Air Quality Project

REMOTE SENSING TUNABLE LASER MEASUREMENTS OF AIR POLLUTION

October 2001

REMOTE SENSING AIR POLLUTION STUDY IN NORTH MISSISSIPPI

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The National Consortium on Remote Sensing in Transportation – Environmental Assessments (NCRST-E) is one of four consortia established by the US Department of Transportation and NASA to lead in the application of remote sensing and geospatial technologies in the transportation industry. The primary mission of the consortium for Environmental Assessment is to develop and promote the use of remote sensing and geospatial technologies, and requisite analysis products by transportation decision-makers and environmental assessment specialists to measure, monitor, and assess environmental conditions in relation to transportation infrastructure.

OBJECTIVES OF AIR QUALITY PROJECT

The NCRST-E air quality project is focused on remote sensing laser measurements of air pollutants and air quality impact of transportation systems. This approach can quantify the contribution of mobile sources of air pollution. The primary objective is the development of a state-of-the-art protocol for air quality analysis using remote sensing laser measurements of significant air pollutants related to traffic and transportation infrastructure.

The project involves: (a) comprehensive literature search and review of air pollutant databases, transportation related air pollution data, air pollutant concentration and dispersion modeling, and available remote sensing technologies, (b) selection of study sites, (c) deployment of selected remote sensing technology for measuring air pollution at selected sites, interpretation and assessment of data, and study of the adverse effects of weather and urban sprawl on air quality, and (d) modeling of air pollution considering traffic, weather, and land use.

CLEAN AIR ACT REQUIREMENTS

Quality of the human environment in our society is greatly affected by the quality of air that we breathe, and the water that we consume. Increased human activities in the last four decades have disturbed the natural cycles of key elements of life. These concerns led to the creation of a national environmental policy nearly three decades ago. The U.S. Environmental Protection Agency (EPA) has been created to develop specific regulations and monitoring methods to improve the air and water quality. It ensures that the environment quality is not degraded by urban growth, industrial development, increased transportation facilities, and higher traffic volume.

As a continuation of NEPA legislation, 1970 Clean Air Act, Section 309 Public Law 91-604 § 12(a), 42 U.S.C. § 7609, was passed by the U.S. Congress in 1970. In response to the Clean Air Act, the U.S. Environmental Protection Agency (EPA) established National Ambient Air Quality Standards for various “criteria” pollutants that adversely affect human health and welfare. In the past, motor vehicles were a source of lead (Pb) emissions, but are no longer a major contributor because leaded gasoline is no longer available for transportation usage. Compliance with national (and state standards, if more stringent) ambient air quality standards (Table 1) is an important consideration under the Clean Air Act.

Table 1. 1999 Primary Air Quality Standards

<table>
<thead>
<tr>
<th>Transportation Pollutants</th>
<th>Maximum Concentration Standard</th>
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<tbody>
<tr>
<td>Ground-level ozone (O₃)</td>
<td>0.08 ppm (8-hour average)</td>
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<tr>
<td>Particulate matter (PM₂.₅)</td>
<td>65 microgram/ m³ (24-hour average)</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>9 ppm (8-hour average)</td>
</tr>
<tr>
<td>Sulfur dioxide (SO₂)</td>
<td>0.14 ppm (24-hour average)</td>
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<tr>
<td>Nitrogen dioxide (NO₂)</td>
<td>0.053 ppm (annual average)</td>
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<td>(one of the primary precursors of Ozone)</td>
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KEY POLLUTANTS AFFECTING AIR QUALITY

Key sources of air pollutants are: point and area sources, mobile sources (vehicular traffic, railroad, and non-road engines), aviation, fires, and natural emitters such as Nitrogen Dioxide (NO₂) formation by lightning and biogenic emission of VOC. Air pollution contributions from vehicle emissions — particularly volatile organic compounds (VOC) or Hydrocarbons, PM, CO, and NOx — result from fuel combustion, fuel evaporation, and refueling losses. Vehicles are becoming more efficient and cleaner (Figure 1), however, vehicle-miles traveled have tripled over the last 40 years.

Ground-level tropospheric Ozone, a major air pollutant, is the most abundant tropospheric oxidant. It is formed by a photochemical reaction involving VOC, NO₂, and sunlight. Tropospheric Ozone is toxic, contributes to smog, and negatively affects health. Elevated concentrations of ground level Ozone that principally occur during the summer months have been shown to be harmful to human health and damaging to vegetation. Regulation of Ozone precursor emissions under the U.S. Clean Air Act of 1970 and its subsequent amendments has been partially successful in reducing human exposure, but many areas of the country are still subject to episodes of high ambient Ozone levels. Ozone and smog created by NO₂ are particularly high during hot summer days (Figure 2), especially in urban and metropolitan areas where paved surfaces and constructed roofs cause up to 20 to 30 degree higher temperatures. On warm summer days, the air in a city can be 6-8°F hotter than its surrounding areas. Traffic gridlocks also result in more Ozone pollution. Despite considerable regulatory and pollution control efforts over the last three decades, high Ozone concentrations in urban, suburban, and rural areas continue to be a major environmental and health concern. Numerous cities and urban areas are listed as nonattainment areas for Ozone.

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<tbody>
<tr>
<td>CO</td>
<td>11.3</td>
<td>9.5</td>
<td>81.7</td>
<td>3.0</td>
</tr>
<tr>
<td>Volatile Organic Compounds</td>
<td>3.8</td>
<td>2.1</td>
<td>16.8</td>
<td>1.2</td>
</tr>
<tr>
<td>NOₓ</td>
<td>24.5</td>
<td>8.0</td>
<td>3.2</td>
<td>0.6</td>
</tr>
</tbody>
</table>

(source: EPA and FHWA)

Figure 1. Reduction in vehicle emissions

Figure 2. Smog resulting from NO₂ pollution

Nitrogen Dioxide is primarily the result of gases from motor vehicle exhaust and stationary fuel combustion sources like electric utilities and industrial boilers. It can also be produced from gas stoves and heaters. Human activities now account for more than 90 percent of NO₂ emissions in the United States, between 20 and 23 million metric tons since 1972 which is double the 1950 value. Nitrogen Oxides can react with SO₂ and other chemicals in the air to form acid rain. NO₂ absorbs the blue band of light and can lead to the brownish haze, also known as “smog” over metropolitan areas (Figure 2). At a high concentration level, NO₂ has a bleach-like odor and may contribute to chronic lung diseases such as asthma. “Silo filler’s disease” is a term used to describe a syndrome of acute pulmonary toxicity experienced by farmers exposed to high levels of NO₂ while working in silos that house decomposing fertilizer.

The EPA national strategy for air pollution abatement relies on the fixed point monitoring of air pollutants within the troposphere. Figure 3 shows the Ozone and PM data collected in 1999 at the Tupelo Airport air pollution station, established by the Mississippi Department of Environmental Quality (DEQ) for monitoring EPA standards of air pollutants. This is the traditional standard EPA method of air pollution monitoring.
REMOTE SENSING DIAL TECHNOLOGY FOR MONITORING AIR QUALITY

Principles of Real-Time Laser Measurement of Air Pollution

The tunable pulse laser measurement of air pollution uses laser pulses to transmit and receive electromagnetic radiation. The majority of gas pollutants present or formed in air exhibit optical absorption bands in the ultraviolet (UV), visible (VIS), or infrared (IR) portions of the spectrum. Figure 4 shows the electromagnetic spectrum in terms of wavelength. The wavelengths of the light range from about 1 mm for the far infrared to about 10 nm for the extreme ultraviolet. LIDAR is an acronym for Light Detection And Ranging. The concentration of gas pollutants can be monitored by using a pulse LIDAR over a long distance, noting the absorption obtained at one wavelength corresponding to a strong absorption band in the gas, and comparing it with the absorption at an adjacent wavelength where the gas does not absorb. This is the basic principle of tunable pulse laser measurement of concentrations of air pollutants.

The Electromagnetic Spectrum - Wavelength Range Required

Ozone (O₃): 280 – 310 nm (UV)  
Nitrogen Dioxide (NO₂): 435-450 nm (Blue)

Figure 4. The UV and Blue visible bands for LIDAR measurements of Ozone and NO₂
Overview of Remote Sensing DIAL Technology

Differential Absorption LIDAR (DIAL) has been used successfully to monitor atmospheric pollutants, such as O₃, NO₂, Hydrocarbons, SO₂, and Mercury vapors. Non-invasive remote sensing DIAL systems operate on the principle that the absorption of light by the atmosphere and air pollutants varies at different wavelengths. The laser is tuned between ultraviolet, visible, near infrared, and thermal infrared spectral regions. The difference in the absorption of light at these different wavelengths can be used to determine the concentration of air pollutants (Figure 3). The portable solid state laser systems operating in the infrared (IR) band offer a higher relative degree of eye safety as compared to the visible and UV regions. However, the data interpretation and discrimination of CO, CO₂, and other air pollutants in the IR range become complex.

Truck mounted and/or airborne DIAL technology uses active tunable laser sensors, operating in the visible and UV bands, that are capable of measuring real-time air pollutants in the atmosphere with high temporal and spatial resolutions (Figure 5). Most of these pulse LIDAR systems are more costly, require water-cooling, have a dedicated electrical supply system, and generate electrical interference. Several remote sensing air pollution monitoring systems using DIAL technology have been developed during the last two decades in the United States, Germany, Japan, and Russia.

The DIAL remote sensing technology has been used for 2-D and 3-D mapping of air pollutants using aircraft, vehicles, and building tops. This research indicates that the tunable DIAL pulse measurement, combined with modern GPS based georeferenced location and time stamping, is the most promising remote sensing technology for monitoring the concentration of NO₂ and O₃ air pollutants from a sampling distance of several hundred meters away. Measurements have been made from up to a 5-km range. The real-time in situ remote sensing spectroscopic DIAL technology allows measurements of air pollutants as they naturally exist in the atmosphere over long pathlengths. The remote sensing DIAL measurements are more representative of actual volume-averaged concentration than the point monitoring method, which depends upon the collection of air samples in specialized bottles/canisters for post-sampling laboratory analysis.

Figure 5. Operating schematic of tunable DIAL technology

The tunable pulse laser DIAL technology has been selected in this study for use on selected highway test sites to measure independent O₃ and NO₂ concentrations related to transportation and their effects on air quality. The tunable DIAL remote sensing technology on mobile (truck or van) and airborne platforms can provide real-time measurement and data analysis, wide-area and vertical profile monitoring from a distance of up to 2 km or more, and multi-pollutant concentration measurements. Figure 6 shows the absorption band of O₃. Figure 7 shows the sensitivity of O₃ and NO₂ concentration as a function of pathlength range. Cost and complexity of operation, as well as inadequate research support, so far have prevented wide applications of the DIAL technology.
PILOT EVALUATION OF DIAL TECHNOLOGY ON A RURAL HIGHWAY SITE

The remote sensing tunable pulse LIDAR technology, implemented by Skyborne, Inc., presented the most promising option for measuring NO2 and O3 air pollutants. The system has been adapted as a basic truck mounted DIAL equipment, as shown in Figure 5. The high–rep rate narrow linewidth Lambda Physik XeCl excimer dye lasers are operated using xenon chloride. Approximately 90% of the energy taken by the lasers is emitted as heat which must be dissipated using an integrated cooling system for reliable operation. The tropospheric Ozone molecules can be measured in the Huggins-Hartley absorption band using two wavelengths and care is taken to minimize SO2 interference in the measurement (Figure 6). The equation used to derive the concentration is a variant of the well known Lambert-Beer Law of optical absorption.

In simple terms, the DIAL long-path optical measurement is merely a normal absorption spectroscopy measurement which is made in situ through the atmosphere over a given pathlength rather than through a conventional sample gas cell. The intensity of the backscattered light is determined by the spectroscopic absorption cross-section of the target molecule at the on- and off- resonance wavelengths chosen for the measurement, the pathlength the light travels over is measured, and the concentration of the molecule is thereby determined. By comparing the intensity of the backscattered light to the transmitted light at on- and off-resonance wavelengths, a reading of the concentration of the target air pollutant can be made.

Selection of Absorption Wavelength Pairs and DIAL Equipment Setup

There is no competing species to NO2 in the 4,500 Angstrom band. There is a rather large differential volume scattering coefficient between 308 nanometers and 4,500 Angstroms, due to differential Rayleigh and Mie scattering; however, because of the convenient availability of the XeCl 308 nanometer output and because of the possibility that simultaneous (or near-simultaneous) measurements of both NO2 and O3 could be made with the proper combination of wavelengths, 3080 Angstroms (308 nanometers) was chosen as the on-resonance wavelength for Ozone for this work, 4478.5 Angstroms (447.85 nanometers) was chosen as the on-resonance wavelength for NO2, and 4500 Angstroms (450 nanometers) was chosen as the off-resonance wavelength for both NO2 and O3. Around 4,500 Angstroms, the nitrogen dioxide absorption is largely interference free. The strong visible absorption band of this molecule, making it easy to measure, also makes it lose the sky’s lovely blue color; thus, the brown color of smog is not just due to the presence of soot and particulate matter, it is largely due to a paucity of blue light (Figure 8).

In the first part of Year 2, The airborne XeCl excimer dye laser equipment setup was modified, and a single laser system was adapted as a truck mounted unit for horizontal measurements by Skyborne, Inc (Figure 8). The DIAL measurements were carried out in May 2001 by tunable DIAL equipment in the first pilot air quality study in Oxford, Mississippi. The laser beam could be seen as blue light at nighttime in the NO2 spectral band, as shown in Figure 8 (b). The laser beam in UV range for Ozone measurement was not visible.
Results of Air Pollution Measurements and Discussion

The first test site is adjacent to MS Highway 6 in Oxford, Mississippi (Figure 9). This section carries a typical weekday traffic volume of 20,000 to 22,000 vehicles per day. Near-simultaneous measurements of Ozone and NO₂ were made using the differential wavelength pairs by making only minor modifications of the tunable DIAL system. The Newtonian telescope was set up pointing toward the target retroreflector at nighttime because it was easy to see the blue laser beam hitting the target and the back reflection (Figure 8). The on- and off-resonance beams were directed out from the back of the LIDAR truck toward the retroreflector. Full daylight measurements of NO₂ using sequential tuning between the on- and off-resonance wavelengths were made. The DIAL Measurements were made at different times of the day to analyze temporal variations. Three different measurements were made on NO₂ concentration. The first was made on the evening of May 19 at 10 PM. The second was made on the evening of May 24 at 11 PM. The last measurement was made during the morning of May 25 at 10 AM. On May 24, the concentration of O₃ was measured within 30 minutes after the NO₂ measurement. The detailed results are included in the project report (Reference 1).

During the measurements at this site, moderate traffic was observed on the highway during day, and very low traffic was observed during the night. Traffic data were collected on the test site as a part of the on-going City of Oxford’s Intelligent Transportation System (ITS) study, funded by the US DOT and conducted by the University of Mississippi. Airborne LIDAR and color aerial photo missions were completed in March-April 2001 to develop a comprehensive GIS of the Oxford area. Wind and other weather data were collected from the nearby NOAA SURFRAD weather station in Batesville. The DIAL results showed nearly 25 times more NO₂ concentration at 10 AM (daytime) compared to the measurement at 11 PM (nighttime) when the traffic was minimal (Figure 10). Daytime traffic volume on Highway 6 was 6.4 times the traffic at nighttime. Higher NO₂ concentration was also associated with higher air temperature in the daytime measurement. These results are greater than 30 ppb which is generally assumed for natural background level of NO₂ in rural areas.
Tupelo is another test site with both a higher population and traffic volume. The DIAL test site was located near McCollugh Boulevard, off US Highway 78 East. In Tupelo, two different DIAL readings were made of Nitrogen Dioxide. All of the measurements were made during the evening of 31st May following a break in the afternoon rain. The measured NO2 concentration at 10:00 PM was 13.8 ppb, and almost no detection was made at 10:40 PM. The insignificant amounts of NO2 concentration measured in Tupelo is reasonable considering the effects of heavy rain on both days, and very small traffic on surrounding roads during the night.

This study indicates that a good air pollution prediction model should include traffic volume and air temperature variables. The air quality degradation, affected by diffusion and dispersion of air pollutants, depends upon topographic, climatic, and weather conditions. The project is developing an enhanced model of air pollution for assessing the air quality impact of transportation systems, which significantly affect the quality of life.

Because the tunable laser measurement is real-time and uses a long sampling distance, it is less time consuming and is free from sampling inaccuracies which plague the conventional monitoring stations and direct vehicle exhaust measurements. The effect of transportation e emissions on air pollution can be assessed, and the uncertainty in many parameters of dispersion models can be reduced if an investment is made on laser based remote sensing monitoring of air pollution. The real-time in situ character of the long-path spectroscopic measurement allows the concentrations of trace gases to be measured as they naturally exist in the atmosphere, over pathlengths which are more representative of actual volume-averaged concentrations than point monitors.

Further DIAL data collection and air quality modeling effort in Years 2 and 3 will include the accelerated highway test track site of the National Center for Asphalt Technology (NCAT) at Auburn University. Records of fuel and oil consumption will be available for calculating vehicle emissions to enhance the air quality model. The cooperative agencies involved in this study are: the City of Oxford, Mississippi Department of Environmental Quality (DEQ), the City of Tupelo, and NCAT at Auburn University.