# STUDY OF SOUND PROPAGATION IN AIR

MISSISSIPPI UNIVERSITY

PREPARED FOR
ARMY RESEARCH OFFICE

JUNE 1976

ARO 11223.8-E

# STUDY OF SOUND PROPAGATION IN AIR



FINAL TECHNICAL REPORT

BY

HENRY E. BASS

15 JUNE 1976

U. S. ARMY RESEARCH OFFICE

CONTRACT NUMBER 1123-E

PHYSICAL ACOUSTICS RESEARCH GROUP
DEPARTMENT OF PHYSICS AND ASTRONOMY
THE UNIVERSITY OF MISSISSIPPI
UNIVERSITY, MS 38677



APPROVED FOR PUBLIC RELEASE;
DISTRIBUTION UNLIMITED.

THE FINDINGS IN THIS REPORT ARE NOT TO BE CONSTRUED AS AN OFFICIAL DEPARTMENT OF THE ARMY POSITION, UNLESS SO DESIGNATED BY OTHER AUTHORIZED DOCUMENTS.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|---|---|
| 1. REPORT NUMBER<br>ARO 11223.8-E | 2. GOVT ACCESSION NO. | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle)<br>STUDY OF SOUND PROPAGATION IN AIR | | 5. TYPE OF REPORT & PERIOD COVERED<br>FR: 1 Jul 73 - 30 Jun 76<br>6 PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s)<br>Henry E. Bass | | 8. CONTRACT OR GRANT NUMBER(s)<br>DAHC04 73 C 0033 |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS<br>University of Mississippi<br>University, Mississippi 38677 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS |
| 11. CONTROLLING OFFICE NAME AND ADDRESS<br>U. S. Army Research Office<br>Post Office Box 12211<br>Research Triangle Park, NC 27709 | | 12. REPORT DATE<br>June 1976<br>13. NUMBER OF PAGES<br>8p 11 |
| 14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) | | 15. SECURITY CLASS. (of this report)<br>Unclassified<br>15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Atmospheric Sound Propagation
Vibrational Relaxation in Gases
Rotational Relaxation in Gases

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This report summarizes research on sound absorption performed over a three-year period. This research indluded measurements of the rotational relaxation time in air at elevated temperatures and measurements of the vibrational relaxation of water vapor during collisions with water vapor, oxygen, nitrogen, and argon. As a result of these measurements the range of temperatures over which these basic physical properties can be accurately predicted over the temperature range normally encountered on the surface of the earth. References to the work published

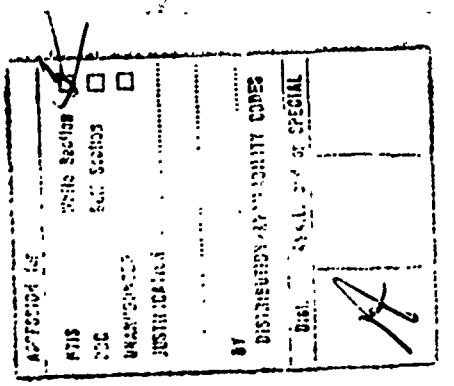


DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

Unclassified

20. ABSTRACT CONTINUED: 11223.8-E

in the open literature is given as well as a brief description of how this work contributed to the development of a new procedure to predict sound absorption in still air.



# INTRODUCTION

The absorption of sound by the atmosphere must be known to predict sound levels at receiving sites well removed from the noise source and to correct recorded noise spectra to standard conditions when making relative comparisons of the noise generated by different sources. The factors which affect the intensity of the sound arriving at the receiving site can be classified as

Spreading Losses

- Uniform spherical spreading
- Non-uniform spreading
  - Reflection by finite boundaries
  - Refraction by non-uniform atmosphere
  - Diffraction (scattering by non-stationary atmosphere)

Absorption Losses

- Absorption by ground and ground cover
- Absorption by the atmosphere
  - Classical absorption
  - Molecular relaxation absorption

Of these sound propagation effects, different ones may be the controlling factor for different atmospheric conditions and for varying source-receiver placement; however, for any type of condition or any type of sound propagation path, the absorption due to classical and molecular effects are fixed for a homogeneous atmosphere and are functions only of the propagation path distance, the humidity content, gas impurities, and the temperature. The purpose of the research reported here was to establish the correct values of those fixed absorption losses.

Prior work in collaboration with Wyle Laboratories, with U. S. Army support, led to the development of a theoretical model of sound absorption in air.[1] This model requires as input parameters, the rate at which vibrational and rotational energy is transferred during binary molecular collisions. There are twenty four energy transfer rates important for an

accurate prediction of sound absorption by the atmosphere. Fortunately, many of these rates are available in the literature over a wide range of temperature. The purpose of this study was to measure those for which values were uncertain. Specifically, the objectives of the research reported here were to:

1. Measure the vibrational relaxation time of $H_2O$ during self collisions and collisions with $N_2$, argon, and $O_2$ at elevated temperatures in order to establish the temperature dependence of these mechanisms.

2. Measure the temperature dependence of rotational relaxation in air.

3. Prepare supporting documentation for a simplified procedure to predict sound absorption in the atmosphere and/or tables of sound absorption.

4. Identify areas for further investigation (effect of fog and suspended particles, turbulence, or ground cover).

In addition, a simultaneous effort by Wyle Laboratories was launched to measure the rate of vibrational deexcitation of nitrogen in the presence of water vapor.

The details of the work performed are included in several articles published or accepted for publication in the open literature. In the body of this report, these articles will be summarized and their contribution to the overall effort explained.

## Results and Conclusions

The major mechanism responsible for absorption of sound at moderate temperature and humidity (20°C 50% relative humidity) at intermediate frequencies (500 Hz to 20 KHz) is the vibrational relaxation of oxygen. There are several kinetic processes which serve to relax $O_2$. These are

$$O_2^* + M \rightleftarrows O_2 + M \qquad 1a$$

$$O_2^* + H_2O \rightleftarrows O_2 + H_2O^* \qquad 1b$$

and

$$O_2^* + CO_2 \rightleftarrows O_2 + CO_2\ (\nu_2)^{**} \qquad 1c$$

where * denotes a quantum of vibrational energy, $_2$ denotes the bending mode of $CO_2$ and M can be any collision partner ($O_2$, $N_2$, $H_2O$, Argon, $CO_2$, or $H_2$). The rates for Reaction 1a with M=$O_2$, $N_2$, argon, and $CO_2$ are well established[2] over a wide range of temperature as is the rate of Reaction 1c.[3] Reaction 1b presents additional problems since the progress of Reaction 1b depends on the rate at which $H_2O^*$ is deexcited by reactions of the type

$$H_2O^* + M \rightleftarrows H_2O + M. \qquad 2$$

For intermediate and high humidities, Reaction 2 represents the rate limiting process hence the rate at which Reaction 2 proceeds dictates the vibrational relaxation time of $O_2$ and hence is of critical importance in predicting sound absorption.

The first task undertaken in this study was to determine the rate of Reaction 2. This effort was started using data collected by the author at Oklahoma State University and by Dr. R. C. Amme at the University of Denver with M = $H_2O$. The results are reported in The Journal of the Acoustical Society of American, Volume 56, page 1455, 1974. The rate for Reaction 2 was measured at temperatures from 373 to 946°K and the results extrapolated to room temperature. As a result of this study, the rate of Reaction 2 with M = $H_2O$ is now known over a range of temperatures wide enough to allow extrapolation to any temperature of interest in the field. A discrepancy between the extrapolation of these results to room temperature and prior determination at room temperature were noticed in this paper. This discrepancy will be discussed in more detail later in this report.

While this initial study was in progress, a new instrument was constructed to measure sound absorption at high frequencies. The choice of a high frequency instrument was dictated by laboratory convenience and in no way limits the application of the resulting rate constants to the audible frequency range. Following initial calibration with argon and helium, the new instrument was used to measure sound absorption in air at high frequencies over the temperature range 302-689°K. These measurements served to check the computed classical absorption contribution to sound absorption and to determine the temperature dependence of the rotational relaxation time of air. These results were published in the Journal of the Acoustical Society of America, Volume 58, page 110, 19 5.

It should be noted that although the frequency of maximum absorption for rotational relaxation of air is above 100 MHz, for typical atmospheric conditions, at 1 KHz, rotational relaxation is still responsible for about 10% of the sound absorption coefficient.

In 1971, the American National Standards Institute appointed working group S1-57 to prepare a standard for sound absorption in still air. This new standard is based on the general theory of sound absorption discussed earlier and the author was responsible for preparing the theoretical supporting documentation for this standard. This supporting documentation is now being prepared for publication in "Physical Acoustics", W. D. Mason, Editor, to be published by Academic Press. During the course of examining prior data on which to base this standard, an equation was developed using the results of the research reported above (J. Acoust. Soc. Amer. 58, 110 (1975)) and other work. This equation and supporting material have been incorporated into a manuscript entitled "On the Rotational Collision Number for Air at Elevated Temperatures", which has been accepted for publication in the June 1976 issue of the Journal of the Acoustical Society of America.

In addition to M = $H_2O$ in Reaction 2, the effects of M = $N_2$ and M = argon must be considered. Measurements were conducted in the new tube with binary mixtures of $H_2O$ and $N_2$ and argon. The measurements were made at 500°K in order to maximize the absorption due to vibrational relaxation of $H_2O$. It was found that argon and $N_2$ are very inefficient in deexciting $H_2O$ and in practical applications can be ignored in Reaction 2. Further, based on theory, these 500°K results can be coupled to the higher temperature results of Kung and Center[4] to provide an extrapolation to room temperature. This extrapolation could be in error by a factor of two or so at room temperature, but even with a factor of two error, $N_2$ and argon as collision partners for $H_2O$ in Reaction 2 can be ignored when computing sound absorption in air. These results have been accepted for publication by the Journal of the Acoustical Society of America in a manuscript entitled "Vibrational and Rotational Relaxation of Water Vapor by Water Vapor, Nitrogen, and Argon at 500°K."

In addition to M = argon and $N_2$ in Reaction 2, $O_2$ must also be considered. Actually, since $O_2$ is similar in mass and intermolecular potential to $N_2$, there is no reason to suspect, based on the results of the previous paragraph, that $O_2$ would be an important collision partner

for relaxation of $H_2O^*$. However, in mixtures of $O_2$ and $H_2O$ Reaction 1b becomes important as does Reaction 1c with M = $H_2O$. Sound absorption measurements were made at 500°K and these rates were extracted. Coupled with room temperature results taken from the literature, the rate of Reaction 1a with M = $H_2O$, Reaction 1b, and Reaction 2 with M = $O_2$ have been determined. The results are reported in a manuscript entitled "Vibrational and Rotational Relaxation in Mixtures of Water Vapor and Oxygen" which has been accepted for publication in the Journal of the Acoustical Society of America. During the course of this study it was found that the rate of Reaction 2 with M = $H_2O$ was difficult to determine uniquely from humid air data. It was concluded that this difficulty is primarily responsible for the large variation in values reported for the rate extracted from moist air or moist oxygen data.

The final result of this study along with the initial work by Evans and Sutherland at Wyle Laboratories and other members of the S1-57 Working Group is a simple procedure for computing sound absorption in still air[5] accurate to within ±10% over the temperature range 255.4K (0°F) to 310.9K (100°F) at relative humidities from 0% to saturation, frequencies from 100 Hz to 10 MHz and pressures from 0 to 2 atm (the ratio of frequency to pressure must not exceed 10 MHz/atm). This procedure is as follows:

1. Compute the absolute humidity h (in percent) from the relative humidity $h_r$ (in percent) as

$$h = h_r(P_{sat}/P_o) \;/\; (P/P_o), \text{ percent}$$

where

$$\log_{10}(P_{sat}/P_o) = 10.79586[1-(T_{01}/T)] - 5.02808\log_{10}(T/T_{01}) + 1.50474 \times 10^{-4}(1-10^{-8.29692[T/T_{01})-1]}) + 0.42873 \times 10^{-3}(10^{4.76955[1-(T_{01}/T)]}-1)-2.2195983$$

where $T_{01}$ = 273.16°K

T = atmospheric temperature

$P_0$ = one standard atmosphere

and P = the ambient pressure in atm.

2. Compute the relaxation frequencies of Oxygen ($f_{r,O}$) and Nitrogen ($f_{r,N}$) from the expressions

$$f_{r,O} = (P/P_o)\left\{24 + 4.41 \times 10^4 h[0.05 + h)/(0.391 + h)]\right\}, \text{ Hz}$$

and $$f_{r,N} = (P/P_o)(T/T_o)^{-1/2}[(9 + 350h\exp\left\{-6.142[(T/T_o)^{-1/3}-1]\right\}], \text{ Hz}$$

where $T_0 = 293.15°K$

and the other terms are defined above.

3. Compute the total absorption in db/meter as

$$a = 8.6859.(T/T_0)^{1/2}[f^2/(P/P_0)]\left\{1.84 \times 10^{-11} + 2.1913 \times 10^{-4}(T/T_0)^{-1}\right.$$
$$\times (P/P_0)(2239.1/T)^2[\exp(-2239.1/T)]/[f_{r,O} + f^2/f_{r,O})]$$
$$\left. + 8.1619 \times 10^{-4}(T/T_0)^{-1}(P/P_0)(3352/T)^2[\exp(-3352/T)]/[f_{r,N} + (f^2/f_{r,N})]\right\}.$$

This procedure will soon be submitted for publication as an ANSI standard. There was no way to foresee at the beginning of this study that such an accurate and simple computational technique would evolve, however, the fact that it did provides the author with a great deal of personal satisfaction and the engineering community a readily useable tool.

The final phase of this research effort was an examination of areas for future study. Referring to the list of factors which affect sound propagation given on page 1, as a result of this and other work, it is the author's opinion that absorption of sound by the atmosphere is now sufficiently well understood and requires no additional study. This cannot be said for any of the other factors (except perhaps for non-uniform spreading due to refraction which can be computed if sufficient atmospheric data is available). The fields of absorption by ground and ground cover, scattering by a non-uniform (turbulent atmosphere), and reflection by finite boundaries all deserve additional study. However, if one adopts a building block approach, the affect which is least variable should be investigated first. For this reason, a study of absorption by ground and ground cover now appears most promising. Once this affect is fully understood, absorption by the atmosphere and the surface can be controlled or corrected for in future studies of sound scattering by turbulence.

Absorption by ground and ground cover has received an increasing amount of attention in recent years[6] due to applications in community noise predictions. The basic equations for sound propagation over a surface are available and well documented for cases where the surface impedance is known or can be measured. At this time, the only surfaces for which this

data is available are "institutional" grass and asphalt. Before the theory can be used to predict sound absorption under field conditions, the impedance for a wider variety of surfaces is required. A study of such surfaces should have as a long range goal a model of the acoustic properties of surfaces which will allow one to compute the impedance and a study of the role that various layers of cover have on the impedance.

## References


1. L. B. Evans, H. E. Bass, and L. C. Sutherland, "Atmospheric Absorption of Sound: Theoretical Predictions", J. Acoust. Soc. Am. 51, 1565-1575 (1972).

2. T. L. Cottrell and J. C. McCoubrey, Molecular Energy Transfer in Gases, pages 81-84 (Butterworths, London, 1961).

3. H. E. Bass, "Vibrational Relaxation in $CO_2/O_2$ Mixtures", J. Chem. Phys. 58, 4783-4786 (1973).

4. R. T. V. Kung and R. E. Center, "High Temperature Vibrational Relaxation of $H_2O$ by $H_2O$, He, Ar and $N_2$", J. Chem. Phys. 62, 2187-2194 (1975).

5. L. C. Sutherland, J. E. Piercy, H. E. Bass, and L. B. Evans, "Method for Calculating the Absorption of Sound by the Atmosphere", J. Acoust. Soc. Am. 56, S1 (1974).

6. T. F. W. Embleton, J. E. Piercy, and N. Olson, "Outdoor Sound Propagation Over Ground of Finite Impedance:, J. Acoust. Soc. Am. 59, 267-277 (1976).

## List of Participating Scientific Personnel

1. Faculty

Henry E. Bass, Principal Investigator
Lee N. Bolen, ground cover measurements, summer 1974
Roy T. Arnold, design and construction of new transducer holders, summer, 1975
Donald L. Thompson, theoretical calculations of water vapor relaxation, 1975-1976

2. Students

Steven D. Hottman (Ph.D summer of 1974)
Roy G. Keeton (MS fall 1975)
Robert E. Losey (MS summer 1974)
James C. Brown (Ph.D. candidate)