Optical Remote Sensing of Atmospheric Pollutants Using an AOTF Based Imager

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April 1996

Introduction

Environmental pollution from industry and automobiles has been a global problem for decades. While regulations are demanding strict emissions standards from auto manufacturers and factories, increasingly sophisticated pollution monitoring techniques are being deployed everyday. There are increasing demands for systems capable of pollution mapping at a reasonable installation cost as well as ease, without compromising the quality of measurement. The primary species of interest are sulfur dioxide (SO_2) and nitrogen dioxide (NO_2). In the past, many lidar systems have been developed to monitor these species. A lidar design, in general, involves an elaborate optical design for the transmitter, and, more importantly, the detection system. Recently, through the advancement of the acousto-optic devices, it is possible to design more versatile detector systems. This paper proposes a system design that is versatile, i.e. capable of making multiple wavelength measurements, and compact. The prototype is designed around an Acousto-Optic Tunable Filter (AOTF) and CCD imagers.

Pollutant Characteristics

Table 1: Air Pollutants (condensed from [1])

Pollutant	Major Sources	Comments
Carbon monoxide (CO)	Motor-vehicle exhaust; some industrial processes	Health standard: 10 mg/m^3 (9 ppm) over 8 hr; 40 mg/m^3 over 1 hr (35 ppm)
Sulfur dioxide (SO_2)	Heat and power generation facilities that use oil or coal containing sulfur; sulfuric acid plants	Health standard: 80 μg/m^3 (0.03 ppm) over a year; 365 μg/m^3 over 24 hr (0.14 ppm)
Nitrogen oxides (NO, NO_2)	Motor-vehicle exhaust; heat power generation; nitric acid; explosives; fertilizer plants	Health standard: 100 μg/m^3 (0.05 ppm) over a year for NO_2; react with hydrocarbons and sunlight to form photochemical oxidants
Photochemical oxidants (primarily ozone [O_3]; also peroxyacetyl nitrate [PAN] and aldehydes)	Formed in the atmosphere by the reaction of nitrogen oxides, hydrocarbons, and sunlight	Health standard: 235 μg/m^3 (0.12 ppm) over 1 hr

Table 1 summarizes the air pollutants and their sources and corresponding health standards. These standards are enforced by the *Clean Air Act Amendments of 1990* (U.S. Environmental Protection Agency). In particular, we note the health standard figures for SO_2 and NO_2 to be 80 $\mu g/m^3$ and 100 $\mu g/m^3$ over a year respectively. The major sources of these species are motor vehicles, power generation plants, sulfuric acid plants and fertilizer plants. An accurate measurement technique for these chemicals complements the health regulations to achieve the requisite goals of reducing pollution levels. The levels of SO_2 and NO_2 found in the atmosphere are $\sim 10^{-2}$ ppm. The object of the AOTF based instrument is to be able to monitor short term and long term changes in the species. The device should be capable of remote operation. We describe the proposed design in the following section.

System Description

A detection system using the AOTF is currently being developed at Penn State to image industrial pollutants. Figure 1 shows a schematic of the system.

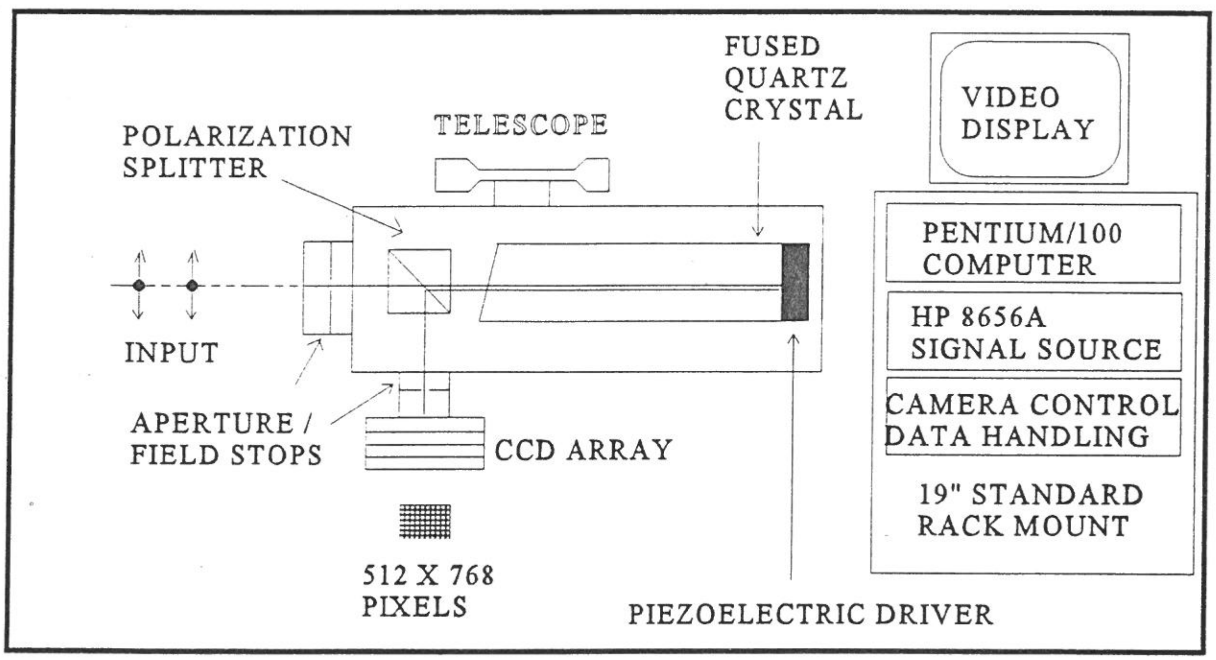

Figure 1: AOTF Based Imager System

The system essentially comprises of the AOTF interfaced with a CCD imaging unit. The incident light enters the AOTF through an aperture stop at the front end. The AOTF has an entrance angle of 2°, and allows light to be incident on the polarization splitting cube. The active area of this cube has a diameter of 6 mm. One polarization component of the light traverses through the fused quartz crystal. The crystal is subjected to acousto-optic stress via the piezoelectric driver which sets up a variation of index of refraction along the light path. This causes light with the wavelength of interest to traverse in an orthogonal polarization through the crystal. This light gets reflected from the back surface of the crystal and returns to the polarization splitting cube. Once again the two polarization components are separated and the wavelength of light to be observed is incident on the CCD imager. The wavelength is selected by a sinusoidal signal that drives the piezoelectric unit.

The CCD imager comprises of a two dimensional array (512 X 768) with a 16 bits per pixel resolution. The imaging array is built onto a thermoelectric cooler that improves the shot noise performance of the CCD array. This imager has a SCSI link to the computer for transferring images and for controls such as integration time, resolution, temperature etc. We use a commercially available 25 mm focal length CCTV lens for this imager. The lens has a field stop for restricting the field of view of the camera. The integration time of this camera can be varied from 1 ms upwards to capture images. The images are stored as standard Tagged Image File Format (TIFF) files. In addition, the use of a sighting telescope allows us to point the camera at a distant object with a fair amount of precision.

The control and data acquisition system is mounted on a standard 19" rack. Images can be viewed in real time on the video display. The computer controls the HP8656A synthesized signal generator in addition to providing links to the camera. The frequency range of the synthesized signal between 60-140 MHZ @ 1V p-p controls the center wavelength of the AOTF from the ultraviolet through the visible region of the spectrum. The synthesized signal has a harmonic purity of better than 50 dB, which is a critical factor in the AOTF performance.

Measurement Technique

A differential absorption technique is used to image atmospheric pollutants. The key feature of an AOTF is the versatility which has been used here. It is possible to step through several wavelengths of interest by control of software in making Differential Absorption Spectroscopy (DAS) measurements of various species. Table 2 lists some absorption lines in the spectrum corresponding to different pollutants. For a particular species, the corresponding absorption line can be used as λ_{ON}, and a suitable line as λ_{OFF}.

Table 2: Absorption Lines (condensed from [2])

Species	Wavelength (nm)
SO_2	286.55
O_3	279.20
NO	226.80
NO_2	448.10

The AOTF is centered around these wavelengths. Images from a single target, such as a smoke stack, are taken at online and nearby offline wavelengths such as these in turn. A pixel-by-pixel difference of the two images gives the required image for a particular species. By comparing a time series of such images, spatial and temporal properties of the species can be inferred. With an acceptance angle of 2°, a region 7m in diameter can be observed at a distance of 100m from the AOTF. An improved algorithm to retrieve an image includes the background measurement of the signal as well. An image is taken during which the AOTF is disabled. This corrects for any light leaks within the system. This image is subtracted from the corresponding signal images.

The imaging system allows complete control via software for making the DAS measurements using the AOTF. The filter accuracy is better than 5Å, and depends only on the quality of the acoustic signal. A strong highlight of the system is its repeatability of measurements that results in easier calibration restraints. The spectral resolution of the AOTF is 1.5-2.0 Å, which is imperative in detecting trace constituent using the DAS technique. The power requirements for the entire system are less than 500W (120 VAC @ 4A). These features, along with the compact size of the system, make remote installation of this imager possible. The CCD cameras have been deployed and tested in field experiments in the past and have proven to be excellent tools for remote sensing.

Data Analysis

Figure 2 shows a flowchart for the data acquisition process.

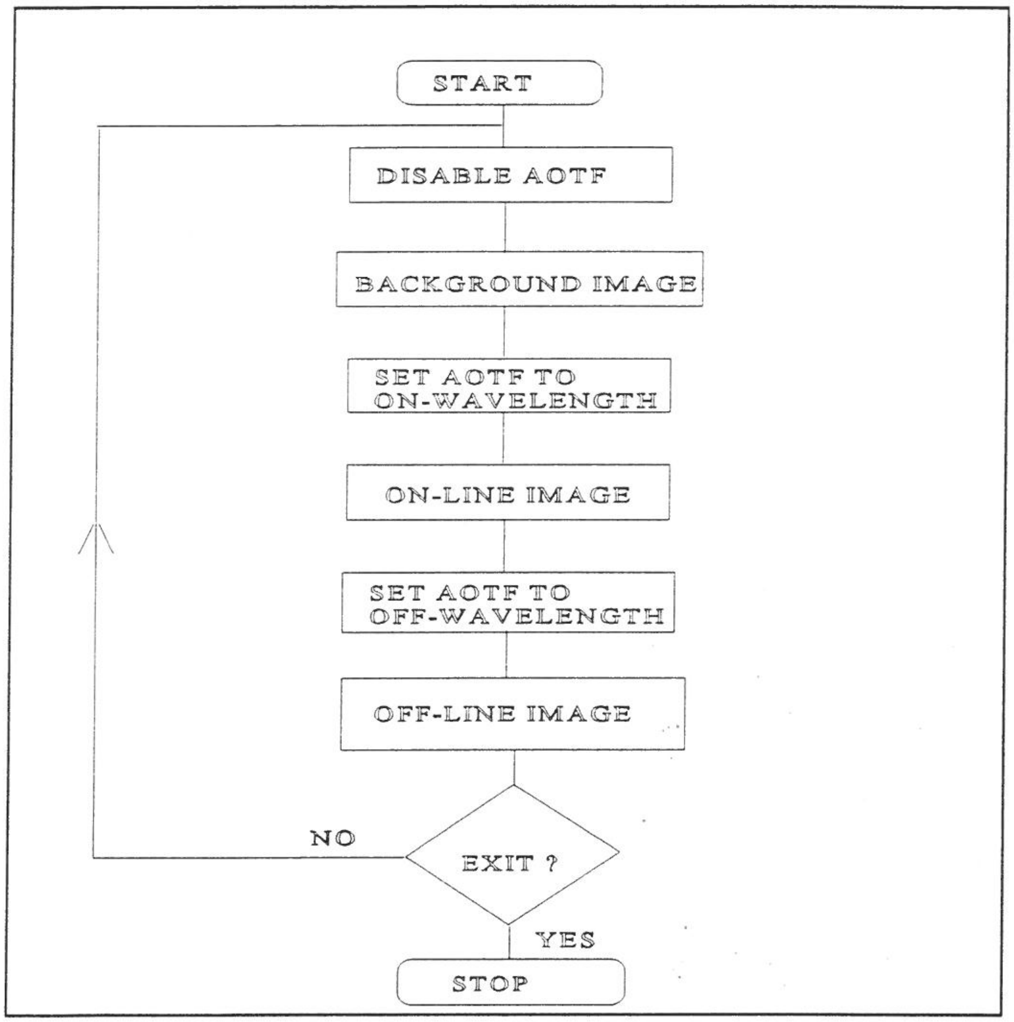

Figure 2: Data Acquisition Algorithm

As a first approach, we used the above algorithm for data acquisition. The image obtained from one cycle of the algorithm provides images at the on- and off- wavelengths and can be corrected for any bias resulting from extraneous light entering the system.

The concentration of a species using the DAS technique is given by

$$\rho_{con}(r) = \frac{1}{2\Delta\sigma}\frac{d}{dr}\ln[\frac{S_{\lambda ON}}{S_{\lambda OFF}}] \qquad (1)$$

where $\Delta\sigma$ is the difference of absorption cross sections of the species at the two wavelengths, and S represents the measured signal value. If the on- and off- wavelengths are selected very close to each other, the error in $\Delta\sigma$ is reduced, which considerably improves the data retrieval. The ratio of the two signals allows cancellation of attenuation effects through the atmosphere of the two wavelengths. $S_{\lambda ON}$ and $S_{\lambda OFF}$ are obtained by subtracting the background image measurement from the signals received at the on-line and the off-line respectively. Equation (1) gives the path-integrated concentration of the species using these signal values. An image of the spatial distribution of the pollutant can be obtained using this technique.

The AOTF works on the principle of photoelasticity. The relationship between the acoustic frequency f, and the center wavelength of the passband λ_0 is given by

$$f = \frac{K}{\lambda_0} \qquad (2)$$

where K is the calibration constant of the AOTF. K depends upon the crystal characteristics and the electronics of the acoustic driver [3,4,5]. Figure 3 shows a plot of K versus λ_0.

The mean value of K from the plot is 52025 nm-MHz. For example if we wanted to tune the instrument to λ_{ON} of 448.10 nm, the corresponding driver frequency would be 116.1 MHz. A careful calibration is necessary for obtaining the on- and off-lines precisely for a species.

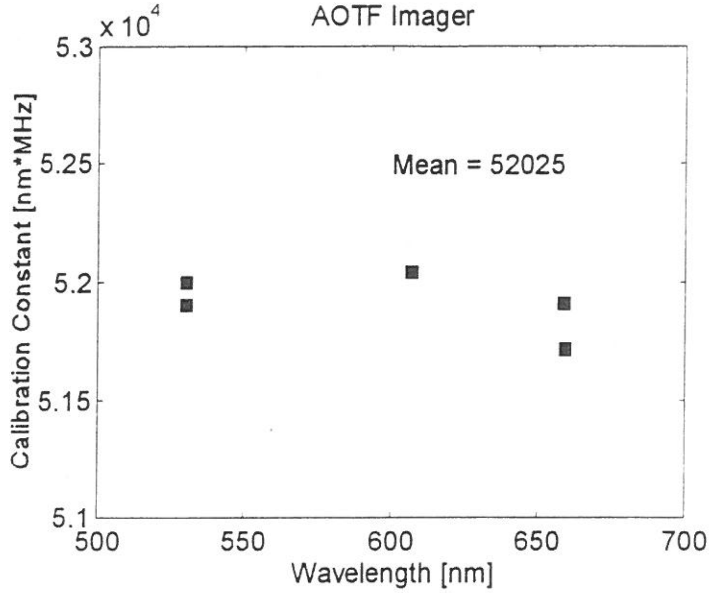

Figure 3: AOTF Calibration Constant

Conclusions

A design for an AOTF based imager has been developed for Differential Absorption Spectroscopy of trace species in the atmosphere such as sulfur dioxide and nitrogen oxides. The system description is presented in detail along with specifications and data acquisition algorithms. The system can be used to detect pollutant concentration in a smoke plume from a power plant or to monitor the spatial/temporal distribution of automobile pollution using the DAS method. The measurements are possible using the sun as a source and imaging the on- and off- lines through a scattering volume onto a CCD array. The system is very compact and field deployable. All controls are established through software and can be operated remotely over a phone line. Commercially available image processing packages such as Matlab or Spy-Glass Transform may be used to manipulate the images and retrieve data. The 16-bit resolution of the CCD array allows a large dynamic range which compensates for the varying transmission through the AOTF with frequency. The small entrance angle of the AOTF causes the imager to have a smaller footprint, thereby giving it the ability to image areas with greater resolution.

Future work using the AOTF imager includes optimization of the optical system. The imaging lens will be matched to the angular specifications of the AOTF. All optical mounts and fittings should be compatible so as to minimize light leakage. In addition, software, preferably in C language, will be developed for operation, diagnostics and data analysis. A major effort (with cooperation from the U.S.E.P.A. possibly) would be an intercomparison of data obtained from other DIAL or Raman lidar systems.

References

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3. Xu, J. and R. Stroud, *Acousto-Optic Devices Principles, Design and Applications*, John Wiley and Sons Inc., 1992.

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ACOUSTOOPTIC FILTER PHOTON-1101.

Description and Operation Manual.

1. Description.

1.1. Purpose.

1.1.1. Acoustooptic filter Photon-1101 is designed to extract narrow spectral line from wide spectral range. Wavelength and intensity of extracted spectral line can be changed by control signal.

1.1.2. Filter is delivered in version suitable for operation in lab conditions.

1.2. Specifications.

1.2.1.	Material	SiO_2
1.2.2.	Spectral range, nm	350-540
1.2.3.	Control signal range, MHz	128-64
1.2.4.	Spectral resolution, nm	0.14-0.39
1.2.5	Control signal time-average power, Wt	<3
1.2.6	Mode of operation	continuous or impulse
1.2.7.	Input characteristic impedance, Ohm	50
1.2.8.	KSVN less than	2.5
1.2.9.	Light Window (range), diameter, mm	6
1.2.10.	Difractive efficiency	
	at wavelength 325 nm (115 MHz), %/WT	70/15
1.2.11.	Entrance angular aperture, ang.degrees	2.0

1.3. Filter Design and Operation.

1.3.1. Filter consists of metal case, in which input polarizer from calcite($CaCO_3$), acoustooptic cell from crystallic quartz(SiO_2) and output polarizer, orthogonal to the input polarizer, are consequently arranged. Converter from lithium niobates ($LiNBO_3$) and sound absorber are attached to the cell. Filter has a connector for control signal line, 2 windows for optical input and output, and base plate with 4 mounting holes.

1.3.2. Optical scheme of the filter is shown in Figure 1.

Figure 1.

1 - incident non-polarized light;

2 - input polarizer;

3 - polarized light (O-ray);

4 - acoustooptic cell;

5 - converter;

6 - sound absorber;

7 - diffracted and non-diffracted light (E- and O-rays correspondingly);

8 - output polarizer;

9 - diffracted light (E-ray).

1.3.3. Filter operation is based on acoustooptic effect. Alternating electric field (control signal) applied to the converter excites acoustic wave in crystallic quartz, causing periodic perturbations of the refraction index, i.e. creating phase grating in the medium. Diffraction of light collinear to the acoustic wave occurs on this grating, moreover, as result of diffraction, light polarization changes to the orthogonal. As result, non-diffracted ray with original polarization (O-ray) and diffracted ray with orthogonal polarization (E-ray) are observed at the cell output. Output polarizer extracts from these 2 rays only diffracted E-ray.

Filter selectivity is determined by 1-to-1 relationship between wavelength of diffracting light and frequency of the acoustic wave. This relationship can be expressed as

$$f = \frac{K * \Delta n}{\lambda},$$

where f - frequency of the control electric signal,

λ - wavelength of the diffracting light,

K - coefficient,

$\Delta n = no - ne$, no and ne are refraction indexes of the ordinary and extraordinary rays correspondingly.

2. Operation Manual.

2.1. General Instructions.

2.1.1. Power of the control signal should not exceed average-in-time value of 3 Wt, i.e. for the continuous control signal P_o<3 Wt, and for impulse control signal P_i /N<3 Wt, where N=T/t, t-impulse duration, T-impulse period.

2.1.2. Tuning to the various wavelength of the transmitted wave is achieved through change of the frequency of the control electric signal. Relationship between wavelength and frequency is given as

$$f * \lambda = K * \Delta n,$$

where K=3.97*10^5 MHz*nm.

$\Delta n = no - ne$ for crystallic quartz.

[f] - MHz,

[λ] - nm.

2.1.3. Intensity modulation of the filtered light is achieved through control signal electric power modulation.

2.2. Order of Operation.

2.2.1. Fix filter in the required place of the optical path. Window closest to the control signal connector is output window.

2.2.2. Assemble system in accordance with Figure 2.

2.2.3. Connect filter to the control signal source (driver).

2.2.4. Align filter, so that incident light beam hit the center of the input window orthogonal to the window plane. It is necessary to form the beam so that it's divergence did not exceed filter's angular aperture $\pm 1°$.

2.2.5. Apply control signal to the filter in accordance with 2.1.2.

2.2.6. With additional alignment achieve maximal intensity of the filtered light.

2.2.7. Overall dimensions of the monochromator are shown in the Figure 3.

2.2.8. Correspondence between frequency (f) of the HF-signal and wavelength of the transmitted wave is shown in the table.

Table of the Correspondence between Excitation Frequency and Wavelength of the Transmitted Signal for the Acoustooptic Monochromator.

λ,nm	253	260	270	280	300	325	350	400	450	480	500	532
f, Hz	160	155	146	139.5	127.5	115	104.8	89.8	77.8	72.3	69	64.5

АКУСТООПТИЧЕСКИЙ ФИЛЬТР PHOTON-1101

Техническое описание и инструкция по эксплуатации

I. Техническое описание

1.1. Назначение

1.1.1. Акустооптический фильтр Photon-1101 предназначен для выделения из широкого спектрального диапазона электромагнитного излучения узкой линии, длина волны и интенсивность которой изменяются в соответствии с электронным управляющим сигналом.

1.1.2. Фильтр поставляется в исполнении, пригодном для эксплуатации в лабораторных условиях.

1.2. Технические данные

1.2.1.	Материал	SiO_2
1.2.2.	Спектральный диапазон, нм	350 - 540
1.2.3.	Диапазон управляющих частот, МГц	128 - 64
1.2.4.	Спектральное разрешение, нм	0,14 - 0,39
1.2.5.	Управляющая средняя по времени мощность, Вт, не более	3
1.2.6.	Режим работы	непрерывный или импульсный
1.2.7.	Входное волновое сопротивление, Ом	50
1.2.8.	КСВН, меньше	2,5
1.2.9.	Световое окно (рабочий диапазон), диаметр, мм	6
1.2.10.	Дифракционная эффективность на длине волны 325 нм (115 МГц), %/Вт	70/15
1.2.11.	Входная угловая апертура, угл.град.	2,0

1.3. Устройство и работа фильтра

1.3.1. Конструкция фильтра представляет собой металлический корпус, в котором последовательно расположены входной поляризатор из кальцита ($CaCO_3$), акустооптическая ячейка из кристаллического кварца (SiO_2) и выходной кальцитовый поляризатор, уставленный ортогонально входному. К ячейке присоединены

2.2. Order of Operation.

2.2.1. Fix filter in the required place of the optical path. Window closest to the control signal connector is output window.

2.2.2. Assemble system in accordance with Figure 2.

2.2.3. Connect filter to the control signal source (driver).

2.2.4. Align filter, so that incident light beam hit the center of the input window orthogonal to the window plane. It is necessary to form the beam so that it's divergence did not exceed filter's angular aperture $\pm 1°$.

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