Ozone Dial Scanner

Clayton Craft

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Ozone Dial Scanner

CLAYTON CRAFT

Advisor: Dr. Michael Newchurch
ESSC
April 24, 2015
Abstract

This describes the building and incorporation of a scanning Differential Absorption Lidar into the University of Alabama in Huntsville’s options for taking ozone profiles of the troposphere to better ensure that the area is within appropriate levels of ozone, observe ozone transport phenomena, and provide measurements for the simulation of ozone movement patterns to better predict dangerous areas of high ozone levels. The lidar was constructed and is currently housed in the National Space Science and Technology Center. The lidar comprises mirrors and controls, a telescope, mount, receiver, detectors, and data acquisition computers. The mirrors and controls were salvaged from a previous system. The telescope, mount, receiver, detectors, and data acquisition computers are all new. Although the system has been run, no calibrated or interpreted data is yet available; but again, the system is functional and the expected exponential decaying signal has been retrieved. This report contains the details of the instrument, how it was built, various solutions to potential problems, future plans, and the specifications of the components. From this project, the Atmospheric Chemistry Team of UAH expects to be able to move to a mobile scanning system to be able to track ozone movement outside of the surrounding three kilometer area of Huntsville, which can give a warning of high ozone level movements into Huntsville or out of Huntsville into surrounding areas. This encourages a procedure that warns of high ozone as opposed to only reacting when the levels are already too high.
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**Background**

Ozone is sometimes thought to be an overall good gas by laymen due to the association with fixing the “Hole in the Ozone Layer.” However, ozone is not desired everywhere all the time. In fact, it is considered a pollutant if it is close to ground level (tropospheric ozone). Even if the ozone is in the stratosphere, it can transport into the troposphere and become a problem (Kuang et al., “Stratosphere-to-Troposphere”)

Ozone is an oxidizing agent; that is, it burns most things it touches. It is also a gas, so it enters the lungs, reacts with the antioxidants there, and if enough ozone is present, will react with the lung tissue. This reduces lung function and will cause inflammation or even death in cases where there is already a problem with the lungs such as asthma or chronic obstructive pulmonary disease. At the time a report by The Royal Society was written, ozone contributed to 21,400 deaths annually in the European Union. Furthermore, chronic exposure to high ozone may cause permanent damage to the lungs (Fowler, 67-74).

Ozone will also react the same way with plants which results in harming the crops. There is an estimated loss of 2-4 billion dollars from crop reduction due to tropospheric ozone in the United States alone (Fowler, 75-80).

Tropospheric ozone is produced from reacting nitrogen oxides and volatile organic compounds in sunlight. These are produced from the burning of carbon containing matter like coal or gasoline, so the ozone concentrations are usually at a maximum in the suburban areas outside of cities. The goal set
by the World Health Organization is to have ozone under a guideline of 50 ppb, but the background levels around Alabama are close to 40 ppb (Fowler, 1). Putting it all together, by being close to a city, those around Huntsville are often in danger of harmful levels of ozone (Kuang et al., “Nocturnal Ozone”). This is why UAH tracks ozone levels around the Huntsville area – not as an academic exercise, but a real and practical check on the health of the local population.

This, however, leaves open the question of how to watch ozone. If ozone monitors are kept on the ground in a wide array, then it is impossible to detect large quantities of ozone falling from the upper troposphere. The next solution is to release weather balloons to obtain a vertical picture of ozone distribution. UAHuntsville does this, but it is labor intensive and the sondes are not immediately reusable, which results in a somewhat costly measurement.

The preferred solution is lidar, a play on “light” and “radar”. This instrument sends out a light signal which has a chance of bouncing off molecules in the atmosphere and returning to the laboratory where it can be detected. Based on the lidar equation (Equation 1) and how long the light was in the atmosphere, a researcher can calculate how far away the molecule that backscattered the light is (Kovalev and Eichinger, 53-103). However, lidar is restricted in close field measurements because the laser light must diverge enough so that the diameter of the beam is as large as the diameter of the aperture of the receiving system, normally a telescope.
The system is not as simple as it sounds, and in order to interpret the data, the lidar equation (single wavelength) must be used.

\[ P(r) = C_0 T_0^2 [\beta_n(r)/r^2] \exp[-2\int_{r_0}^r \kappa(r')dr'] \]  

[1]

Where \( P(r) \) is the signal measured, and it is a function of the distance of the molecule scattering the light, \( r \). \( C_0 \) is a system coefficient. \( T_0 \) is an unknown variable until \( r \) equals \( r_0 \) in which it goes to unity. \( \beta_n \) is the total backscattering coefficient. The extinction coefficient, which is a measure of atmospheric absorbance at a wavelength, and \( r' \) is the distance along the path of the light.

The point of including the equation is this: this backscattering process can happen off of any molecule because \( \beta_n \) is for the total backscattering coefficient of the part of the atmosphere, not just ozone. To get around this, two wavelengths are used, one that is absorbed by ozone and another that is not—that is, different \( \kappa \) values. Based on the ratio of absorbed light to unaffected light, the concentration of ozone it travelled through can be calculated (Kovalev and Eichinger, 331-385). This is known as the ozone mixing ratio, and it is the variable that we are trying to find. The technique of using two wavelengths of lasers is called the \textbf{D}ifferential \textbf{A}bsorption \textbf{L}idar technique (DIAL), and this is the method we use at UAH (Kuang et al., “Differential Absorption Lidar”).

The DIAL equation simplifies to Equation 2.

\[ n_{O3} = -1/(2\Delta O_3)(d/dr)[\ln P_{on}/P_{off}] + \Delta n_{O3} \]  

[2]
Where \( n_{O3} \) is the ozone density, \( \Delta O_3 \) is the differential ozone absorption cross section, \( P_{on} \) refers to the absorbed wavelength, and \( P_{off} \) refers to the other wavelength. The dependence on \( r \) has been suppressed, but all variables are dependent on \( r \) (Kuang et al., “Ground-Based Lidar”).

We use a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser that has been Raman shifted using hydrogen or deuterium to the wavelengths 299 nm, 289 nm, and 283 nm.

Because of the \( T_0 \) value, it is extremely difficult to determine the ozone concentration until there is a full overlap of the signal and the telescope. That is, if there is a smaller telescope aperture, then measurements can be taken at lower altitudes, but this also leads to the signal fading away at a lower altitude. To solve this, UAH has multiple, independent telescopes at 1 inch, 4 inches, and 16 inches. Furthermore, if the signal is split into 90\% and 10\% components, the range can be lowered even more – from 1 km to .4 km in the Huntsville system (Kuang et al., “Ground-Based Lidar”).

The current system, however, can only measure vertically. This is why UAH is upgrading its lidar to allow for a way to scan the sky around Huntsville. This is called the Ozone DIAL Scanner (ODS). The old system will still have a wider range, and so that UAH does not have to purchase new lasers and Raman cells, both systems will be used by being able to swap between two optical pathways after the wavelength shift.
Overview

Since the receiver is made up of multiple sections, it is better to give a full picture understanding of the receiver and then break the sections down into their own parts to really understand how the details work together to make the system function.

General

The general receiver is shown in Figure 1.

Figure 1: General Configuration of Receiver (All photos taken by Clayton Craft unless otherwise specified)
The signal is able to enter into the telescope, get focused into the cube system (series of black cubes), go through lenses and filters, and enter into photon counters which can detect the amount of light that was backscattered.

**Telescope and Mount**

The telescope is a customized Vixen VC200L Telescope. This has a 200 mm (8 inch) aperture. The standard BK-7 focusing lenses, which absorb strongly in the UV range (the range used at UAH), were removed by NASA Goddard Space Flight Center.

![Figure 2: Beam Diameter as seen from 2 feet away (Image by Martha Dawsey)](image)

At that time, Goddard also collimated the light to a size of 6.4 mm in diameter using a Thorlabs LD4293-UV - Ø1" UV Fused Silica Bi-Concave Lens which has a focal point of -50 mm and does not absorb in the range of interest. This lens is held in the lens tube shown in Figure 2.
Adjustments can be made with a focusing knob that moves the eyepiece components closer or farther away.

The mount consists of an arm that allows for vertical adjustments on a rail attached to the telescope. The arm is bolted into an aluminum plate which forms a 30-60-90 triangle as shown in Figure 3. The mount had to be raised onto posts because the lens tube which held the collimation lens was much longer than expected. Plate 1 is a 2 ft. x 1 ft. x ½ in. plate, and Plate 2 is a 1 ft. x 1 ft x ½ in. plate. They are mounted on Thorlabs AP30 mounting brackets. The posts are Thorlabs RS4P Ø1 in. Pedestal Pillar Post, length 4 in. secured by Thorlabs CF175C Clamping fork. If the mount rocks back and forth, the AP30 mounting brackets can be adjusted against the plates which gives allows for vertical adjustments until all posts are on the same horizontal plane.

Figure 3: Telescope Mount and Angles
**Cube System**

The cube system is the main part that had to be built by The UAH Atmospheric Chemistry Team for this project. This is the housing for the lenses, mirrors, and photomultiplier tubes (PMTs, which are just photon counters) that may get damaged and need to be replaced. Its configuration is shown in Figure 4.

The signal light enters the dark blue cube from above. The cube holds a greater than 98% effective Newport broadband mirror at an elevation angle of 45° so that the light is then reflected to the right where it is incident on the 299 nm/ 283 and 289 nm beamsplitter (dark red box) which is held at an azimuthal angle of 45°. The longer wavelength is shorter wavelengths are reflected. The 299 nm wavelength then hits a Materion narrowband filter (pink box) to absorb any wavelengths that are not 299 nm which are present due to contamination of the signal with solar light. It then passes onto a Chroma beamsplitter (brown box) that reflects 90% of the incident light, and transmits the other 10%. The 90% light is detected by a Hamamatsu gated PMT (dark grey box), and the 10% light is detected by a Hamamatsu ungated PMT (small light grey box). Both pathways have an independent opportunity to enter into a
neutral density filter for a null reading (lavender box). This option is necessary for calibration of the system. The shorter wavelength photons have a similar pathway. They are reflected by the Materion beamsplitter (dark red box) and travel into a Newport filter to remove wavelengths outside the appropriate range. This travels into another Chroma 90/10 beamsplitter which reflects 90% of the light into a gated PMT, and transmits 10% of the light into an ungated PMT.

The difference in the gated and ungated PMTs is that the ungated PMTs are always on and the gated PMTs shut off for a specified length of time to prevent being overwhelmed by signal.

The PMTs work by having plates where one electron from a plate can be excited by light. It can then fall off the plate and be directed by a voltage to another plate where it can excite more electrons to fall of that plate where the process can repeat. The cascade is controlled by a voltage between the plates. The voltage is controlled by an adjustable power supply.

The signal output is run through a transient recorder that interprets the data. The transient recorder connects to a computer which runs custom programs created off of the IDL programming language to visualize the data.

In order to make the cubes completely sealed so that light cannot seep through and interfere with the data (this is called making the system light-tight). All holes were filled with a silicon rubber gasket maker.

The cubes with and without the silicon rubber is shown in Figure 5. The tube connections between the cubes are assumed light tight as they are
threaded and have a metal annulus heavily tightened, locking them in place. In order to test if the system was light tight, the signal was compared with the lights on and the lights off, but no change in signal could be observed. This indicated that the system is reasonably sealed.

The cube for the shorter wavelength, ungated PMT can be rotated until it is horizontal, facing the other arm of the cube system. This is to help in securing the PMT for vibration control for an upgrade of the lidar into a ground based mobile laboratory.

![Figure 5: Cube with Silicon Rubber vs. Cube Without](image)

**Outlet and Scanner**

The telescope is beneath a hole in the roof to let the signal out or in. A tower covers this hole in order to keep out the weather, but to enable scanning
capabilities to the DIAL, two mirrors have been placed on the top of the tower to control the azimuthal and elevation angles. The hull of this can be seen in the left part of Figure 6, and the details and angles of rotation can be seen in Figure 7. The hull is covered with a tarp to protect against debris or precipitation in Figure 6 and uncovered for use in Figure 7.

Inside the tower, the floor is a grate that can be raised up to allow the light from the laser to pass through, or lowered to be able to stand on it during maintenance as this tower allows access to the cable system that connects the computers in the lab to the mirrors for angular control. The grating is shown in the right side of Figure 6, and the interior view or the mirrors and cable system is shown on the left side of Figure 7.

In the lab, just above the telescope, there is a plastic shield to prevent debris from landing on the telescope and damaging the optics. Like the grating, this too must be moved when the laser is turned on; otherwise, it will reflect too much signal into the telescope potentially harming the PMTs or optics.

**Figure 6: The Scanner Tower.** Light can be seen coming from the main lab from the grating in the floor of the tower.
A view of the angular position of the mirrors and how it corresponds with the direction of the beam can be gathered from Figure 7.

![Figure 7: Rotation Angles and Mirrors](image)

The red arrow shows the rotation for the azimuthal adjustments and the green arrow shows the rotation of the elevation adjustments. On the left side, the scanner is in a north facing down position, and on the right side the scanner is in an east facing up position. With these two mirrors it is possible to orient the system to any point in the sky using polar coordinates.

The computers used to control the motors that adjust the angle of the mirrors are from a previous setup, and could not be replaced. They are, however, functional. A close up of the lower computer is shown in the right part of Figure 8. The computer is run off of MS-DOS and only has one program: lidar, which returns the angle of each mirror. The motor toggle turns on the power to the motors, and the emergency stop is located just above that. The
other computer is more recent. The program LIDAR Scanner Control is the interface used to control the angle of the telescope. It only requires two inputs: the desired azimuthal angle and the desired elevation angle. The mirrors are typically stored facing east and down to avoid any damage on the optics from the tarp decaying from the sunlight.

Figure 8: Angle Control Interface

Data

Using the system, we have obtained a raw signal decay curve shown in Figure 9, and from these results, we currently expect to reach a range of 3 km. That is, the system is functional, but it is not calibrated. An expected exponential decay can be made out from Figure 9, but it would be difficult to divine any kind of quantitative science from the figure without processing the data. However, once processed and put into a readable form, a graph similar to Figure 10 will be generated. Keep in mind, however, that it is only a sample.
That is, the system is functional, but it is not calibrated. An expected exponential decay can be made out from Figure 9, but it would be difficult to divine any kind of quantitative science from the figure without processing the data. However, once processed and put into a readable form, a graph similar to Figure 10 will be generated. Keep in mind, however, that it is only a sample.
This shows a single directional sampling of ozone profiles and two separate occasions of tropopause level ozone drop into the troposphere. These movements are scientifically interesting because it puts so much ozone into the troposphere, which can then cause damage to plants or people. The desire is to watch these movements spatially instead of just with respect to time as we are currently only getting some of the process.

**Future Upgrades**

The current system is exceedingly useful for its purposes, as it allows us to scan over to the mountains in east Huntsville; however, it is entirely possible that we would like to be able to scan beyond the Huntsville’s eastern mountains. This is best resolved by moving this into a mobile system.

Many lidars have been put into air-borne mobile systems to collect data (Alvarez et al.; Burris et al.; Goldberg et al.; Uchino, O and I Tabata; Whiteman et al.). In other words, lidars are often flown in planes; however, planes are expensive and often require a special campaign to look at some specific event.

The intermediate of these is mentioned in Whiteman et al, where the airborne lidar was put into a mobile trailer for secondary measurements (1). The possibility of an eventual upgrade to a trailer has influenced some of the choices made for developing this system.

The mounting place will likely be replaced with a leg system to allow for more controlled alignment. The three legs will form a plane that will minimize rocking once bolted into the table, which is crucial for a mobile system.
As stated previously, the tarp covering for the scanning mirrors breaks down very easily. Ideas for a more permanent system are being investigated, but it is likely that the tarp will be replaced by a plastic shell. The simplest idea is for half of a plastic barrel to be attached to the tower by a hinge.

## Appendix: Parts Information

This section provides the details and specifications for components used in the receiver.

<table>
<thead>
<tr>
<th>Item: 90/10 Beamsplitter</th>
<th>Item: Cell Window for RAMAN Tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer: Chroma</td>
<td>Manufacturer: CVI Laser Corporation</td>
</tr>
<tr>
<td>Part Number: 90/10 UV bs</td>
<td>Part Number: W2-PW1-2037-UV-248-3550</td>
</tr>
<tr>
<td>Description: 2 inch beamsplitter to reflect 90% of incident light and transmit 10%. Used in the cube system to send light into the gated or ungated PMTs (brown box in Figure 4).</td>
<td>Description: This window allows light to enter or exit the Raman cell.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item: 266 nm Wavelength Mirror</th>
<th>Item: Broadband Mirror</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer: CVI Laser Corporation</td>
<td>Manufacturer: CVI Laser Corporation</td>
</tr>
<tr>
<td>Part Number: Y4-1025-45</td>
<td>Part Number: MPQ-245-390-5010</td>
</tr>
<tr>
<td>Description: This is a mirror that turns the laser light before it has been Raman shifted.</td>
<td>Description: Turns the incoming downward pointing light into the cube system (dark blue cell in Figure 4). This item is not very wavelength selective in the range of interest.</td>
</tr>
<tr>
<td>Item: Gated PMT</td>
<td>Item: Ungated PMT</td>
</tr>
<tr>
<td>----------------</td>
<td>------------------</td>
</tr>
<tr>
<td>Manufacturer: Hamamatsu</td>
<td>Manufacturer: Hamamatsu</td>
</tr>
<tr>
<td>Part Number: H10721P-110</td>
<td>Part Number: H11526-110-NN</td>
</tr>
<tr>
<td>Description: Counts photons by amplifying the signal through a series of gates with an applied voltage. Can reverse voltages to turn off system for a specified length of time (dark grey cell in Figure 4).</td>
<td>Description: Counts photons by amplifying the signal through a series of gates with an applied voltage (light grey cell in Figure 4).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item: Power Supply for PMTs</th>
<th>Item: C-Mount Ring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer: Hamamatsu</td>
<td>Manufacturer: Hamamatsu</td>
</tr>
<tr>
<td>Part Number: C7169</td>
<td>Part Number: A9865</td>
</tr>
<tr>
<td>Description: Variable DC power supply for PMT. It allows for an adjustment in the voltages for both PMTs</td>
<td>Description: Light tight connector to attach the PMTs to the cube system</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item: Transient Recorders</th>
<th>Item: Dichroic Beamsplitter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer: Licel</td>
<td>Manufacturer: Materion</td>
</tr>
<tr>
<td>Bid Item: B002297.RV01</td>
<td>Part Number: F-BS-0013535</td>
</tr>
<tr>
<td>Description: Signal recorder to allow for the storage of photon count information according to time and distance from receiver.</td>
<td>Description: Beamsplitter to reflect 283 and 289 nm wavelength light and transmit 299 nm light (dark red cell in Figure 4).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item: 283/289 Filter</th>
<th>Item: 299 Filter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer: Newport</td>
<td>Manufacturer: Materion</td>
</tr>
<tr>
<td>Bid Item: B002302.RV02</td>
<td>Part Number: F-NB-0011941-1</td>
</tr>
<tr>
<td>Description: Short pass filter to allow 283 and 289 nm wavelengths through (light blue cell in Figure 4). It reduces solar and 299 nm contamination (See Figure 11).</td>
<td>Description: Narrow band filter to only allow 299 nm light through (pink cell in Figure 4). It reduces solar and 289/283 nm contamination (See Figure 12).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Item: Cage Cube</th>
<th>Item: Oscilloscope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manufacturer: Thorlabs</td>
<td>Manufacturer: Tektronics</td>
</tr>
<tr>
<td>Part Number: LC6W</td>
<td>Part Number: TDS2024C, from Entest</td>
</tr>
<tr>
<td>Description: Cage Cube. It is the basic component of the cube system, and where to start looking for accessory components.</td>
<td>Description: Oscilloscope to align the laser and visualize signal without using the transient recorders.</td>
</tr>
</tbody>
</table>
**Item: PMT adapter**
Manufacturer: Thorlabs
Part Number: SM1A39
Description: Adapter for Hamamatsu C-Mount Ring to Thorlabs Cage Cube

**Item Cage Cube Connector**
Manufacturer: Thorlabs
Part Number: SM2T2
Description: This connects the cubes to each other.

---

**Figure 11: Transmission Spectrum of Newport 283/289 nm Bandpass Filter**
Figure 12: Transmission Spectrum of Materion 299 nm Narrowband Filter

Appendix: Validation Procedures

The system has parameters that must be adjusted in order to be verified. Without these, we cannot be sure of the accuracy of the data received. For validation, we use an ozonesonde and a surface air ozone detector.

Ozonesondes

The Ozonesondes come from Droplet Measurement Technologies. They are flown on weather balloons as described in the UAHuntsville NOAA/ESRL
These work by a redox reaction between iodide and ozone. In order for the reaction to proceed, a charge transfer must take place. This is carried through wires and the charge transferred per unit of time is the current. The ozonesonde reads the current, and from it determines the amount of ozone that must have reacted for the reaction to occur. It can then use the volume of air that it pumped to determine the concentration of ozone in the atmosphere.

It takes one to two weeks to prepare a sonde for launching, so it is often beneficial to have a spare sonde available at all times for validation procedures.

The preferred method of validation for the lidar system is to tether the balloon instead of letting it fly freely by connecting the balloon to a mechanical rod and reel, letting it rise to 300 feet and collect data, and pulling the balloon back down using the rod and reel. They will be connected to a weighted box with a battery attached to the reel. Once the balloon is back down, it can be briefly stored so it can be flown again a few days later if more data is needed.

This is how we can find altitude dependence of near field ozone. For far field ozone, the balloon can be flown freely.

**Ozone Monitor**

The Model 205 Ozone Monitor is a specially designed photometer from 2B Technologies. A single wavelength of light that is absorbed by ozone with a well-known absorptivity is shown into a cell from the ambient air. It also uses a sample of filtered air as a null standard. This method requires a replacement of the ozone scrubber every six months, and replacement of the air pump after it
fails (around 7 months of continuous usage). Every year, the instrument must be recalibrated. This is done by connecting the exhaust of the 2B Model 306 Ozone Calibration source to the intake of the monitor. A value for the concentration of ozone is selected for the calibrator, and the value read from the monitor can be used to create a linear regression that will be used to calibrate the monitor. The readings are taken every few seconds, but they are time averaged into 1 to 5 minute intervals.

References


