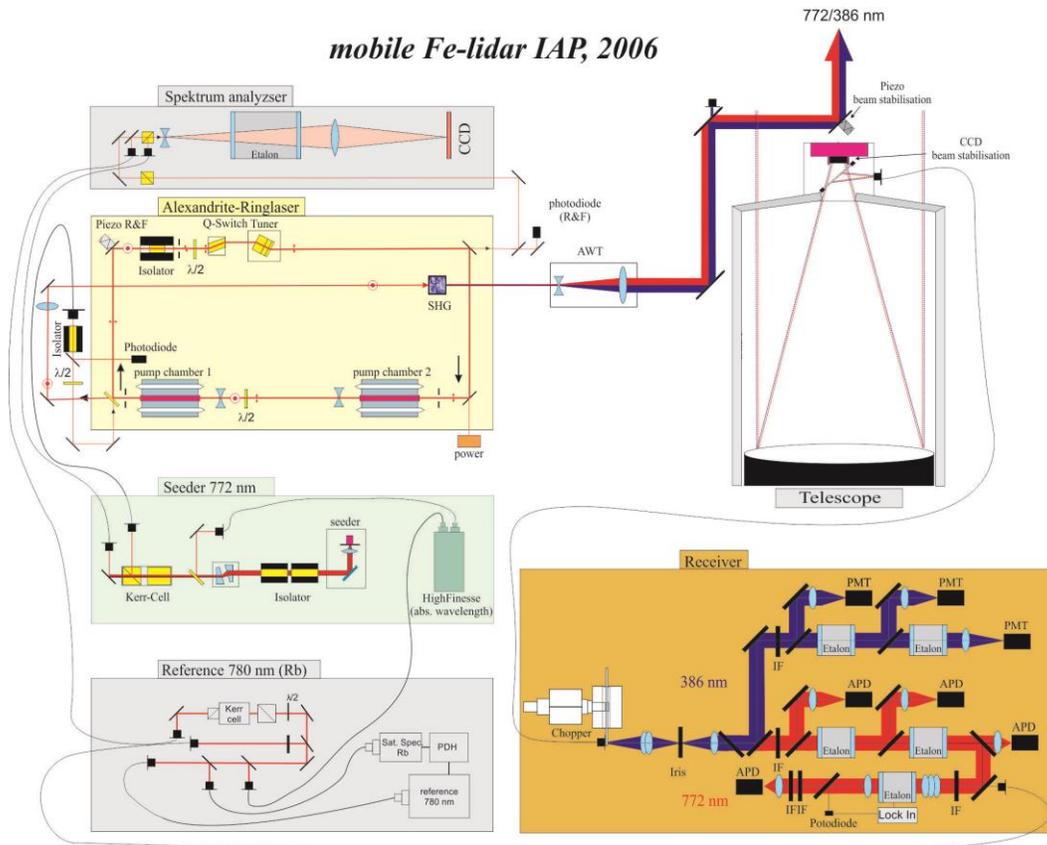


Figure 1. The mobile Fe-lidar of the IAP (2006) for Doppler Aerosol/Rayleigh (772 nm) and Doppler iron (386 nm). Observations at daytime with negligible background are possible due to the unique atomic physics of iron.

By improving the system with an additional laboratory reference, Doppler-wind measurement in the order of a few cm/sec, as required e.g. for tides in the vertical wind, become possible by measuring the frequency of each single laser pulse and compare the measured frequency against a reference at a different wavelength. After many years operating as potassium lidar at 770 nm without reference, the nowadays Fe-lidar⁴ operates at the iron resonance line of 386 nm with a frequency reference at the rubidium line at 780 nm. Figure 1 shows the optical setup of the lidar, which measures altogether two wavelength with 8 channels and 5 interferometers. Different to sodium and potassium nearly background free observation with orders of magnitude lower background at daytime are possible at the iron line. Even though several iron Doppler lidar are under development since many years now, no other iron lidar has achieved routine Doppler measurements so far or has demonstrated the capability for Doppler measurements at challenging daylight conditions. Because of its age, we will replace the lidar within the next few years by a novel, more advanced system, which is currently under development.

2. A GENERAL PURPOSE APPROACH FOR SPACE MISSION

For future space missions, not only the laser technology but also the complete technology required for spectral measurements has to be robust, reliable, compact and highly efficient. For this reason, we tested an early prototype of a diode pumped alexandrite ring laser in a novel lidar, observing aerosols in the stratosphere and potassium in the mesosphere with high spectral resolution⁵. To demonstrate in particular the capability of diode-pumped alexandrite ring lasers, we will show here a tropospheric/stratospheric aerosol and a mesospheric potassium measurement.

The pulsed laser is only the light source of a Doppler lidar. Depending on the wavelength, other lasers like Nd:Yag might be used. Still, fast tuning of the wavelength, obtaining a 'spectrum' on one, several, or many frequencies, narrow band stable filtering in the receiver, or a compact frequency reference system are in most cases required. Changing the wavelength and/or scientific target ends up often in a more or less complete new design of the lidar, with major modifications. The mobile lidar however is a general-purpose approach and not limit to a single wavelength, required number of frequencies, or scientific task. Changing the wavelength still needs replacing some optical components, such as interferometer, interference filter or may be detectors, but the overall approach is completely wavelength independent. Switching between 770 nm (K) and 386 nm (Fe) and back from one day to the next by additionally SHG and adding a channel for 386 nm without changing the ring laser, seeder or reference or any other major subsystem is possible⁶. To our knowledge, no other system has this unique capability. For future space missions, alexandrite ring laser can already address many different wavelengths either directly or by nonlinear conversion to a shorter or longer wavelength. The most straightforward approach from space for the mesosphere is the potassium line at 766 nm, which is to a certain degree blocked in the lower troposphere. For this reason, ground-based potassium lidar operate at the less efficient line at 770 nm. Beside Fe, also Ca⁺, the only ion accessible from ground, requires 393 nm and is accessible by SHG of alexandrite laser. The proposed metastable He⁷ in the thermosphere requires 1083 nm, which is accessible by stimulated Raman emission, or with lower cross section by SHG at 389 nm. Raman shifting the wavelength to 1178 and additional SHG has already reached the sodium line in the past with flash lamped pumped ring laser⁸. Another example of the capability of alexandrite laser is water vapor⁹. Since Rayleigh/Mie scattering is not wavelength depended, it is possible selecting the wavelength in this case for low background (e.g. Fraunhofer line of potassium, 766 nm or 769 nm) or improved eye safety by tuning the laser to a more efficient absorption band in the lower atmosphere. As an advantage compared to Nd:Yag, no SHG is needed to access the visible range. Replacing the laser against other laser technologies may be more efficient or required, but still, spectral filtering, frequency reference, data acquisition and many subsystems are unchanged, reducing the cost for future space missions once developed.

3. A COMPACT DEMONSTRATOR FOR SPACE

As has been demonstrated now over decades by Doppler measurements around the world, scanning lidar can address many scientific fields, including stratospheric, mesospheric aerosols (NLC), meteors in the mesopause region, metals in the mesosphere, thermosphere (topside), gravity waves and tides, temperature and wind. The recently discovered mesopause jump in the southern hemisphere¹⁰, as a response to changes in gravity waves and filtering in the stratosphere and mesosphere, show the robustness of the instrument and the importance of measurements at mesopause altitudes in summer time at polar latitudes for a better understanding of gravity waves and or ice clouds (NLC/PMSE). However, flash lamp pumped laser are not suitable for space and even difficult to handle at remote locations on ground. Additionally, the 20-year-old optical setup above is quite complex and out of date and now superseded by a novel compact approach with less components and electronics in an optimized experimental setup.

In cooperation with the Fraunhofer Institute for laser Technology (ILT), Aachen, Germany, we have developed an early breadboard demonstrator (DALI-1) of a diode pumped alexandrite ring laser with a novel advanced ramp&fire technology as demonstrator for future lidar in space. Figure 2 shows DALI-1, which has been developed within ALISE (diode-pumped Alexandrite Laser Instrument for next generation Satellite-based Earth observation) before integrating into the lidar demonstrator. A second-generation breadboard demonstrator (DALI-2) of higher performance and less complexity will replace the existing laser. A compact and further advanced third generation laser is under construction.

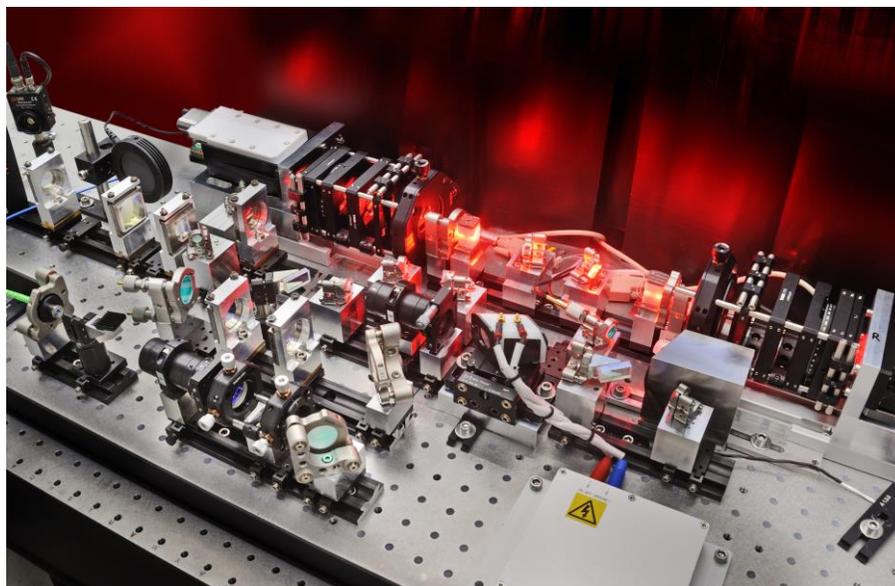


Figure 2. Breadboard demonstrator DALI-1 at the ILT before integrating into the lidar demonstrator at the IAP.

In parallel, the IAP develops already a second-generation, more compact, scanning lidar with a size of 1 m^3 . This system replaces the currently relative large system, which has been developed as a ground based lidar demonstrator within ALISE. Major goals are maintenance free observation at harsh conditions, fast assembling, reduced complexity and an improved optical setup. Similar to the old Fe-lidar, this system will be able to perform Doppler measurements of all kinds at daylight. The 50 cm telescope is part of the housing as well as all other required hardware for remote operation. The design of the system allow daylight measurement with a field of view below $50 \mu\text{rad}$ and spectral filtering in the order of the line width of the laser.

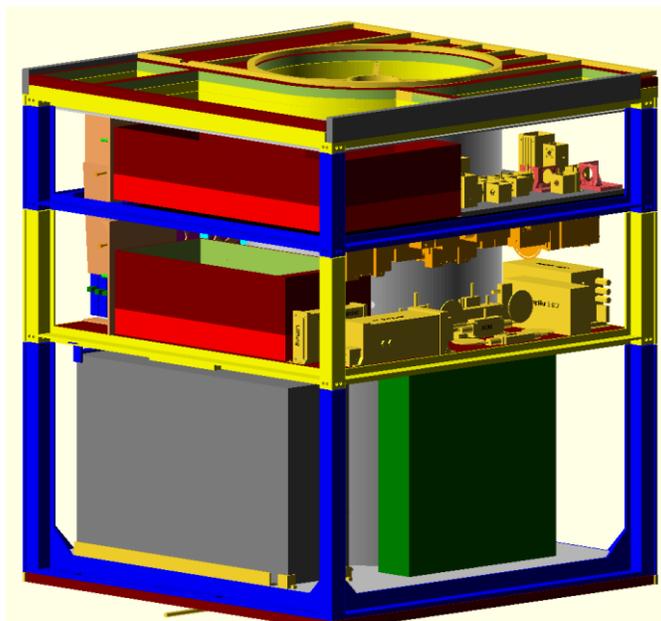


Figure 3. Second-generation mobile Doppler lidar for a third generation compact alexandrite ring laser. The insulated housing of 1 m^3 contains all hardware for automatic operation at extreme cold and harsh condition.

For measurements at daytime, either long-term stable Faraday filter or etalons are used. Besides reducing the background, Faraday filter can simultaneously serve as a frequency reference within the system for wind measurements. A potassium lidar with this technology does not need any conventional reference frequency at all and can additionally perform Doppler Rayleigh measurements with the advantage of low background at day due to the deep Fraunhofer line. More Details of Faraday filter are given by¹¹.

To demonstrate the capability of diode pumped alexandrite ring laser for Doppler aerosol observation, we show in Figure 4 an aerosol measurement at cloudy conditions at the potassium line. The black channel is the signal behind the Faraday filter and serves only as a reference signal for the blue channel here. A cloud at ~10 km altitude increases the signal by one order of magnitude but the remaining Rayleigh/Mie signal above the cloud is still traceable up to ~25 km altitude. During such conditions, the background at day rises by roughly one order of magnitude compared to clear sky and the remaining noise after subtracting the mean background is visible at the upper part in this channel. The blue channel is the signal behind a confocal etalon (CFE) with 7 MHz FWHM only. The frequency of the alexandrite laser is set to the peak of the CFE. Due to the narrow line width of the pulsed laser in the order of 5 MHz FWHM, the backscattered Mie signal from the clouds passes through the filter, whereas the Rayleigh signal is efficiency blocked by the CFE. The Mie signal therefore increases compared to the Rayleigh signal and the signal of the cloud stands out more clearly from the largely reduced Rayleigh background. We note that the weak signal above the cloud up to 20 km altitude is also given by Mie scattering and therefore aerosols. Only a few photons from noise are visible at higher altitudes. The CFE allows background free Doppler aerosol observations at full daylight, only limited by the dark counts of the detector (~20 Hz). We give more details about Doppler Mie measurements with this technology in a future publication.

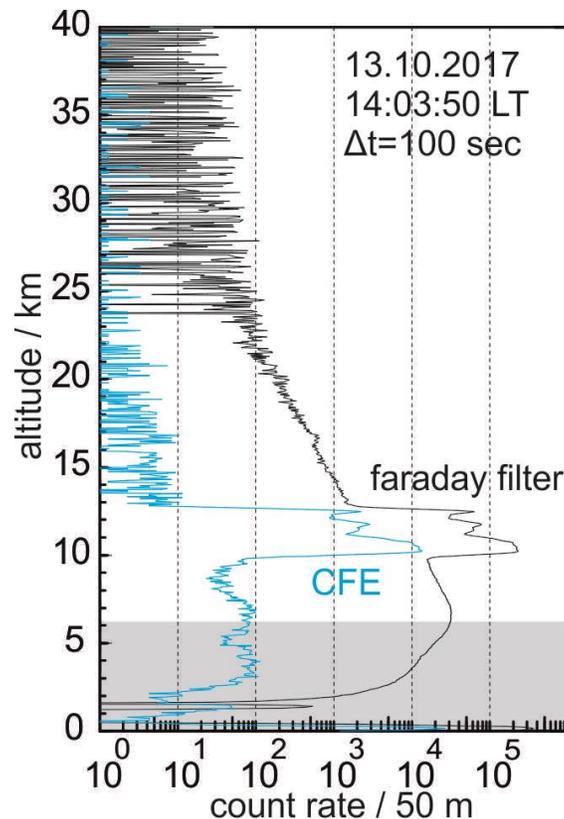


Figure 4. Aerosol measurement at cloudy condition with the breadboard demonstrator of ALISE (DALI-1). Black: Typical Rayleigh signal behind a Faraday filter at daytime. Blue: Signal behind a confocal etalon enhancing Mie scattering compared to Rayleigh scattering.

4. A POSSIBLE FUTURE MESOSPHERIC SPACE MISSION

As an example for a possible future space mission, we focus now on the mesosphere. Compared to iron and sodium, a potassium Doppler lidar is straightforward without the complex laser technology needed for nowadays sodium lidar. Iron still has the disadvantage of additional SHG and fast degrading of optics due to a UV wavelength. Both, Fe and Na require finally SHG of the pulsed laser. A general disadvantage of Na and Fe is therefore also the lack of a reference at the seeder wavelength. Potassium is an elegant and highly efficient alternative, avoiding complex optical setups with a laser system operating close to maximum gain at the required wavelength. As frequency reference, potassium saturation spectroscopy is straightforward, similar to the well-known rubidium saturation spectroscopy. However, as discussed before, rubidium saturation spectroscopy or a Faraday filter is also a possible solution.

We can derive a realistic estimation of the signal strength from space by extrapolating ground-based observations of the former mobile potassium lidar of the IAP. For comparison, Figure 5 shows on the left side a potassium measurement with DALI-1, operating at ~0.15 W in a preliminary, not optimized optical setup. With 60 cm telescope and a Faraday filter, the setup is similar to the former potassium lidar, except we observed only half of the resonance signal at one polarization. The laser was operating for 47 min at the center frequency of the atomic line. The right side shows the signal of a Doppler temperatures measurement at Spitsbergen, 78° N in 2001, with the flash lamped ring laser operating at approx. 4 W with 80 cm telescope and Double Faraday filter. For Doppler measurements, we tuned the frequency from pulse to pulse about the atomic line. The shown integrated resonance signal represents therefore a reduced average signal about all frequencies for 102 sec.

With this setup, first Doppler temperature measurements within summer time at a polar region show exceptional low temperatures in summer¹² and mesospheric clouds (NLC), observable roughly 70% of the time. The signal of the strong NLC in this example is 80 photons/sec/200 m and therefore sufficient to detect such an ice cloud in less than one second in the mesosphere. The signal from the potassium layer is lower and suffer from strong saturation due to the small field of view required for daylight observations from ground. Still, we obtain 10 photons/sec/200 m, even though we scan the atomic line observing a reduced signal. Because of the high pulse energy of the flash lamped pumped laser, we cannot measure any signal below about 45 km altitude since the detector is saturated. A mechanical chopper avoiding nonlinear response of the signal at higher altitudes by blocking the signal below about 45 km altitude.

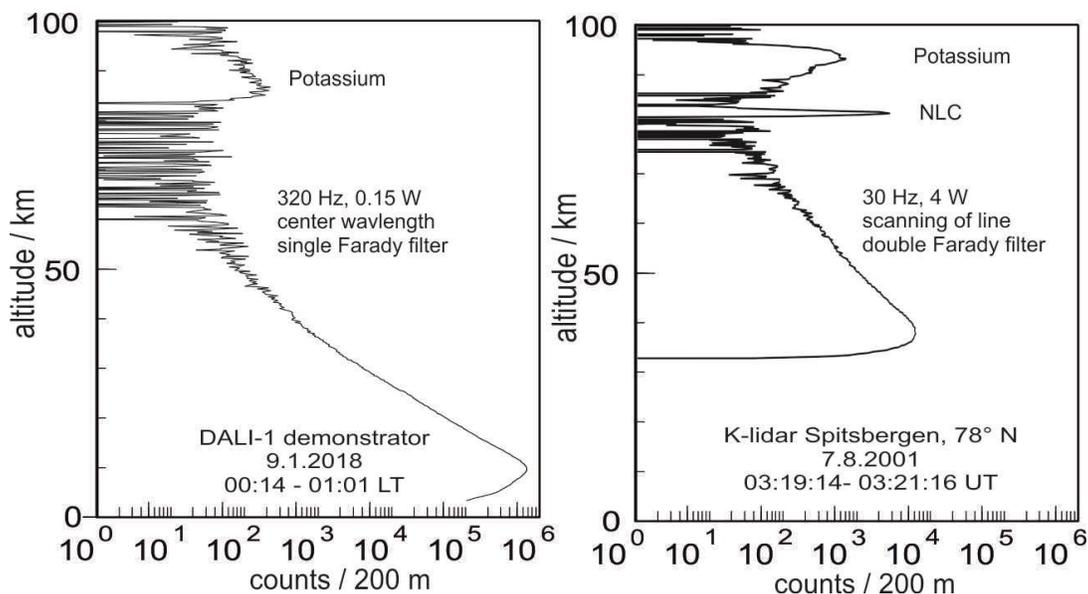


Figure 5: Left side: Demonstration of a mesospheric measurement with DALI-1. Right side: Potassium layer and NLC at daytime in 2001 with a flash lamped pumped alexandrite ring laser, scanning the atomic line for Doppler temperatures.

From space, a three time's larger signal from potassium avoiding saturation is measured. The transmission through the lower atmosphere for ground-based observations at clear sky is ~ 0.78 . From space 766 nm is accessible with approx. twice the backscatter coefficient. By replacing the 20-year-old optics with a better interference filter, polarizers and a high transmission Faraday filter, the signal gain by 1.5. With these improvements alone, the signal from the potassium layer increases altogether by more than one magnitude. Since the distance from ground is ~ 90 km, we can expect the potassium signal shown above at the right side for a satellite with similar parameters at three-four times larger distance, or roughly 400 km altitude. At such a distance, the NLC is still detectable with \sim six times reduced signal within a second. The overall capability for Rayleigh, Mie and resonance measurements is finally given by the field of view of the system, spectral filtering (background) and orbit parameters and can therefore only be calculated more accurate for a given space mission and laser parameter. Depending on the required laser performance, a optimized single crystal ring laser similar to DALI-2 may achieve already all requirements without even additional amplification stage and therefore increased complexity. We give details of DALI-2 in a separate conference paper.

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