SUBMILLIMETER RESEARCH: A PROPAGATION BIBLIOGRAPHY

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This report is an annotated bibliography given on the subject of submillimeter propagation. Several articles are recommended as a good starting point for reviewing the current state-of-the-art.
ACKNOWLEDGMENT

The authors would like to thank Dr. D. A. Stewart, Dr. J. Q. Lilly, and S. L. Johnston for their assistance in developing this bibliography.
This annotated bibliography was prepared to provide an introduction to the field of submillimeter propagation. Several articles are recommended for those just beginning to review the field; these articles are marked by a * in the listing. To aid in visualizing the behavior of atmospheric propagation in the submillimeter wave region of the spectrum, three figures are included in this bibliography. Figure 1 shows the attenuation due to absorption in decibels/kilometer as a function of wavelength (from reference 119). Figure 2 shows a theoretical estimate of scattering losses at these wavelengths (from reference 33). Figure 3 shows experimental data superimposed on the theoretical absorption curve.

The list of references in this bibliography is not meant to be exhaustive but it will provide the user with an easy entry into the field.
Figure 1. Absorption from 10 to 5000 $\mu$m at 1-atm pressure,
293$^\circ$K, and absolute humidity $\zeta = 7.5$ gm/m$^3$. Shape:
Zhevakin-Naumov.
Figure 2. Cloud scattering losses.
Figure 3. Comparison of theoretical and experimental atmospheric absorption between 0.2 and 4.0 mm.\(^*\) (The solid curve labeled H\(_2\)O is the theoretical curve for water vapor; experimental points are indicated).

BIBLIOGRAPHY


Absorption coefficients for water vapor are calculated for constant pressure and temperature range of 173°K to 373°K. Temperature dependence can be modeled by $T^{-n}$ where $3.2 < n < 4$ in the transmission windows.


An echelette grating spectrometer with a mercury arc for a source and an InSb detector used to measure absorption over a path length from 25 to 125 m. Almost quadratic pressure dependence found. For 7.5 gm, 760 mm Hg and 20°C:

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<thead>
<tr>
<th>Wavelength</th>
<th>Absorption</th>
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<tr>
<td>0.29 mm</td>
<td>236 dB/km</td>
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<tr>
<td>0.36 mm</td>
<td>63 dB/km</td>
</tr>
<tr>
<td>0.45 mm</td>
<td>67 dB/km</td>
</tr>
</tbody>
</table>


Measured dielectric constant of water. At wavelengths less than 1.6 mm, the dielectric constant of water differs from the Debye behavior.

Theory developed for propagation of a plane monochromatic submillimeter wave in the surface layer of a turbulent atmosphere. Experiment carried out in the wavelength range of 0.88 to 0.99 mm. Theory and experiment show qualitative agreement on the fact that the intensity of the fluctuation decreases with an increase in absorption. Experiment shows a larger effect than theory predicts.


In Spanish, a review.


Measurement of attenuation in snowfall up to 2 mm/hour over a 680-m path. The attenuation in snow is 30% to 40% larger than the attenuation in rainfall of the same rate. Between 0.4 and 1.8 mm/hour the attenuation (dB/km) is given by 0.7 + 2.3I, where I is the snowfall rate.


Attenuation of rain in summer thunderstorms. Used backward wave oscillator (BWO) and an InSb detector. Between rainfall rates of 0 to 12 mm/hour the attenuation at 0.96 mm is 2.5 to 3 dB larger than the attenuation at 8.6 mm. The attenuation (dB/km) can be approximated by 1.531.0638, where I is the intensity of rain in mm/hour.

Description of equipment to be used in propagation measurements in the wavelength range of 0.83 to 1.2 mm.


Calculations of atmospheric absorption in the range of 0.25 to 4.0 mm. Compared results to experiments. Contains a brief review of experiments conducted before 1966.


Measurement of attenuation of solar radiation by clouds at 1.2 ± 0.4 mm. Used an objective diffraction grating on a telescope.


Used laser sources at 337, 311, 195, 190 and 118 μm to measure absorption of the atmosphere and of pure water vapor. The attenuation obtained at 293°K was as follows:

<table>
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<th>Wavelength (μm)</th>
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<td>337</td>
<td>7.89</td>
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<tr>
<td>311</td>
<td>46.3</td>
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<td>195</td>
<td>86.2</td>
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<tr>
<td>190</td>
<td>118.7</td>
</tr>
<tr>
<td>118</td>
<td>114.3</td>
</tr>
</tbody>
</table>


Fourier transform spectrometer and white cell used to obtain line positions and attenuation in the atmospheric windows in the wavelength range from 1.0 to 0.1 mm. Comparison is made to theory.

Measurements made in laboratory of atmospheric attenuation from 500 to 1500 GHz.


Fourier transform spectrometer used to obtain absorption data over 121- to 469-m path length. Samples were pure H₂O or H₂O + N₂ or air. Total pressures were from 2.5 torr to 1 atm; temperature was 296 K. Source was a high pressure Hg-arc lamp; detector was a helium cooled, gallium doped, germanium bolometer.


Measurements at 337 μm over horizontal path in a fog. Visibility measurements were used to deduce fog water content. Comparisons were made to measurements conducted in a controlled atmosphere.


Complex index of refraction of water, 0.1 to 1.0 mm wavelength. Frequency dependence of real and imaginary parts of dielectric constant does not correspond to Debye relaxation formula.


Complex refractive indices measured in the wavelength range from 100 to 500 μm over the temperature range of 5°C to 70°C.

Reflectivity of water was measured at ambient temperature in the wavelength range of 100 to 500 μm.


Used superheterodyne radiometer to measure attenuation of 34 dB/km/g/m horizontal attenuation with respect to water vapor density. Used path lengths between 3 and 70 m.


Computation of all available attenuation coefficients due to aerosols as a function of wavelength. Very little data in the submillimeter range.


(See Reference 24)


Used same equipment described in Reference 24 and 26. Attenuation measured at 309 GHz was 3.35 dB/km and at 316 GHz was 5.55 dB/km per g/m³ of water vapor density.


Radiometric measurements of atmospheric absorption for frequencies above 100 GHz.

Determination of functional relationship between rainfall intensity and the attenuation coefficient.


The most consistent sets of optical constants for water and ice are presented graphically.


Theoretical calculation to estimate some extreme situations to illustrate the magnitude of attenuation to be expected in clouds and rain. Molecular absorption was ignored.

Final report is Reference 34.


Estimation of water cloud and rain attenuation over the wavelength range of 2 cm to 12 μm. Scattering and polarization properties are neglected.


Emphasis on data below 100 GHz but extrapolation of data to 300 GHz is possible. Good review of meteorological data.


Measurements in the wavelength range of 0.5 to 3.0 mm of atmospheric propagation. Theoretical calculations using kinetic line shape. Line center and line broadening measurements as well as atmospheric window measurements were made. A 6-m path length was used.


Used a grating spectrometer at high altitude (Chacaltaya, Bolivia). Measured water vapor by making radio-sonde measurements.

Room temperature measurements of mixes of water vapor and N₂, CO₂, and O₂. Used a Fabry Perot resonant cavity. Measurements at atmospheric pressure and below. Empirical line shape formulas are obtained.


Measurements made from 55 to 1000 µm using an echelette grating spectrometer. The light source was a mercury lamp. The path length was 5.5 m. Atmospheric pressure and 0.1-mm pressure were the two pressures examined.


Used a Fabry-Perot interferometer at a high altitude site (Pic-du-Midi in the Pyrenees). The sun was the source and a Golay cell was used as a detector. Water vapor concentration was not measured; rather, comparisons were made between different wavelengths down to 0.3 mm.


Detection of solar radiation at 860 µm at sea level. Attenuation at standard conditions was 7.2 dB/km.


A summary of calculations of atmospheric absorption line parameters. Contains approximately 50 references and mentions that Riverside Research Institute has accumulated over 1000 card indexed citations.


Calculation of absorption and complex dielectric constant.


Theoretical calculations but before using these calculations see References 56 and 57.


Simultaneous measurements at 311 and 0.63 μm were made in a fog chamber 6 m long. An HCN laser produced the 311-μm radiation and an InSb detector was used. The result was that the attenuation of 311 μm (in dB/km) equals 0.04 times the attenuation of 0.63 μm (in dB/km). For large density fogs, submillimeter wave attenuation is comparable to molecular absorption in water vapor but for small fog densities, the attenuation is smaller than the molecular absorption.


Theoretical evaluation of correlation and the effects of absorption.


Frequency spectrum of amplitude fluctuations of a plane electromagnetic wave in submillimeter range propagating in a surface layer of turbulent atmosphere.


Computations of variances of phase and amplitude fluctuations at 0.83 to 1.0 mm. Measured data for 0.92 to 0.96 mm over 363 m path at 6.5, 15.5 and 40 dB/km.

Numerical calculations to determine over what range of values absorption reduces amplitude fluctuations and over what range it causes an increase. It is found that fluctuations will be suppressed outside an absorption line but enhanced in a strong absorption line.


Considers the effects of trace gases (CO, N₂O, O₃) on the data reported by others.


Calculation of optical constants of water and ice from 2 to 200 μm.


Continuation of the theme presented in Reference 66.


The influence of the raindrop distribution law on the attenuation coefficient and differential backscattering cross section is calculated for wavelengths between 1 mm and 3 cm.

Drop size for melting granules and soft snow and hail.


A review of propagation is contained in this paper on an all weather application.


A refinement of the analysis made in Reference 72.


Measured vertical absorption as a function of absolute humidity using radio astronomy.


Experimental measurements over 3-km path. A background wave oscillator is used as the source. The dependence of absorption on absolute humidity is determined. The portion associated with the monomer is 30% larger than theoretically predicted; the dimer absorption is 2.5 times smaller than calculated.


Italian. Calculations of submillimeter atmospheric emission used to evaluate the performance of a radiometer used at Testa Grigia.


Measurement over 120-m path. Results for the two wavelengths are similar. The attenuation in dB/km is given by 0.761 for rainfall rates, I, less than 10 mm/hour. For rates between 10 and 50 mm/hour, the attenuation in dB/km is given by 3.2 + 0.33I.


Measurement at standard conditions (7.6 gm/m^3) and temperature of 18°C gave 4.5 dB/km.


Transcript of a popular review of millimeter wave research. It contains a bibliography of eight review papers.


Theoretical scattering and absorption properties of rain, fog, cloud particles and atmospheric aerosols are given for millimeter wavelengths. Information is given for the atmospheric window near 1 mm but Figure 4 is in error.


The backscatter, scattering, absorption, and total attenuation cross sections of water spheres at 18°C are tabulated. Data are given for 1-mm wavelength radiation. Equations used to prepare the tables are given.


Calculated attenuation coefficients over the wavelength range of 0.5 to 3.0 mm for rainfall rates of 0.25 to 150 mm/hour.


Fourier transform spectroscopy to obtain solar spectra at $\lambda > 300 \mu$m. Atmospheric transmission was inferred from the spectra.


Calculations of extinction in clouds and fogs from 0.2 to 2.0 mm. Comparison is made to the only known experimental measurements (Reference 14 and 20).


A survey of the literature is made to allow the development of an empirical model of the complex refractive indices for ice and liquid water; 38 references are given.


Calculation of extinction coefficient in fine-drop clouds and fogs at temperatures from -32°C to 30°C. Warm means T > 0°C.


For papers before 1961, this paper should be consulted.

Attenuation and backscatter cross section of rain are investigated over the range of 0.03 to 10 cm. Calculations and a review of the literature is made; contains 60 references.


Used a 2-mm interval grating at an altitude of 3860 m. Used the sun as a source. Obtained a resolution of 1.0 cm⁻¹.


Experimental data on the absorption of water vapor in air using a backward-wave oscillator (BWO) as a source. Contains 50 references. Data cited in Reference 119 is reworked and a detailed description of the measurements is given. A detailed comparison between available experimental data and theoretical computations is made.


Used BWO for a source. Attenuation was given to absorption due to water vapor dimers. Comparison is made to theory and other experimental values.


Attenuation at standard conditions was found to be 16.3 dB/km. Used a BWO as a source.

Used mercury arc for source, an echelette grating spectrometer, and a Golay cell for a detector. Measured absorption around the wave-lengths 0.2, 0.29, 0.36, 0.45, 0.73 and 0.87 mm. At standard conditions:

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<th>Wavelength (mm)</th>
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<td>336</td>
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<td>0.36</td>
<td>66.7</td>
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<tr>
<td>0.45</td>
<td>73</td>
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<td>0.73</td>
<td>23.2</td>
</tr>
<tr>
<td>0.87</td>
<td>17</td>
</tr>
</tbody>
</table>


From measurements taken at 35, 70 and 140 GHz, discusses restrictions placed on applications due to propagation.


Five of the papers were on "Propagation." Most of the papers were on devices and applications.


Measurement of absorption using Fourier transform spectrometer.


Measured the absorption of ordinary and heavy liquid water using an echelette grating spectrometer.

Calculation of attenuation over the wavelength range of 0.63 to 100 \( \mu \text{m} \). Experiments only for 10.6 \( \mu \text{m} \) and below.


Review of theoretical and experimental propagation studies; 30 references.


Reviews possible applications of submillimeter waves considering 1970 technology. Part of this paper also appears in Reference 101.


Calculations of attenuation by rain over the wavelength range of 0.1 to 2.0 mm. See Reference 11.

107. Sokolov, A. V. and Sukhonin, Ye. V., "Problem of Attenuation of Radiowaves in 0.1-2\( \mu \text{m} \) Range by Rains of Different Intensity," Proc. 9th All-Union Conference on Radiowave Propagation, June 1969.


Submillimeter radiation generated by a harmonic multiplier and detected by a Si bolometer. Rotational transitions in \( ^{18} \text{O}_2 \) were measured with high precision.


Measurements and calculations on the effects of pressure, temperature, and gas mixture on the transmission properties.

Theoretical calculations at 4, 14, 28, and 41 km using Air Force atmospheric-absorption-line parameter data tape.


Radiometric measurements using the sun at two zenith angles as a source and a helium cooled Ge bolometer. Bandpass filters were used. Minimum attenuation in this region was at 240 GHz.


Theoretical and experimental investigation of rain attenuation at millimeter waves, used combined Debye and Frohlich components of polarization.


Measurement of absorption of water vapor between 0.98 and 1.6 mm at sea level in various latitudes. Used sun as a source and InSb as a detector. An echelle grating spectrometer gave wavelength selectivity. Minimum absorption was at 1.26 mm and was 0.6 dB/km/g/m³.


Covers attenuation only, no backscatter. Very large bibliography of 40 references on propagation and 84 references on equipment and procedures. Work performed in the USSR from 1957 to 1967.


Calculates the absorption coefficient of water vapor dimers.


Calculated scattering coefficients of single drops from 0.5 to 7.0 mm diameter, at 30, 100, 150, 300 GHz; ice spheres from 1.0 to 7.0 mm diameter, and on distribution of raindrops for 0.25 to 150 mm/hour, also attenuation and absorption using Mie, Aden, and Laws and Parsons. Attenuation compared with Medhurst, Asari, and Setzer. Angular dependence of Mie scattering plotted.


The first part of the study calculates atmospheric transmission at different altitudes and for various weather conditions using a simple absorption model. The second part evaluates technology and looks at communications and fuzing applications.


Used echelette grating spectrometer with a 10-m enclosed path. Measurements were made at 293°K with a water vapor concentration of 10.5 g/m³.


Reviews state of knowledge in 1967 concerning propagation in the atmosphere with 199 references and presents effect of water vapor monomers and dimers and molecular oxygen. Comparison of spectral lines by Lorentz, Van Vleck and Weiskoff, and author. Discusses natural atmospheric waveguides.


See Reference 131 for improved data. Index of refraction is calculated and compared to experiment. In the wavelength range of λ = 0.5 to 5 mm, the derivatives of the index of refraction with respect to humidity and temperature are computed.


See Reference 130


Computations of the absorption of water vapor for elevations of 10 and 20 km.


Calculations of absorption coefficients for monomers of water vapors and oxygen for altitudes of 0 to 45 km, winter and summer.


Calculations over the wavelength range of 0.7 mm to 32 cm.


Quantitative evaluations of the influence of the magnetic permeability on the value of the atmospheric index of refraction are made around 2.5 mm.


Optical constants of liquid water were experimentally obtained over the wavelength region of 1 to 10 μm.
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