

A PHOTOPHONIC INSTRUMENT CONCEPT TO MEASURE
ATMOSPHERIC AEROSOL ABSORPTION

by

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INTRODUCTION

The role played by atmospheric aerosols is many faceted. They range from the nostalgic wood smoke laying in a valley in West Virginia to the impact upon the thermal balance of the earth. Some of the facets, such as the effect on visibility and the effect on global and regional temperatures, have resulted in many studies to better understand and quantify the effects of aerosols while the nostalgic has been left to the poets.

One class of these studies is aimed at determining the influence that aerosols have on the earth's global and regional temperatures. These studies have resulted in contradictory conclusions. Some conclude an earth warming effect while others conclude the effect is a cooling one. Compared to atmospheric gases the effect of aerosols is not well understood and is much more complicated.

However, the impacts of aerosols compared to gases are not insignificant. For instance, the absorption of solar radiation by aerosols in a reasonably clear air is comparable to that of the atmospheric gases, and in an urban area can be four times that of the absorption by gases (1).

The research reported in this thesis was done to determine the feasibility of a conceptual instrument to measure the earth's atmospheric aerosol absorption.

The best measurement instrumentation in use today to supply the required information is the opal glass integration method. This method and its variations acquires an aerosol sample at the desired site and time and the absorption of the sample is later measured under laboratory conditions. This method is reported to be accurate within $\pm 100\%$ (2, 3). Therefore, a need exists for an instrument that can provide in situ measurements of the absorption coefficients in real time and with an improved accuracy. It is hypothesized that the conceptual instrument reported in this thesis can measure the absorption coefficient of atmospheric aerosols.

The objective of the research reported in this thesis was to determine the feasibility of an instrument, based upon the photophonic effect and the double Helmholtz resonator, to measure the absorption coefficients of atmospheric aerosols in the range expected in the earth's atmosphere.

LITERATURE REVIEW

This section will consist of three subsections. 1, a review of photophonic phenomenon's discovery and some of its applications. 2, a review of Helmholtz resonators and some of their uses. 3, a review of the extinction of solar radiation on its way through the atmosphere.

Photophonic Phenomenon

Bell (4) reported in 1880 that while studying the effect of light on the electrical resistance of selenium he had the thought that selenium, under the influence of light, might produce sound much as iron does under the magnetising influence of an intermittent electrical current. And though no sound was heard from the selenium, the thought resulted in a series of experiments that eventually led to success. He found that by holding a sheet of hard rubber close to his ear while a beam of intermittent light fell on the sheet, he heard a distinct musical note. Bell (5) reported in 1881 that tobacco smoke captured in a test tube also produced sound when lighted by an intermittent beam of light.

After Bell's time nothing was reported on the photophonic phenomenon until the work of Viengerov in the late 1930's. Rosengren (6), citing Viengerov, stated that Viengerov constructed a photophonic gas concentration measurement instrument.

Kerr and Atwood (7) reported in 1968 their work on the spectrophone, which measured gas absorption, in which they used a laser as the radiation source. They reported that most of the noise was associated with interaction of the window of the chamber and the laser beam. Two methods of reducing this source of noise will be discussed later in this thesis.

Recent work on the use of the photophonic phenomenon to measure the absorption of aerosols under laboratory conditions was reported by Terhune and Anderson (8). They used a laser radiation source combined with a cylindrical resonant acoustic cavity operating in its lowest order circumferential mode. They measured absorption down to a level of 10^{-7} meter⁻¹ (m) and showed that their instrument was insensitive to scattered light. Their work had limitations imposed by their use of a high chopping rate of 4000 Hz. and the monochromatic nature of lasers. Quimby et al. (9) made use of the photophonic phenomenon in their photoacoustic spectroscopy instrument used to measure the optical absorption spectra of solids.

Helmholtz Resonator

Lamb (10) reported that Helmholtz used the single Helmholtz resonator in his research on the quality of musical sounds. Poynting et al. (11) stated that Helmholtz had a number of spherical resonators he used to analyze the harmonic content of complex sounds. Lamb (10) said that Helmholtz listened for the sympathetic vibrations in the resonator to indicate the presence of that frequency in the sound under study.

Poynting et al. (11) reported on their use of a single Helmholtz resonator in a hot wire microphone used to detect the sound of enemy guns. They also reported on the use by Paris of a double Helmholtz resonator in a hot wire microphone to compare the sound of sirens. They also reported on their use of a double Helmholtz resonator in the determination of the velocity of sound in gases and vapors.

The double Helmholtz resonator was used by Quimby et al. (9) in their photoacoustic spectroscopy instrument used to measure the optical absorption spectra of solids. They found disagreements of about 2 to 1 between the calculated and the measured resonant frequencies of their double Helmholtz instruments. They found disagreements of as much as 100 to 1 between their calculate and measured quality factors. Their major source of in-phase noise was due to cell

wall absorption of the beam energy rather than light scattered into the microphone. Since they lighted only one chamber this noise source could be expected. It will be shown in this thesis that lighting both chambers reduces the noise from this source.

Atmospheric Extinction

The earth's atmospheric extinction of the sun's radiation is the scatter and absorption of a fraction of the sun's direct radiation on its path through the atmosphere to the earth's surface (12). This relationship can be expressed by the Beer Lambert law (2). However, this is an oversimplified expression (13) of a complicated relationship. It assumes that the concentrations of the scattering and absorbing components of the atmosphere are independent of altitude. Which is certainly not true in the case of aerosols which have their largest effect in the lower part of the troposphere (14). Thus, the attenuation of the direct solar energy in the atmosphere is complicated by the variability, in both space and time, of the principle scattering and absorbing components, gases, aerosols and clouds (12).

The absorption by atmospheric aerosols is comparable to that of atmospheric gases in reasonably clear air and in

urban areas can be as much as four times greater (1). Thus, Benjamin Franklin was right when he suggested that atmospheric dust may affect the temperature of the earth (13).

But, do the aerosols tend to have a warming or cooling effect on the earth? We still do not know (2, 14, 15, 16).

THEORETICAL CONSIDERATIONS

Three subjects will be covered in this section. One, the definition of absorption, two, discussion of the photophonic phenomenon and three, a description of the double Helmholtz resonator.

Absorption

The absorption of radiation by an aerosol is the conversion and retention of the intercepted energy by the particles with an accompanying increase in the particles' temperatures (17).

Photophonic Phenomenon

The photophonic effect was discovered and reported by Bell (4) is the fundamental phenomenon operating in the instrument concept reported in this thesis.

To better understand, both qualitatively and quantitatively, the phenomenon the following description and derivation is provided.

Assume a pressure chamber which contains an aerosol and air. According to the equation $P_t = P + PBt$ (18), a change

in the temperature of the chamber air will cause a change in the chamber pressure. In the equation:

P_t = Chamber Pressure at Temperature t

P = Initial Chamber Pressure

B = Pressure Coefficient

t = Temperature Change

defining $\Delta P = P_t - P$

then $\Delta P = PBt$

Another equation, which relates the energy required to cause the change in the temperature of the air, is

$Q = Cgt$ (18) Where

Q = Energy Absorbed by Aerosol

C = Specific Heat of Air

g = Weight of the Chamber Air

A new equation is produced by combining $\Delta P = PBt$ and $Q = Cgt$ which relates the chamber pressure change to the energy absorbed.

$$\Delta P = PBQ/Cg$$

Though this equation is somewhat ideal, because of such factors as the particles' thermal time constants, air being a real gas and the liquid content of some aerosols, it can be used to satisfactorily describe the fundamental relationship in the photophonic effect.

$$\Delta P \propto Q$$

A fixed volume of air when heated by an absorbed energy Q will have an increase in the chamber pressure ΔP . The pressure change can be sensed by an ear, a microphone or other pressure sensitive device to detect the presence of the pressure change and, thus, that the absorption occurred.

Double Helmholtz Resonator

The single Helmholtz resonator used by Helmholtz in his research on the quality of musical sounds were subject to the two important constraints that apply to all Helmholtz resonators (10).

The first is that the linear dimensions of the chamber must be many times greater than the dimensions of the aperture of the throat. Second, the wavelength of the resonant frequency in air must be long compared to the dimensions of the chamber.

The double Helmholtz resonator (11) is fundamental to the instrument concept reported on in this thesis. A qualitative understanding can be acquired, refer to Figure 1, by considering the air in the connecting tube or throat to be a piston which can move inside the tubing. A pressure increase in one chamber will move the piston toward the second chamber compressing that chamber's air, while tending to decrease the pressure in the first chamber. Producing a

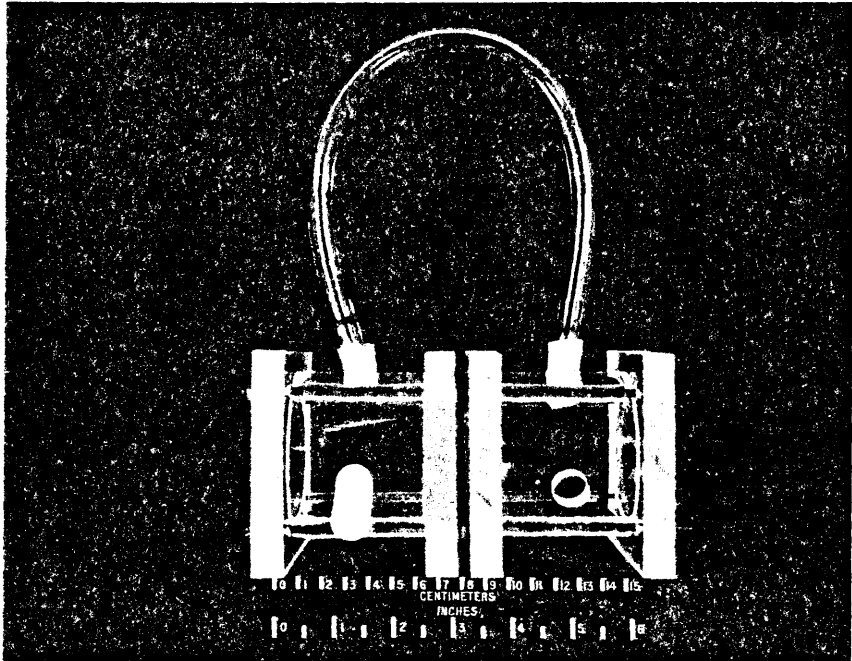


Figure 1 Photograph of a Double Helmholtz Resonator

restoring force proportional to the piston's displacement along the throat. Thus, the double Helmholtz resonator is an acoustical oscillator analogous to the classical mechanical oscillator (9) of a mass between two springs.

A quantitative understanding of the undamped resonant frequency of the double Helmholtz resonator is shown by the following equation reported by Quimby (9).

$$F = C (A/LV)^{1/2}$$

where:

F = Resonant Frequency

C = Speed of Sound

A = Throat Aperture Area

L = Throat Length

$V = V_1V_2/V_1 + V_2$

V_1 = Volume of One Chamber

V_2 = Volume of the Second Chamber

EXPERIMENTAL PROCEDURES

This section on the methods and materials will contain the description of a typical experiment, a description of what was done to obtain a quantitative evaluation of the level of sensitivity of the concept and an identification or description of the equipment or apparatus used in the research.

Typical Experiment Description

A functional block diagram of the equipment used in the experiments is shown in Figure 2. The light source was an incandescent lamp whose radiation output was controlled by a variable transformer. The light beam, after going through an aperture, was amplitude modulated by a mechanical chopper to produce the desired frequency. The modulated beam was focused by a lens into the double Helmholtz resonator chamber or chambers. When the experiment required an aerosol, cigarette smoke was blown into the aerosol chamber. The pressure variations were sensed by the microphone or microphones and the electrical analogs of the pressure variations were amplified and processed by a differential amplifier and

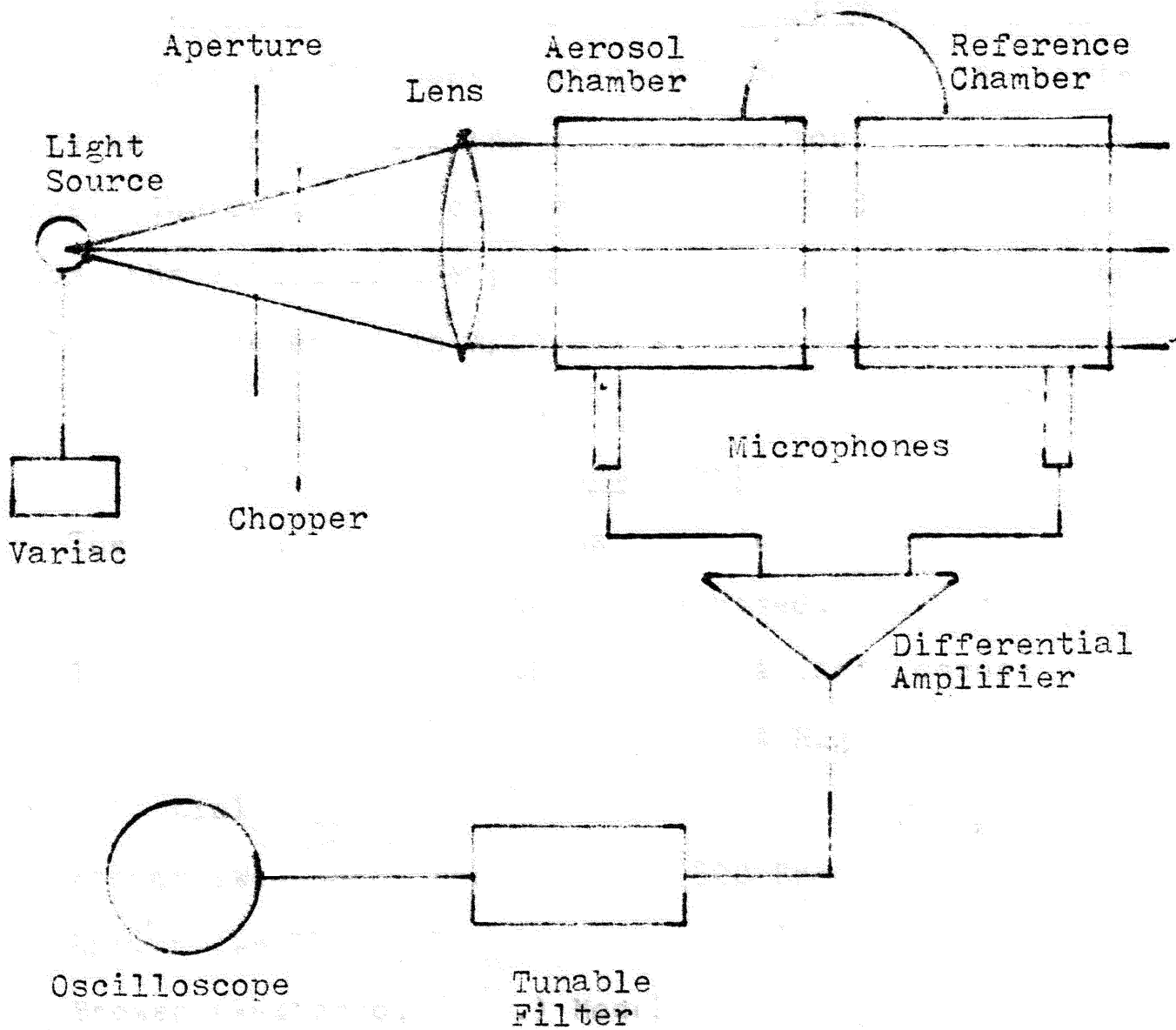


Figure 2 Block Diagram of the Experiment

a tunable filter. The data were then displayed on the oscilloscope and photographed.

Quantitative Confirmation of the Concept's Sensitivity

The quantitative confirmation of the concept's sensitivity was done by using the sun's radiation as the light source. The derivation of the equations used in the calculation, the values of the parameters used and the calculated results are presented in Appendix A.

Equipment Identification

The following equipment was used during the course of the research on which this thesis is based.

Tektronix (Beaverton, OR) Type 535A Oscilloscope

Tektronix (Beaverton, OR) Type 1A7A High Gain Differential Amplifier

Brower (Westboro, Mass.) Model 500 Programmer 4

Brower (Westboro, Mass.) Model 132 Lock-in Meter

Brower (Westboro, Mass.) Model 312 Chopper

Brower (Westboro, Mass.) No. 20 Chopper Blade

General Electric (Cleveland, Ohio) G. E. Quartzline

Lamb DYS/DYV

American Optical (Southbridge, Mass.) Glass Lens 40 mm

Dia., 100 mm Fl.

General Radio (Concord, Mass.) Model 1962-9801 Micro-
phone

General Radio (Concord, Mass.) Model 1560-p42 Pre-Amp
EDMAC Associates (East Rochester, NY) Model 8010 A Tun-
able Filter

Hewlett Packard (Palo Alto, Ca.) Model 796A Oscillo-
scope Camera

General Radio (Concord, Mass.) Model WSMT3 Variac

Double Helmholtz Resonator - See Figure 1

Power Supply and Differential Amplifier, Designed and
Built by the Author, Flat Frequency Response, Gain
of Five.

RESULTS AND DISCUSSIONS

The results of the experiments are the variations in the amplitudes and frequencies of the sounds which occurred in the chambers. The analogs of the sounds were displayed on the screen of an oscilloscope. The oscilloscope displays were photographed for a permanent record of the results. In all of the data presented, the scale of the abscissas is 20 milliseconds per centimeter (MS/cm).

There are two different scales used in the ordinates of the photographic data. Those data called "signals" have a scale of 5 millivolts per centimeter (MV/cm) and those called "noise" have a scale of 0.5 MV/cm.

All photographic data in this thesis are relative. Thus the axes are provided with scales only and are not numbered. The oscilloscope was set on 1 to 300 Hertz (Hz.) bandwidth. The chopper was running during all data periods. The light source was on during some data periods and off during others. Therefore, the status of the light will be stated in the descriptive title of each data figure.

Confirmation of the Photophonic Concept

To provide a qualitative confirmation of the photophonic concept, an experiment was run with the intensity modulated light passed through the pressure chamber containing tobacco smoke as the major aerosol.

The pressure chamber signal in Figure 3 shows a 30 Hz. wave, the same as the chopper frequency, and an amplitude of about 4 MV.

Figure 4 shows the results under the same conditions but without the aerosol in the pressure chamber. The system noise in this photograph has an amplitude of about 0.7 MV. Most of it has the same fundamental frequency as the modulation frequency and some other noise of higher frequencies.

Thus, the combination of the light, the aerosol, and pressure chamber did produce an intelligible signal providing qualitative confirmation that the photophonic concept worked.

The noise data, in addition to indicating the signal to noise limit, also show that the major portion of the noise is at the same frequency as the beam modulation and thus is related to the chopper or the modulated beam. Noise reduction techniques, which will be discussed in later subsections, will attempt to minimize the noise from these two possible sources and others.

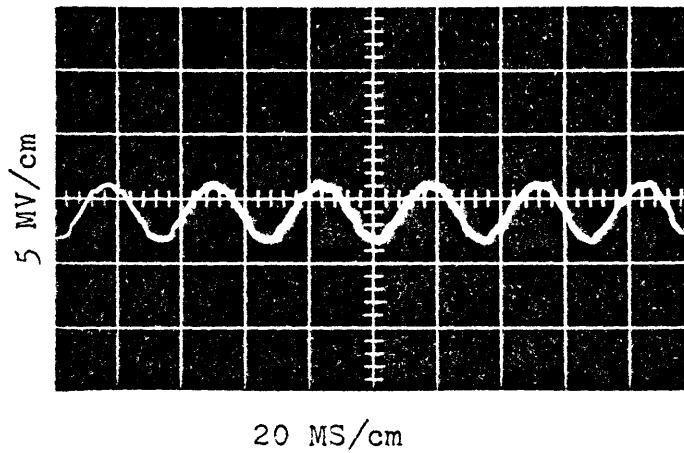


Figure 3 Pressure Chamber Signal, Light On, Aerosol, Confirmation of the Photophonic Concept

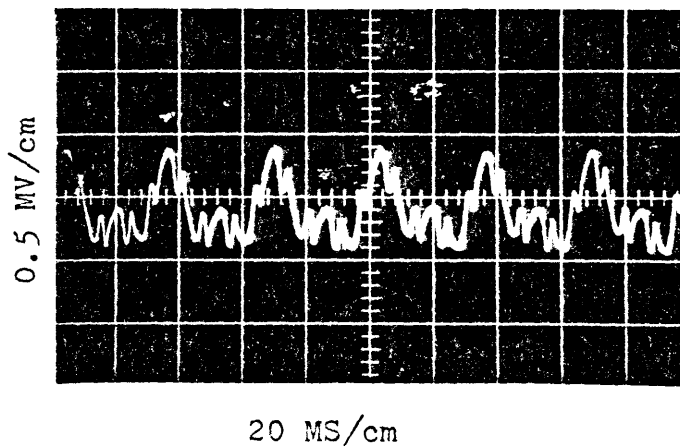


Figure 4 Pressure Chamber System Noise, Light On, No Aerosol, Confirmation of the Photophonic Concept

Double Helmholtz Resonator

This experiment was done to determine what signal improvement the use of a double Helmholtz resonator would have over a simple pressure chamber. The light beam was passed through the pressure chamber, which contained an aerosol, and the pressure chamber signal data were obtained. Then, the pressure chamber was connected to the reference chamber, making a double Helmholtz configuration as shown in Figure 1, and the double Helmholtz data were obtained.

The double Helmholtz signal (Figure 5) has an amplitude of about 24 MV. The pressure chamber signal (Figure 6) has an amplitude of about 5 MV. Therefore, the experiment showed that the double Helmholtz has a signal improvement of about five times greater than the simple pressure chamber.

Double Helmholtz Signal Phase

During resonance of a double Helmholtz resonator the signal pressure changes in the two chambers are 180 degrees out of phase. In this experiment the light beam was passed through the aerosol chamber, and the signal of each chamber was sensed, and the photographic data were acquired.

A comparison of the phases of the signals in Figure 7 and Figure 8 confirms that the chamber signals were 180 degrees out of phase.

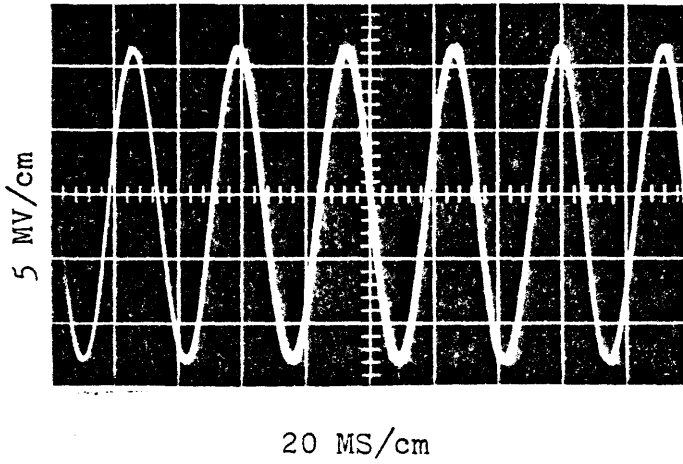


Figure 5 Double Helmholtz Signal, Light on,
Aerosol, Double Helmholtz Resonator

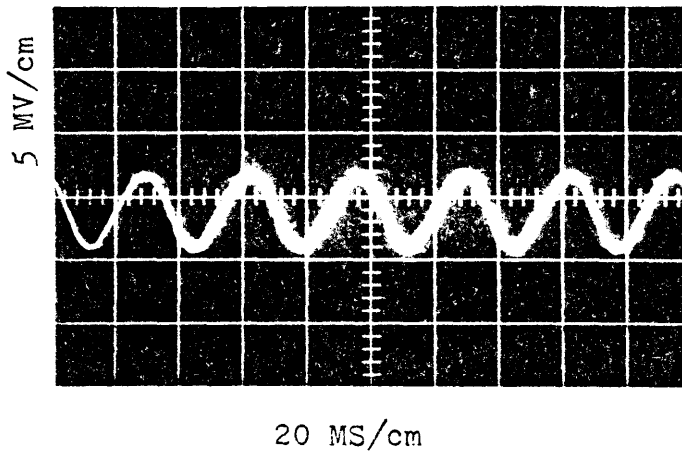


Figure 6 Pressure Chamber Signal, Light on,
Aerosol, Double Helmholtz Resonator

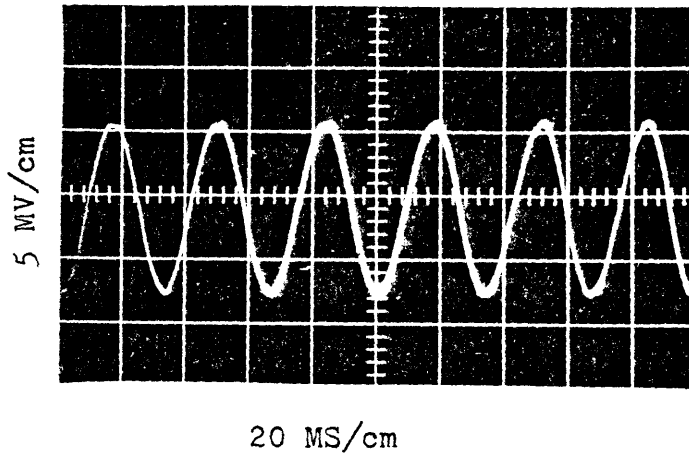


Figure 7 Double Helmholtz Signal,
Reference Chamber, Light On,
Aerosol, Double Helmholtz Signal
Phase

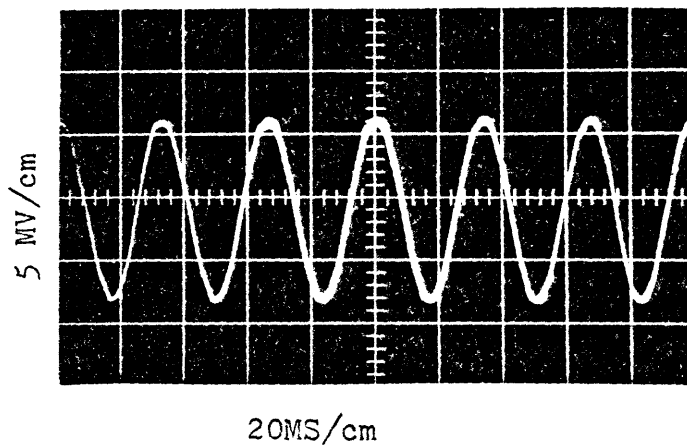


Figure 8 Double Helmholtz Signal,
Aerosol Chamber, Light On,
Aerosol, Double Helmholtz
Signal Phase

This signal phase phenomenon can be used to improve the signal and to reduce the noise. Techniques that take advantage of the phenomenon will be discussed in later subsections of this thesis.

Signal Improvement by Electrical Means

Since the pressure signals exist in both chambers of the double Helmholtz, the signal amplitude could be improved by sensing the signals in both chambers and adding them together. In this experiment the light beam was passed through the aerosol chamber and the signals of the chambers were sensed and photographed.

The signal amplitude in Figure 9, using only a microphone in the aerosol chamber, is about 2 MV. The signal amplitude in Figure 10, using a microphone in each chamber, is about 4 MV. Thus, the two microphone case provided a signal amplitude increase of about two times greater than the one microphone case. This is the gain that was expected. It is important to remember that the two pressure signals were 180 degrees out of phase, as were their respective electrical analogs. The two electrical signals were combined in a differential amplifier which resulted in the two signal amplitude being added rather than subtracted.

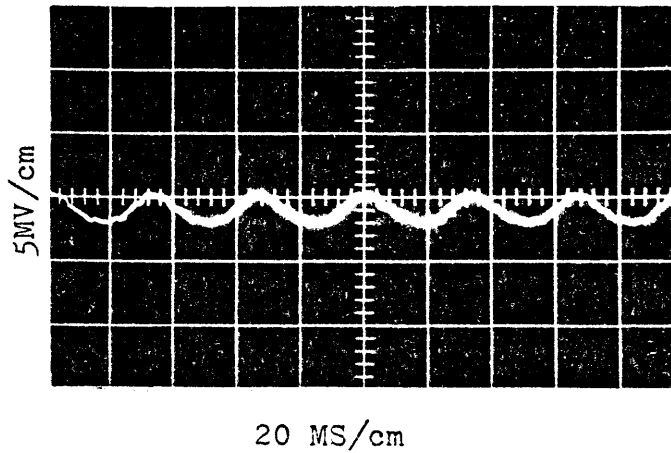


Figure 9 Double Helmholtz Signal,
One Microphone, Light on,
Aerosol, Signal Improvement
by Electrical Means

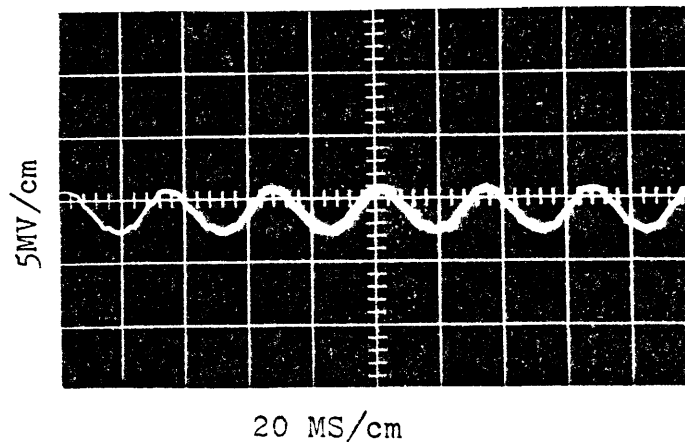


Figure 10 Double Helmholtz Signal,
Two Microphone, Light on,
Aerosol, Signal Improvement
by Electrical Means

Noise Reduction by Electrical Means

The electrical outputs of the two microphones, one in each chamber, were subtracted in the differential amplifier, and any pressure changes that occurred in the chambers that were in phase were subtracted by the differential amplifier. In this experiment the light was off and no aerosol was injected into the aerosol chamber.

The noise output from the one microphone case in Figure 11 has an amplitude of about 1.0 MV while that in Figure 12, the two microphone case, has an amplitude of about 0.3 MV. An obvious reduction in the noise. Since the major component in the noise of Figure 11 was at the modulation frequency and the light was off, the source of the noise was the chopper blade.

Noise Reduction by Acoustical Means

One of the major noise sources in the double Helmholtz concept is the unwanted absorption of the light beam in the test chamber. In one case of this experiment the light beam was passed through only the test chamber and in the other case the beam was passed through the test chamber and the reference chamber. The light was on and no aerosol was injected into the test chamber.

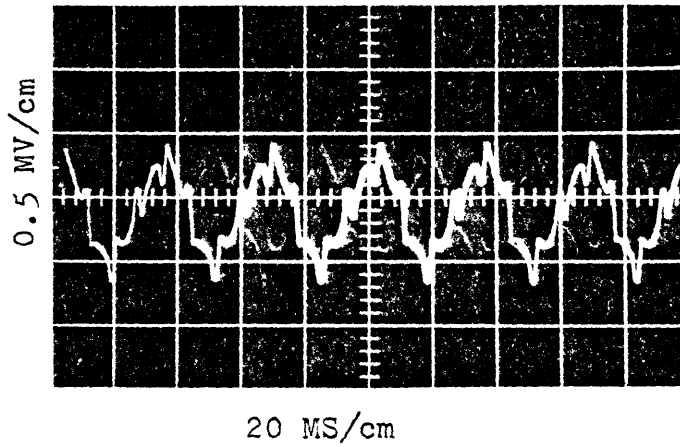


Figure 11 Double Helmholtz Noise,
One Microphone, Light Off,
No Aerosol, Noise Reduction
by Electrical Means.

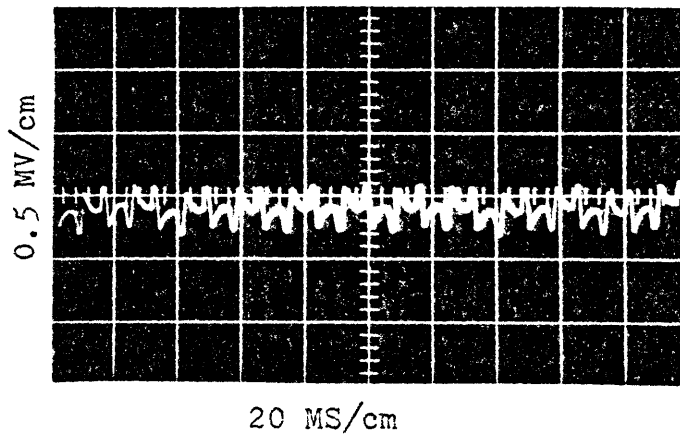


Figure 12 Double Helmholtz Noise,
Two Microphones, Light Off,
No Aerosol, Noise Reduction
by Electrical Means

The noise data in the one lighted chamber case is shown in Figure 13 and has an amplitude of 1.7 MV. The amplitude of the noise in the two lighted chambers case is shown in Figure 14 and has an amplitude of about 0.8 MV. A comparison of these two amplitudes illustrated that the two lighted chambers technique did cause a reduction in the noise.

Quantitative Confirmation of the Concept

In order to justify any further work on this concept it was necessary to determine if the instrument had the capability to measure absorption coefficients in the range expected by the earth's atmospheric aerosols. To provide this confirmation a measurement was done using the sun's radiation and is further described in Appendix A.

The result of the measurement was a 0.2 MV signal. This value was used in the calculation in Appendix A and showed that the concept could measure an absorption coefficient of about 10^{-6} per meter. The range of expected coefficients is from 10^{-3} per meter in a highway tunnel to 10^{-7} per meter at a remote mountain site and 10^{-9} per meter in the stratosphere (3, 19, 20).

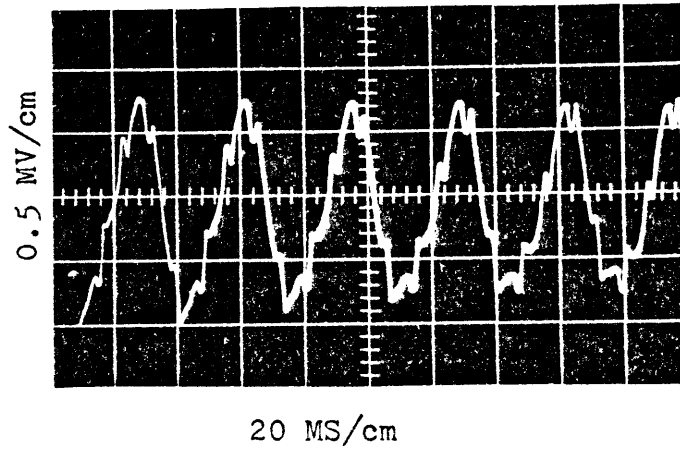


Figure 13 Double Helmholtz Noise,
One Lighted Chamber, No Aerosol,
Noise Reduction by Acoustical Means

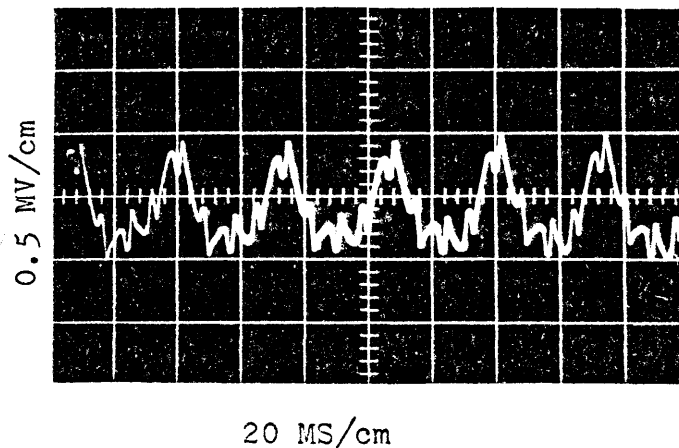


Figure 14 Double Helmholtz Noise,
Two Lighted Chambers,
No Aerosol, Noise Reduction
by Acoustical Means

SUMMARY AND CONCLUSIONS

A laboratory model of an instrument to measure the absorption of atmospheric aerosols was designed, built, and tested. The design was based upon the photophonic phenomenon discovered by Bell and an acoustic resonator developed by Helmholtz.

Experiments were done to show ways the signal amplitude could be improved and the noise reduced and to confirm the instrument was sensitive enough to be practical.

The research was undertaken to develop concepts which show promise of being improvements on the instruments that are presently used to measure the absorption of the sun's radiation by the earth's atmospheric aerosols.

The following conclusions were reached:

1. The concept of using the photophonic phenomenon in a double Helmholtz resonator can provide the basis of an instrument to make in situ and real time measurements of the absorption of visible radiation by the aerosols in earth's atmosphere.
2. The double Helmholtz design provided an improvement in the signal amplitude over the simple pressure chamber.

3. The two microphone technique provides an improvement in the signal amplitude.
4. The two microphone technique provides a reduction in the system noise.
5. The two lighted chamber technique provides a reduction in the system noise.
6. The design has sufficient sensitivity to measure absorptions within the range expected in the earth's atmosphere.

FUTURE WORK

The following are suggested as areas of possible improvement in the instrument concept.

Research should be done to determine the optimum beam modulation frequency. It should be somewhere between the significant $1/f$ noise and local noise as a lower frequency boundary and an upper boundary at the largest particle thermal time constant.

There is an opportunity for significant improvement in balancing the unwanted absorption noise occurring in the chambers. These improvements could take the form of a tunable absorption paddle or a more sophisticated technique of detecting the noise and feeding back the information for acoustical or electrical reduction of the noise.

Multiple passes of the light beam through the chamber have been successful in the sensitivity of other instruments and should be tried in this one.

The slotted blade chopper used to modulate the light beam is a source of noise at the modulation frequency. One technique that should be investigated is the use of an optical chopper disc that has alternating opaque and clear sec-

tors. Another technique to investigate is the use of a solid state chopper such as a liquid crystal.

The use of synchronous detection methods should be tried since they fit well with a constant phase modulated signal instrument.

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APPENDIX A CONCEPT SENSITIVITY

In order to justify further work on this concept it was necessary to determine if the instrument had the capability to measure absorptions within the range expected by the earth's atmospheric aerosols. To provide this confirmation a measurement was done using the sun's radiation as the light source.

Four equations form the basis of the following calculation of the absorption coefficient. The first is the equation

$$\Delta P = PBQ/Cg$$

derived in the Theoretical Considerations section which can be rearranged to the form:

$$Q = \Delta PCg/PB$$

The second equation is:

$$Q_B = IA/F$$

where:

$$Q_B = \text{Beam Energy per Pulse}$$

$$I = \text{Solar Constant}$$

$$A = \text{Chamber Cross Sectional Area}$$

The third equation is:

$$\text{Absorption Coefficient} = Q/Q_B L$$

where:

L = Length of Absorbing Path

Substituting for Q and Q_B :

Absorption Coefficient = $\Delta PCgF/PLBIA$

The fourth equation is:

$$\Delta P = E/SG = 2.5 \times 10^{-4} \text{ } \mu\text{bar or } 2.5 \times 10^{-10} \text{ bar}$$

where:

E = Electrical Signal = 0.2 MV

S = Microphone Sensitivity = 1 MV

G = System Gain = 800

Substituting into the equation:

Absorption Coefficient = $\Delta PCgF/PLBIA$

where:

P = 1 bar

B = $1/273 \text{ } ^\circ\text{C}$

F = 70 Hz.

C = 0.173 Calories/gram $^\circ\text{C}$

I = 0.33 calories/second - cm^2

L = 0.25 meters

A = 20 cm^2

Absorption Coefficient = $10^{-6}/\text{meter}$

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A PHOTOPHONIC INSTRUMENT
CONCEPT TO MEASURE ATMOSPHERIC
AEROSOL ABSORPTION

by

Charles Dennis Engle

(ABSTRACT)

A laboratory model of an instrument concept to measure the absorption of solar radiation by atmospheric aerosols was designed, built and tested. The concept was based on the photophonic phenomenon discovered by Bell and an acoustic resonator developed by Helmholtz.

The design consisted of two chambers: an aerosol chamber and a reference chamber combined into a double Helmholtz resonator configuration. The radiation from the visible light source was amplitude modulated by a mechanical chopper. The modulated light beam was passed through the chambers and pressure variations resulted from energy absorbed by the aerosol in the chamber. The pressure signal was sensed by microphones, then the electrical signal amplified and processed by a differential amplifier.

The testing showed the instrument had sufficient sensitivity and low enough system noise to measure an absorption coefficient of about 10^{-6} /meter. Methods of signal improvement and noise reduction were discussed and tested.

The results showed the instrument could measure absorption coefficients within the range expected by the earth's atmospheric aerosols.

The instrument design was not optimized for maximum signal or minimum noise, but the justifiable conclusion was reached that the concept showed the promise of leading to a useful instrument in the measurement of atmospheric aerosol absorption and an improvement over the present instruments.