Differential Absorption LiDAR for NASA Ozone Mapping

ABSTRACT

Knowing how much and where ozone is in our atmosphere is important to daily life on Earth. Ozone present in the stratosphere is critical to protecting life from harmful radiation, but ozone in the troposphere is detrimental. NASA has created a network specifically tasked with measuring and mapping the ozone in the troposphere. This will allow researchers to analyze potential dangers with ozone levels and propose solutions to these problems. Bridger Photonics has developed a Differential Absorption LiDAR (DIAL) system for this network to measure ozone concentrations in an altitude range of 5 - 8 km in a compact, easy-to-use, and commercially available device. With final ultraviolet wavelength energies of 200 µJ (at 1 kHz repetition rate), Bridger Photonics has designed a high power output, low power consumption, and fast repetition rate solution to ozone concentration measurement.

OZONE BACKGROUND

Ozone in the atmosphere is a critical component to healthy life on earth. Ozone is a colorless gas consisting of three oxygen atoms in each molecule. The ozone shields the earth from harmful ultraviolet (UV) radiation from the sun. It absorbs up to 99% of the sun's UV light. Without the ozone layer, incidences of skin cancer and lung damage would increase, and it would be difficult for plants to live and grow. All of the UV-c radiation is absorbed by ozone, most of the UV-b is absorbed, and almost half of the UV-a radiation from the sun is blocked by the ozone layer.

Ozone is only helpful for blocking the damaging UV radiation from the sun when it is in the stratosphere. When ozone is in the troposphere (below the stratosphere), it can be harmful to life because it reacts with atoms in living things.

Human-produced emissions can have damaging effects on the ozone layer. Chlorine and bromine can react with the ozone layer and start to destroy it. Gases such as chlorofluorocarbons (by-products of human living) reduce ozone in the stratosphere and increase concentrations in the troposphere. The thickness of the ozone layer varies by location and by season. The "Ozone Hole" is a depleted region in the ozone layer of the stratosphere above the Antarctic.

Fortunately, the majority of ozone is in the stratosphere protecting the earth from harmful radiation. This is around 10 - 50 km above the surface of the earth. **Figure 1** shows a typical concentration profile and altitude of ozone in the atmosphere. It is critical to measure the concentration of low altitude ozone for health concerns and pollution limitations.

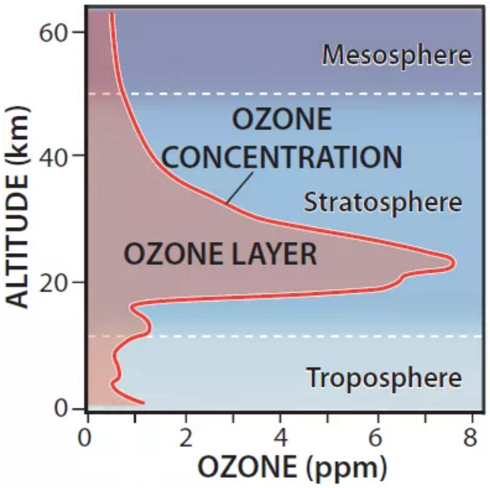

Figure 1. Ozone Altitude Comparison[1]

PROBLEMS WITH CURRENT METHODS

There are many ways to measure and map the concentration of ozone in the atmosphere. These range from mass spectroscopy, local ozonesondes, radiometry, and now LiDAR. Measurements can be made from the ground, or on aircraft, balloons, or satellites. There are tradeoffs with each technique including cost, sensitivity, range, or limited measurement windows.

One way to measure the concentration of the ozone layer is to go outside the ozone layer using satellites. Satellites can use infrared interferometry, spectroscopy, or even sounders (devices measuring radiation) to measure and map ozone in the atmosphere. If only using radiation or reflectance techniques, it can be difficult to distinguish whether ozone is in the troposphere or the stratosphere. Sending any kind of equipment into space is also extremely expensive and has a great deal of risk involved. Maintenance is much more complicated when in space. Ozone mapping from satellites is not immune to these problems.

Another method uses an in-situ technique: balloons. This technique brings the measurement instrument to the ozone layer to collect data locally. This can be effective for measurements in the stratosphere (although it can be limited by altitude and cannot measure the upper limit of the ozone layer), but for measuring the concentration of ozone in the troposphere easier methods can be utilized with the same precision.

There are techniques that exclude lasers, but these methods can only be operated in the daylight if they use radiation absorption of the sun's light or reflection measurements. These methods have reduced sensitivity and limited altitude range. Some systems use visible light absorption from the sun. If measuring the ozone in the stratosphere, the measurement needs to be taken at a low sun position because the path through the stratosphere needs to be as long as possible. Even so, the relatively weak absorption in the visible portion of the solar spectrum limits sensitivity.

There are light detection and ranging (LiDAR) techniques currently in use by NASA.[2] The current research grade systems require a large amount of maintenance which disrupt continuous measurements. These must be operated by scientists and researchers with vast physics background, minimizing the ease-of-use of the systems. Most of the research grade systems do not have high repetition rates of the laser pulses. Details such as low optical power and optic burning are other parameters than can cause problems for the user.

Commercial Differential Absorption LiDAR systems are now available from Bridger Photonics which resolve these issues.

DIFFERENTIAL ABSORPTION LIDAR

Differential Absorption LiDAR (DIAL) is used to measure and map ozone in the atmosphere using ground-based, airborne, and even space based systems. Rather than simply measuring the scattering properties of traditional LiDAR methods, DIAL utilizes absorption of light in ozone to analyze the concentration in the atmosphere at greater distances. DIAL measurements not only give time-of-flight data, but also give the concentration at the location measured.

Two separate wavelengths are used in the system as ozone absorption of light is wavelength dependent. **Figure 2** shows this relationship with two sample wavelengths. One wavelength will be absorbed more strongly by the ozone than the other. A nonlinear conversion technique is used to split the laser into two beams with two different wavelengths.

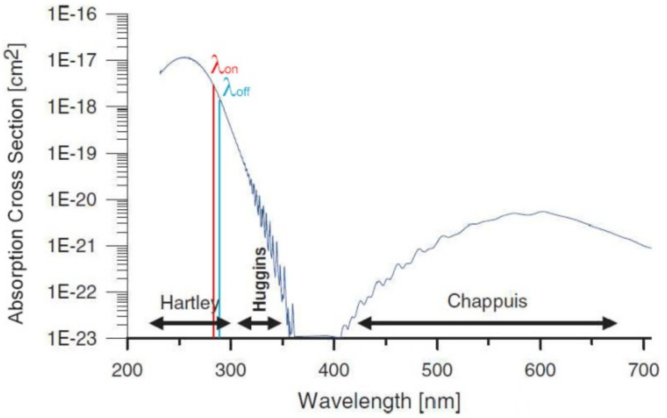

Figure 2. Ozone Absorption Spectrum - how the absorption coefficient varies with wavelength (example wavelength pair: on and off)[3]. Hartley, Huggins, and Chappuis are names of specific absorption bands of ozone.

Depending on the sensitivity of the DIAL system, these wavelengths can be as close as a few nanometers. It is common to use ultra-violet wavelengths that have the greatest absorption in ozone. **Figure 3** shows a simple DIAL diagram.

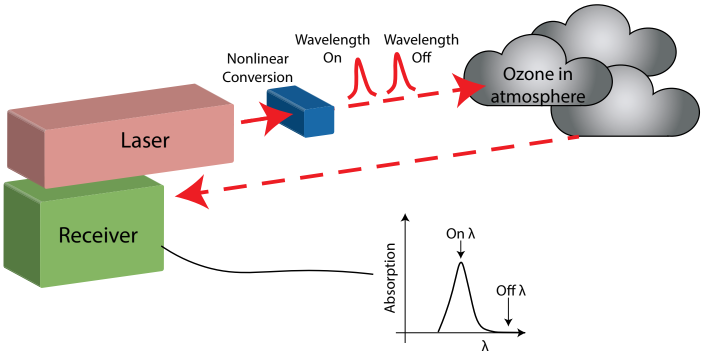

Figure 3. DIAL illustration of measuring ozone concentration

The difference (or relative change) between the intensities of both signals is used to determine the concentration of ozone in the atmosphere. The altitude for mapping the ozone is determined using the LiDAR aspect of the system.

NASA currently has a few ozone research-grade DIAL systems in place, but they hope to soon have a network of commercially available ozone DIAL systems.[2] The ozone concentration across the globe can be mapped in a 3D image by scanning across wide areas using multiple systems in the NASA network.

BRIDGER PHOTONICS' SOLUTION

Bridger Photonics[4] has developed a ground-based Differential Absorption LiDAR (DIAL) transmitter solution (seen in **Figure 4**) to measure and map the concentration of ozone in the troposphere. Because ozone in this region is dangerous to life on the surface of the earth, this system is designed to look at the lower portion of the atmosphere: up to around 10 km in altitude (see **Figure 1**). The core of this commercial transmitter system is a Nd:YAG laser pumped Optical Parametric Oscillator (OPO). The OPO converts the 1064 nm laser beam from the solid state laser to two tunable wavelengths in the 285 - 310 nm range. The OPO contains a crystal that must be temperature stabilized to ensure the correct wavelength is emitted.

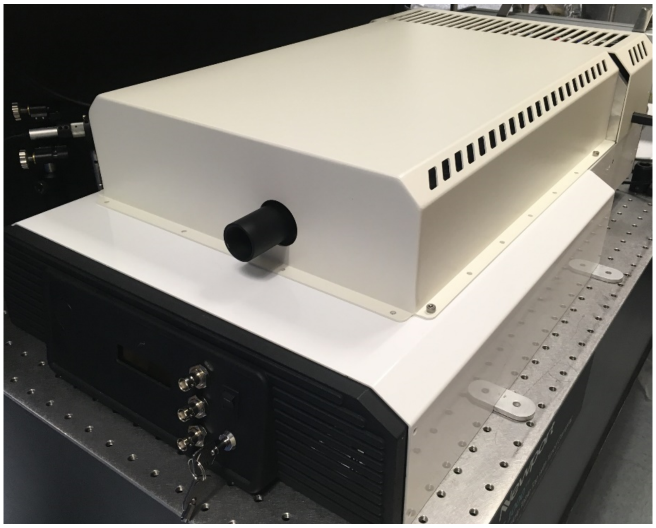

Figure 4. Bridger Photonics' ozone measuring DIAL system[4]

The solid state laser is pumped by laser diode arrays. The more stable the laser diode arrays, the more stable and precise the solid state laser wavelength will be going into the OPO. The base laser (Nd:YAG) is pulsed at 1 kHz (repetition rate) with 9 mJ (energy) for 6 ns (pulse width). The laser has a beam quality factor of $M^2 = 1.3$ for efficiency into the OPO. After the beam has been converted, the ultraviolet (UV) wavelength pulses have powers of about 200 µJ at a repetition rate of 1 kHz.

This system is very compact compared to research grade DIAL systems and still provides the same precision measurement of ozone concentrations. Current LiDAR techniques occupy trailer-sized spaces and are not as easily deployable in the field. Bridger Photonics' solution is compact, can be placed on a benchtop, and is a self-contained, commercial system. The system is designed to be maintenance-free making it easier to deploy autonomously. This commercial system does not exist elsewhere, and it does not require extensive laser physics background in setting it up.

This DIAL system also has the advantages of low power consumption and high total optical power. With the final UV powers of about 200 µJ (at 1 kHz) from the base laser of around 9 mJ (at 1 kHz), the system can provide more signal—making measurement and data collection easier. The 1 kHz repetition rate of the system is much faster than the current research-grade systems.

Using UV wavelengths in optical systems risks damaging the optics in the laser system. The short wavelength has high photon energy emitted. Even if the light is pulsed, the optics can still be damaged. Bridger Photonics' DIAL system is designed to minimize the number of optics the UV light interacts with. The UV wavelength light is produced at the very end of the system to reduce the number of optics that are subject to potential damage and minimizing down time for maintenance.

The main goal of the system is to measure the concentration of ozone in the troposphere. Similar DIAL systems have an altitude range of around 5 - 8 km. Bridger's DIAL system can match this range. Collecting measurements at night also helps to increase the range of the system, and it adds to the versatility of the design.

Although the system is specifically designed to measure the ozone concentration, the base design (the Nd:YAG pumped OPO) could be easily transitioned to measure other atmospheric gases using other wavelengths. Ozone concentration is easy to measure because the absorption is extremely broad (~100 nm). Measuring other broad linewidth gases in the atmosphere could be accomplished with a slightly modified version of this system.

WAVELENGTH'S ROLE

The PTC10K-CH provides stable thermoelectric current to control the temperature of the laser diode arrays and the nonlinear crystal. This controller delivered the precision performance and long-term reliability Bridger Photonics required. The PTC has stability as low as 0.0012ºC, up to 10 A, and offers comprehensive safety including current limits. The proportional-integration control minimizes setpoint overshoot and time to the set temperature.

The LD15CHA delivers up to 15 A of output current to the laser diode arrays which pump the solid state laser. Because Bridger Photonics operates the driver near limit, it is important that the output current never exceed the setpoint. The LD15CHA can be configured (setpoint and limit) without output current enabled.

Both the temperature controllers and laser drivers easily connect to the laser diode pump system. **Figure 5** shows the three PTC10Ks and the two LD15CHAs in the system without the optical components. The controllers can be daisy-chained for clear communication. A single wire from the microprocessor enables the LD15CHA drivers. The controllers and drivers provided the stability and precision needed for DIAL mapping of ozone concentration.

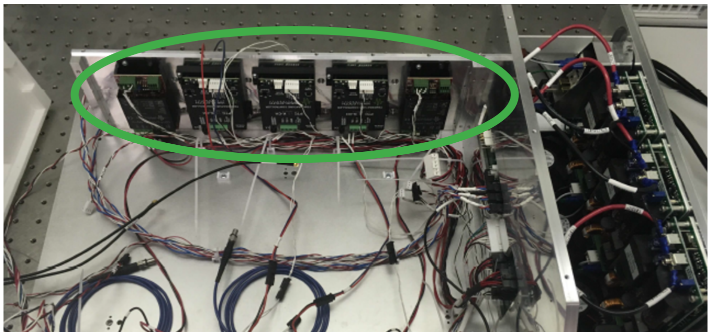

Figure 5. LD15CHAs and PTC10Ks mounted in the DIAL transmitter system showing the electronic layout[4]

REFERENCES

1. Geography, "What Is Ozone and Why Is It So Important," https://ozonewatch.gsfc.nasa.gov/facts/SH.html
2. "Tropospheric Ozone LIDAR Network," National Aeronautics and Space Administration, https://www-air.larc.nasa.gov/missions/TOLNet/index.html
3. Minh, Pham & Bui, Hai & Tien, Tho & Dinh Van, Trung. (2017). "Development of Uv Laser Source Based on Distributed Feedback Dye Lasers For use in Measurement of Ozone in the Lower Atmosphere." Communications in Physics. 27. 345. https://doi.org/10.15625/0868-3166/27/4/10798.
4. Bridger Photonics https://www.bridgerphotonics.com

USEFUL LINKS

- LD15CHA Product Page
- PTC10K-CH Product Page

PRODUCTS USED
PTC10K-CH
LD15CHA

KEYWORDS
Differential Absorption Lidar, DIAL, ozone, atmosphere, remote sensing, pump laser, pulse, dual wavelength, controller, troposphere

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REVISION	DATE	NOTES
A	July 2020	Initial Release