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EVALUATION OF SPECIALIZED PHOTOACOUSTIC ABSORPTION CHAMBERS
FOR NEAR-MILLIMETER WAVE (NMMW) PROPAGATION MEASUREMENTS

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AUGUST 1980

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US Army Electronics Research and Development Command
ATMOSPHERIC SCIENCES LABORATORY

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EVALUATION OF SPECIALIZED PHOTOACOUSTIC ABSORPTION CHAMBERS
FOR NEAR-MILLIMETER WAVE (NMMW) PROPAGATION MEASUREMENTS

Change figure captions to read as follows:

Page 13 Figure 2. Experimental arrangement used to test internally reflecting, spherically resonant absorption chambers.

Page 15 Figure 4. Machined aluminum enclosure.

Page 21 Figure 11. Differential type spectrophone using two electret detectors.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Preliminary studies have been conducted to determine the feasibility of using spherical geometry photoacoustic absorption chambers at near-millimeter wave-lengths (NMMW). New spherical geometry photoacoustic absorption chambers were used in a parallel experimental arrangement to the ongoing (FY 79) NMMW program. Absorption sensitivity, NMMW laser beam handling characteristics, pressure dependence, and temperature effects of the system were evaluated to determine the usefulness and applicability of these new designs for use at			

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20. ABSTRACT (cont)

NMMW. Electret microphones were acquired, and testing was done by using these microphones as detectors in specialized spherical geometry and more conventional design photoacoustic absorption chambers. Results from this study show that numerous problems exist in using the spherical geometry photoacoustic absorption chamber design. The combination of resonant frequency temperature dependence, unstable mechanical chopping, high-Q narrow-bandwidth characteristics, and excessive noise sensitivities have limited the absorption sensitivities obtainable. Electret microphone testing and evaluation have led to the design and construction of several conventional, single-pass type, photoacoustic absorption chambers.

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BACKGROUND/INTRODUCTION

Millimeter wavelengths will apparently play an important role in future military electro-optical (EO) systems. One of the major known attenuators at millimeter wavelengths is atmospheric water vapor. At present several important features of water vapor absorption in the millimeter spectral region are not well understood and require further investigation. These features include: absorption line shape, temperature dependence, pressure dependence, foreign broadening, and the existence of "continuum" type or "cluster" type absorption. Special absorption chambers are required to perform these measurements due to the spatial profile characteristics of the far infrared (FIR) beam emitted from the near-millimeter laser source and its extremely low output powers.

A need thus exists for a device which will enable gaseous absorption measurements to be made at near-millimeter wavelengths (NMMW). Recently proposed and partially developed photoacoustic absorption chambers¹ appear to have features which would be ideal for the measurement of gaseous absorption coefficients at NMMW.

The Atmospheric Sciences Laboratory (ASL) undertook further development, evaluation, and testing of these specialized photoacoustic absorption chambers for NMMW propagation measurements to determine absorption sensitivity, pressure and temperature dependence, NMMW laser beam handling characteristics, and overall suitability for use in measuring gaseous absorption coefficients using low-power, NMMW laser sources.

This need prompted an independent laboratory in-house research (ILIR) effort to study the feasibility of using internally reflecting, spherically resonant, photoacoustic type absorption chambers for measuring gaseous absorption coefficients at NMMW.

This report presents the findings from the ILIR investigation into the use of spherically resonant, photoacoustic absorption chambers at NMMW and the use of transducer electret type detectors in these and other photoacoustic chamber designs.

EXPERIMENTAL APPROACH AND EQUIPMENT SETUP

Most photoacoustic absorption chambers (spectrophones) use a cylindrical design wherein the electromagnetic energy propagates through the test medium only once.² These single-pass, short path length chambers require moderate to high energy levels and well controlled beam geometries due to limited clearances dictated by chamber designs. Such considerations along with present

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²Charles Bruce, 1976, Development of Spectrophones for CW and Pulsed Radiation Sources, ECOM-5802, Atmospheric Sciences Laboratory, US Army Electronics Command, White Sands Missile Range, NM 88002

sensor designs usually result in somewhat delicate and unmovable systems. A possible approach to avoiding such limitations seems to be that of dumping all of the electromagnetic source energy into an internally reflecting, spherically resonant enclosure (figure 1). In effect, the electromagnetic energy reflects numerous times from the walls until dying out. An immediate advantage of such an approach is that the effective path length is increased, thereby leading to increased sensitivity. Electromagnetic energy with a variety of beam shapes and divergence magnitudes can be effectively captured with only a minimal amount being lost back through the input window. In addition, by using sources with low-power outputs, thermal inertia effects are small; thus the energy absorbed by the walls contributes very little to the overall noise level.

The experimental arrangement used to conduct tests on the internally reflecting, spherically resonant absorption chamber is shown in figure 2. The cw CO₂ pump laser was an Advanced Kinetics MIRL-50 with typical output power ranging from 25 to 35 watts. The waveguide type NMMW laser cavity design used has been fully described in a previous publication.³

Data collection and recording apparatus consisted of a Princeton Applied Research (PAR) model 113 linear amplifier and PAR 128A lock-in amplifier for monitoring the phototacoustic absorption chamber signal; a second PAR 128A lock-in amplifier was used to monitor the laser output detector signal. The detector used was a Molelectron pyroelectric model P3-01. Beam splitter material was quartz. A Scientech power meter was used to determine actual NMMW output power by insertion into the laser beam just in front of the sphere.

Two different internally reflecting, spherically resonant enclosures were used. One sphere was a 6-inch I. D. spun aluminum enclosure with a wall thickness of 1/32 inch and a gold coated reflective surface (figure 3). The second sphere was a 6-inch I. D. machined aluminum enclosure with a wall thickness of 3/32 inch (figure 4). The inside surface of this sphere was highly polished with kerosene and crocus cloth.

Each of the spheres was made into a photoacoustic absorption chamber by the placement of miniature transducer electret microphones through the walls of the sphere in such a manner as to be nearly flush with the inside surface. Microphones used were commercially available model CA-1833 electret type detectors manufactured by Knowles Electronics, Franklin Park, Illinois (figure 5). The machined aluminum sphere had four of these detectors tetrahedrally mounted just forward of the spheres equator (figure 3). Only one of these detectors was mounted on the spun aluminum sphere (figure 4). Each sphere had a 5/8-inch aperture with a 1-mm thick quartz window.

The output beam from the NMMW laser cavity was brought up to the input window of the spherical chamber by means of a 7/16-inch I. D. copper waveguide. Upon leaving the waveguide the NMMW beam would pass through the quartz input window--diverging at a rate such that the beam's cross-sectional area would double after traveling a distance of only 8 inches.

3B. L. Bean and S. Perkowitz, 1976, "Far Infrared Transmission Measurements with an Optical Pumped FIR Laser," Appl Opt, 15:2617-2618

EXPERIMENTAL PROCEDURES AND RESULTS

To determine the usefulness and applicability of using a resonant, spherical photoacoustic absorption chamber in the NMMW region, numerous questions must be answered. A careful investigation to determine absorption sensitivity, signal-to-noise ratios, pressure dependence, and temperature effects had to be performed.

The first step was to construct, clean, leak check, and evacuate each sphere to assure that each was contaminant free.

An audio source was used to determine the fundamental resonant frequency of each of the spheres. By using an audio oscillator, speaker, frequency counter, and oscilloscope the spheres could be driven into resonance. This procedure was first done for the machined aluminum sphere under conditions of vacuum and then with 650 torr of N_2 . At an ambient temperature of $22.4^\circ C$, the resonance frequencies were 1936 Hz and 1926 Hz with ± 2 Hz bandwidth, respectively. Each sphere had high-Q characteristics. Signals from the electrets were observed under these conditions and were comparable in magnitude. At this time the resonant frequency of the sphere varied greatly when subjected to even small temperature changes. A temperature change of as little as $1^\circ C$ could shift the sphere's resonant frequency by as much as 15 to 30 Hz.

The NMMW laser frequency chosen was 17.5 cm^{-1} which corresponds to a wavelength of $570.5\mu m$. The pumped medium producing this wavelength was a spectrophotometric grade of methyl alcohol (CH_3OH).⁴ The CO_2 laser pumping line was 9P(16). The NMMW frequency of 17.5 cm^{-1} was chosen because of its relatively low H_2O absorption (10^{-2} dB/km attenuation). Near-millimeter laser power at this frequency was typically 0.2 mW.

Initial noise level measurements were made with the machined aluminum photoacoustic sphere at the NMMW frequency of 17.5 cm^{-1} for conditions both at vacuum and with 650 torr of N_2 . The noise level was on the order of 100 to $120\mu V$, which was totally unacceptable.

The noise level was greatly reduced by insulating the photoacoustic sphere. An enclosure was constructed from 3/4-inch particle board and was lined with 3-inch thick rock wool insulation on all six sides. The sphere was then mounted on isolation shock mounts and placed inside the particle board enclosure. This improved the system noise by bringing the noise level down to between 20 to $30\mu V$. This enclosure also helped to minimize temperature changes and helped to keep the resonant frequency of the sphere from shifting around.

⁴B. L. Bean and S. Perkowitz, 1977, "Complete Frequency Covered for Submillimeter Laser Spectroscopy with Optically Pumped CH_3OH , CH_3OD , CD_3OD , and CH_2CF_2 ," Optics Letters, 1:202

With the noise level substantially reduced and better control of temperature fluctuations, it was now possible to attempt to make signal-to-noise measurements to determine system sensitivity.

While measurements were being conducted a number of important discoveries were made. First, the mechanical chopper was found to be too unstable for use on such a high-Q narrow-bandwidth system. Using the NMMW laser as the electromagnetic source for driving the spherical photoacoustic absorption chamber the resonant bandwidth was now less than 1 Hz. With a bandwidth this narrow it was impossible to tune the chopper to the resonant frequency. Because of instability the mechanical chopper would drift off resonance within a few seconds time.

To complicate matters even more during the short period of time when the chopper frequency was equal to the sphere's resonant frequency, the signal observed underwent phase changes which made normal lock-in amplifier signal processing techniques hard to use.

The lack of feedback circuitry necessary for controlling the CO₂ pump laser output contributed to the overall stability problem. Without this circuitry the CO₂ laser was constantly drifting in frequency which caused the NMMW laser output to drop off.

Table 1 shows the sensitivity results for various gaseous water vapor absorption pressure conditions and system noise levels. All measurements were made using the electret microphone designated as #2 on the machined aluminum sphere for consistency. Transducer electrets 1, 3, and 4 also produced comparable signal level magnitudes.

The same experimental procedures were used in evaluating the spun aluminum sphere enclosure, however, high noise levels with this sphere were not able to be overcome. Even with the spun aluminum sphere enclosed inside of the particle board and rock wool insulating enclosure, the noise level was in excess of 100 μ V and no observable signal was seen even with 14 torr H₂O buffered to 650 torr with N₂ in the spherical enclosure. Therefore no measurements were obtainable from this system.

AFCRL absorption coefficients were calculated for the conditions found in table 1. These results along with their calculated absorption sensitivities [in units of (km-watt)⁻¹] are given in table 2.

ELECTRET DETECTOR INVESTIGATION/NEW SPECTROPHONE DESIGNS

Due to obvious adaptability problems, cylindrical gold or aluminum coated mylar diaphragms like those used in conventional single-pass photoacoustic absorption chambers² (spectrophones) could not be used in a spherical geometry chamber. The internally reflecting, spherically resonant enclosure required

²Charles Bruce, 1976, Development of Spectrophones for CW and Pulsed Radiation Sources, ECOM-5802, Atmospheric Sciences Laboratory, US Army Electronics Command, White Sands Missile Range, NM 88002

TABLE 1. SENSITIVITY RESULTS FOR VARIOUS WATER VAPOR PRESSURE

LASER FREQUENCY (CM^{-1})	H ₂ O (TORR)	TOTAL PRES H ₂ O + N ₂ (TORR)	RESONANCE FREQUENCY (Hz)	NOISE LEVEL (AVG) (μV)	SIGNAL LEVEL (AVG) (μV)	SIGNAL TO NOISE RATIO
17.5	14	650	1926	20 μV	450.	22.5
17.5	7	300	1931	25 μV	200.	8.
17.5	2	300	1932	25 μV	45.0	1.8
17.5	0	650	1926	25 μV	—	—
17.5	0	0	1936	25 μV	—	—

TABLE 2. ABSORPTION SENSITIVITY

LASER FREQUENCY (cm^{-1})	H_2O CONCENTRATION (TORR)	TOTAL PRESSURE $\text{H}_2\text{O} + \text{N}_2$ (TORR)	AVERAGE SIGNAL-TO NOISE	AFCL H ₂ O COEFFICIENT (OCT. 1978 TAPE) (KM^{-1})	ABSORPTION SENSITIVITY (KM-WATT^{-1})
17.5	14	650	22.5	68.19	1.21×10^{-3}
17.5	7	300	8.0	17.37	8.68×10^{-4}
17.5	2	300	1.8	4.695	1.04×10^{-3}

10

NMM LASER FREQUENCY = 17.5 cm^{-1}

λ (μM) = 570.5

OUTPUT POWER = 0.2 mW

CO_2 LASER PUMP FREQUENCY = 9 p(16)

acoustic detectors with good sensitivity which were environmentally rugged and were compatible with this geometry. Miniature transducer electret microphones were chosen to be used as the acoustic detectors. Knowles type CA-1833 electrets were used on both spherical enclosures tested (figure 5). A graph showing detector sensitivity is shown in figure 6.

A parallel investigation was conducted to determine the applicability of single transducer electret type microphones as photoacoustic detectors in a conventional single-pass type spectrophones. Both type CA-1833 and the more sensitive type BT-1834 (also manufactured by Knowles electronics and just recently acquired) were used. Figure 7 shows the BT-1834 electret with its sensitivity curve shown in figure 8. Linearity and sensitivity tests have been run on a single-pass prototype spectrophone using both type detectors with very favorable results obtained in both cases. As a result transducer electret microphones have been incorporated into three different spectrophone designs presently in use at ASL.

An HF/CO₂ pulsed source spectrophone is one such system now incorporating the transducer electret microphones. Figure 9 shows a schematic representation of this system. This system makes use of four BT-1834 type detectors placed 90 degrees apart midway along the length of the stainless steel cavity. The cavity has a 5/8-inch hole bored midway along its length. This cavity is then placed inside of an environmentally controllable vacuum tight chamber having brewster angle windows at each end. As the beam propagates down through the center of the cavity, some of the electromagnetic energy is absorbed by an absorbing media. Heating of the gas occurs with the resultant pressure change creating an acoustic wave. Due to the double open-ended organ pipe design, a pressure maximum occurs midway down the cavity. Because of the symmetric placement of the four detectors in the cavity, the signals from each are in phase with one another. A summing amplifier was then used to sum the in phase signal magnitudes from each of the detectors with a resultant signal four times that of a single microphone signal. The response sensitivity figure from using this arrangement over a conventional mylar diaphragm microphone appears to be better by almost two orders of magnitude. Only continued testing will be able to verify this claim.

A NMMW laser intracavity spectrophone has also been designed incorporating the transducer electret microphones (figure 10). This spectrophone design is very similar to the HF/CO₂ pulsed source type previously mentioned. This system uses only one electret detector (type CA-1833) and the entire spectrophone is contained internal to the NMMW laser. Its placement is such that the optical pump beam from the CO₂ laser must pass down through the spectrophone cavity prior to entering through the rear optic of the near-millimeter laser cavity. By using the intracavity spectrophone, it is possible to optimize the output from the NMMW laser by tuning the CO₂ pump laser to obtain optimum absorption at the CO₂ frequency for the given NMMW laser pumping medium. The intracavity spectrophone has been incorporated into the NMMW laser and has proven to be very useful in optimizing output power of this system.

The third system developed, a differential type spectrophone, was constructed using the electret detectors (one CA-1833 electret in each side of the system). This system is represented schematically in figure 11. Tests have been conducted using this system, and, again, the preliminary findings have produced positive results.

CONCLUSIONS

Numerous problems were encountered with the spherical absorption chamber design. A combination of high-Q narrow-bandwidth characteristics, excessive noise sensitivities, mechanical chopping instabilities, resonant frequency temperature dependence, and continual signal phase changing made evaluation of the spherical spectrophone system extremely difficult. The use of a rock wool outer enclosure helped to eliminate some of the noise problems, but further improvements are required. Elimination of the rotating chopper arrangement by substitution of electronic modulation of the pump laser output would eliminate the chopper wheel resonant noise and the chopper instability problem. The high-Q temperature varying resonance characteristics mandate the use of frequency sweeping methods. This would require the use of computer controlled digital data processing approaches. In addition, amplifiers with phase locking features would be required. From tests performed so far, the absorption sensitivities obtained using the resonant sphere are not large enough to justify additional efforts at the present time.

The transducer electret microphones have been used as detectors in both resonant sphere and more conventional single-pass type resonant spectrophone geometries. Because of their sensitivity, environmental ruggedness, size, and compatibility with various spectrophone geometries, these microphones have proven to be very useful in various spectrophone applications. HF/CO₂ pulsed source, NMMW laser intracavity, and differential type spectrophones have been constructed incorporating the transducer electret microphones as detectors. Each of these three prototype spectrophone systems has produced favorable results in preliminary tests done so far at ASL.

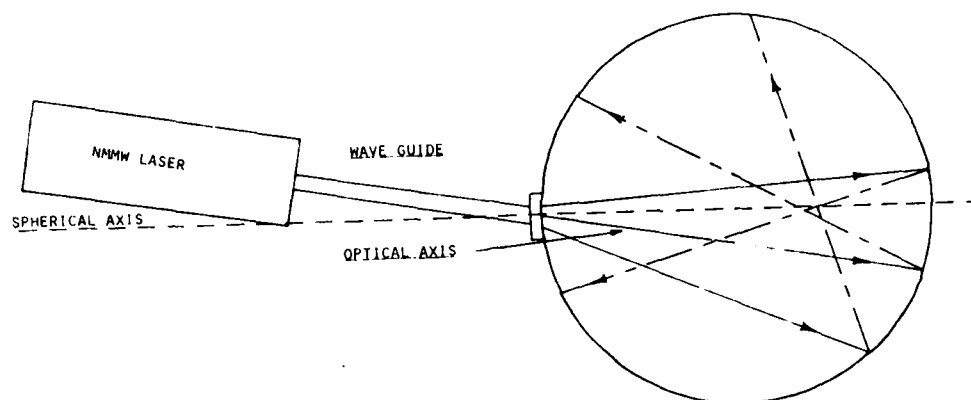


Figure 1. Proposed internally reflecting, spherically resonant enclosure.

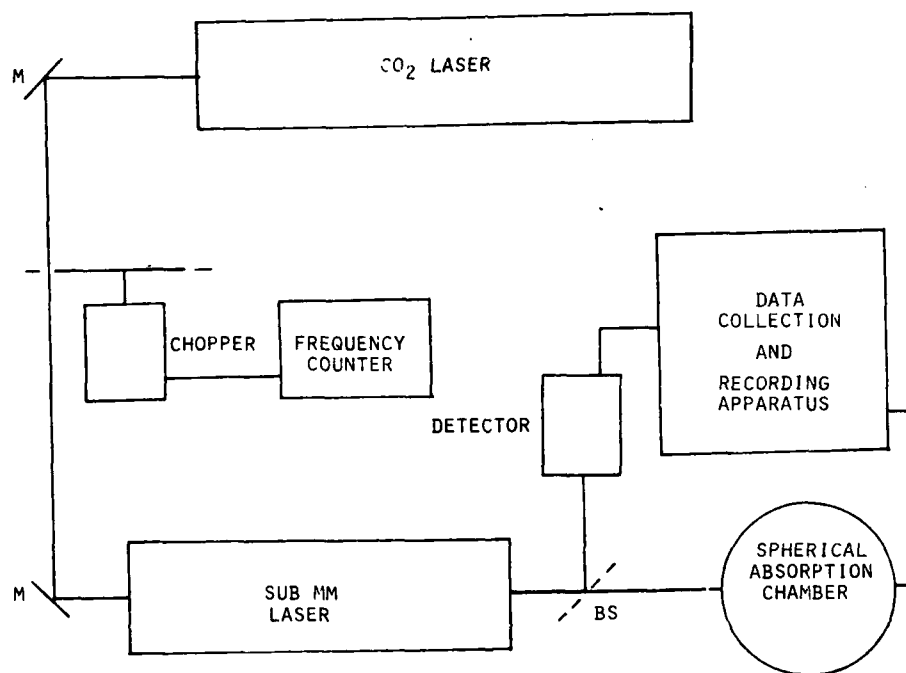


Figure 2. Experimental arrangement used to test internally reflecting, spherically resonant absorption.



Figure 1. Spun aluminum enclosure.

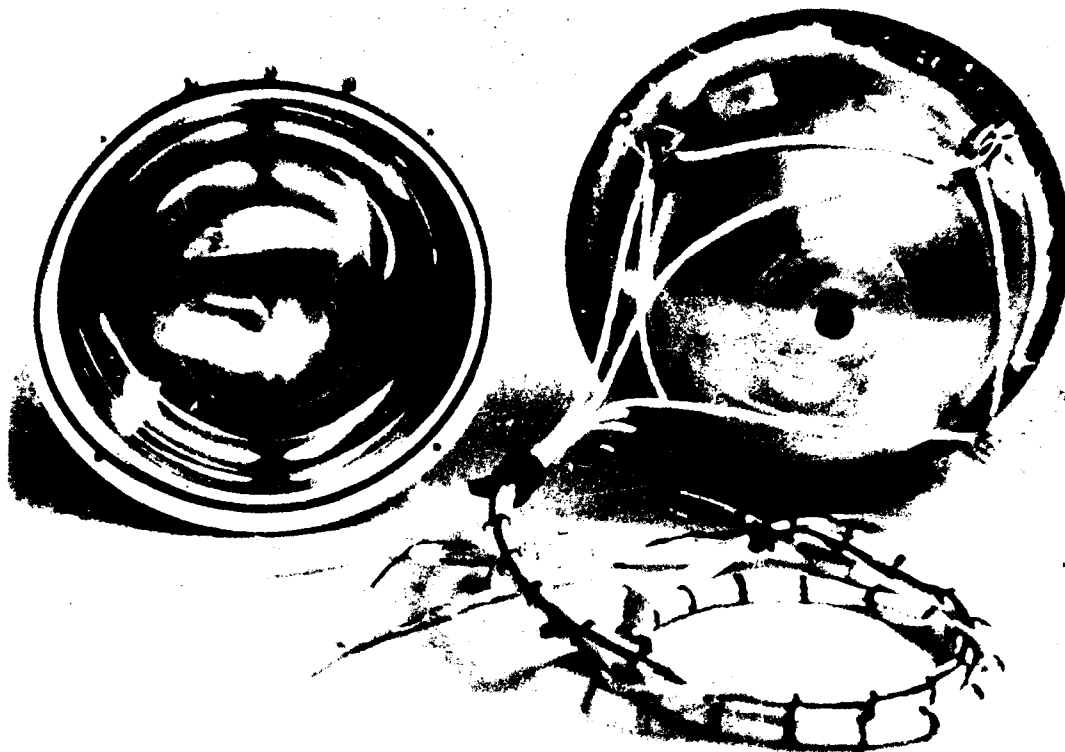


Figure 4. Machined aluminum.

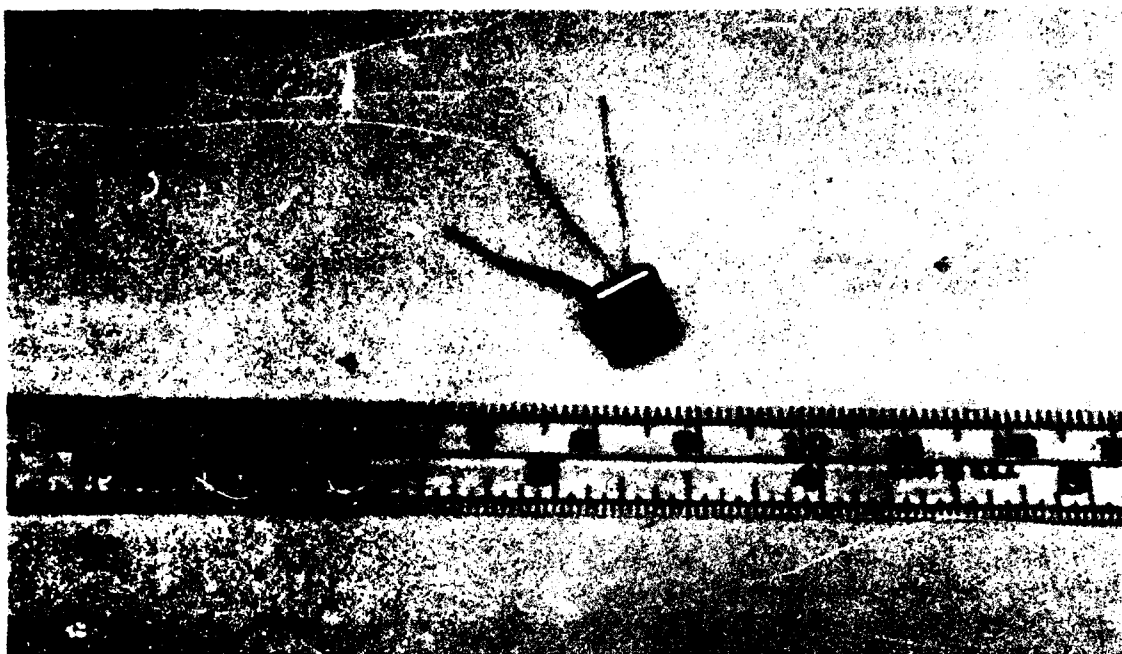
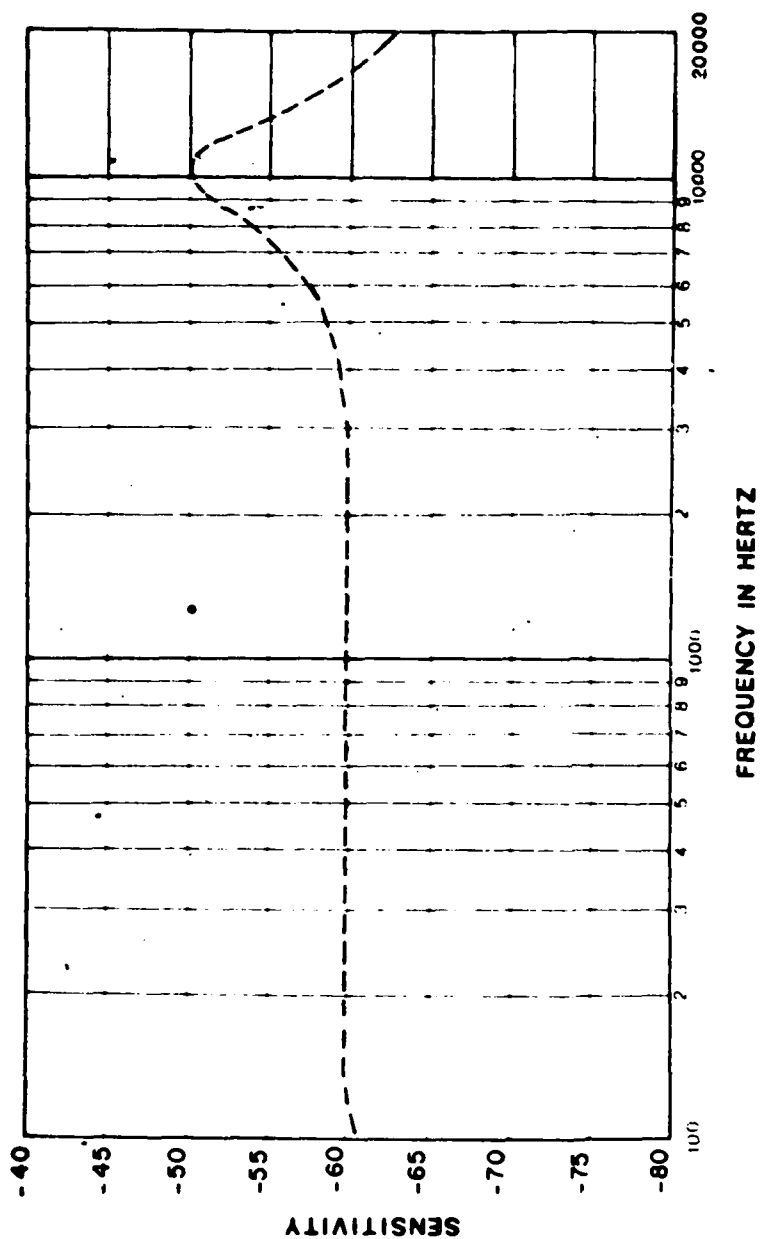


Figure 5. Electret detector type CA-1833.



OPEN CIRCUIT PRESSURE SENSITIVITY IN dB RELATIVE TO 1.0 VOLT/MICROBAR (0.1 N/m²)

FREQUENCY	SENSITIVITY (dB)		
	MIN	NOM	MAX
100	---	-61	---
1000	-63	-60	-57
11000	---	-50.5	---

OUTPUT IMPEDANCE; 2500 OHMS MAX.

Figure 6. Electret detector type CA-1833 sensitivity.

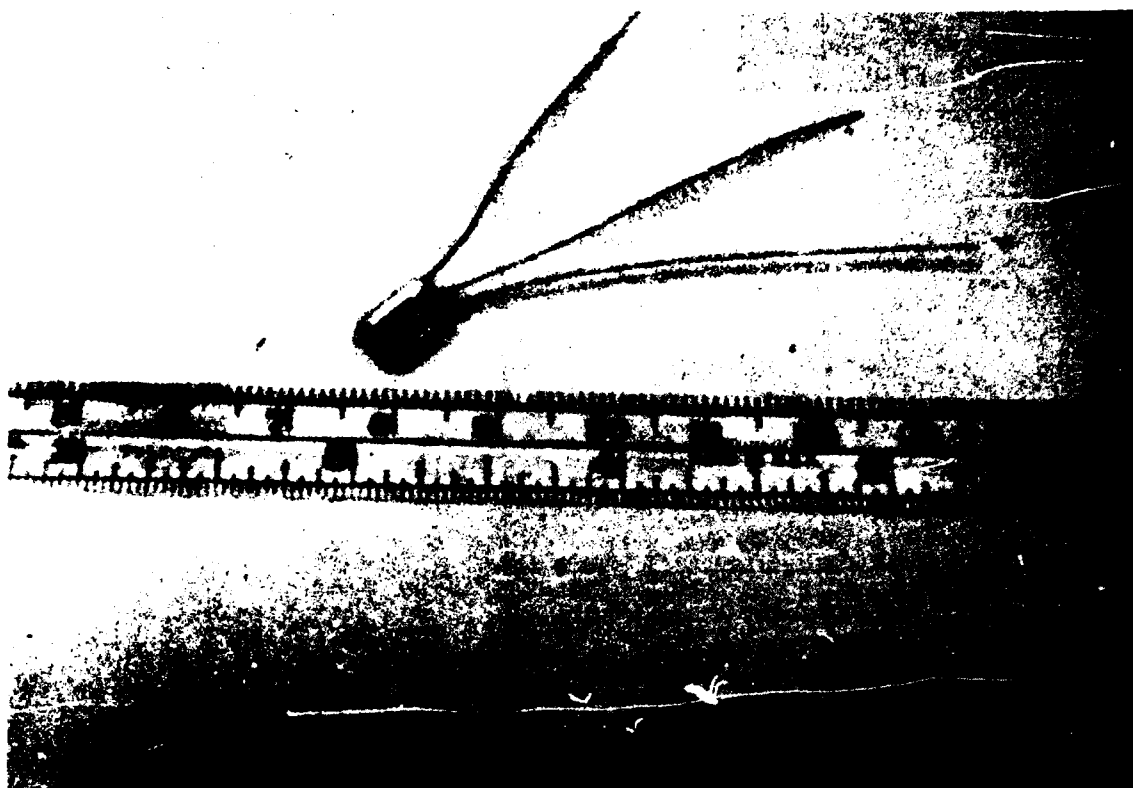
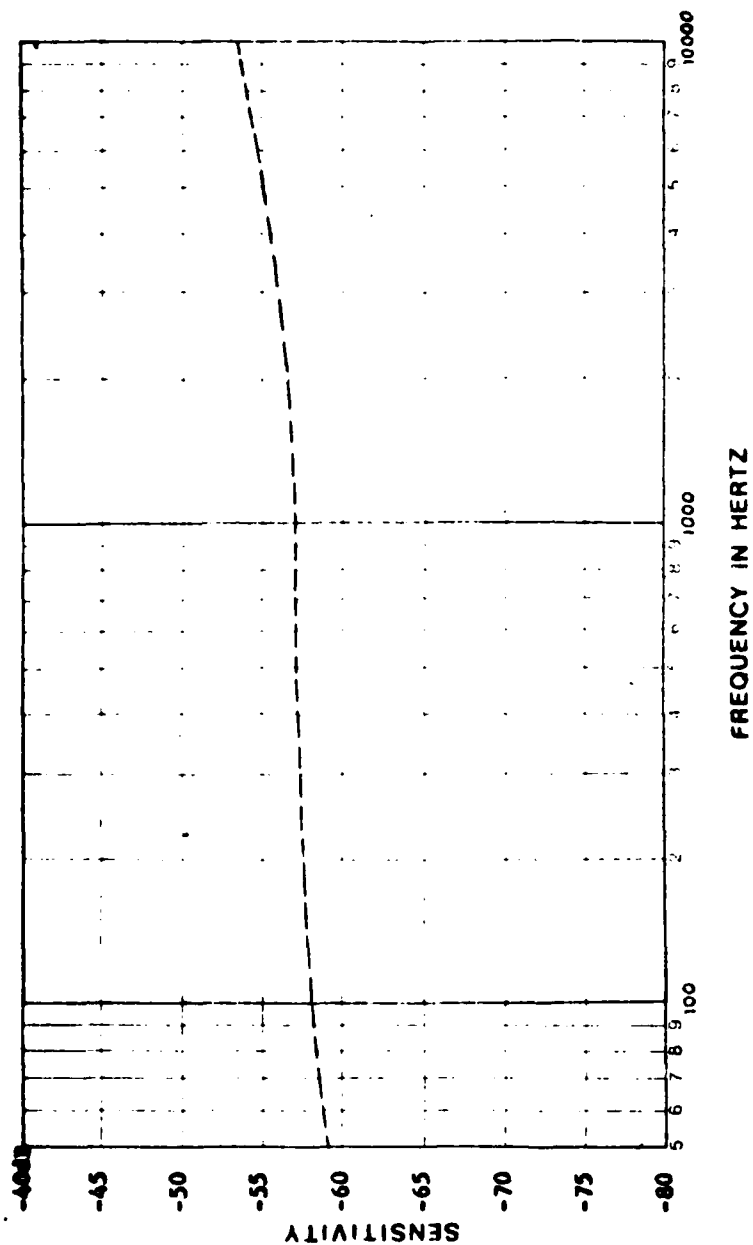


Figure 7. Electret detector type BT-1834.



OPEN CIRCUIT SENSITIVITY IN dB RELATIVE TO 1.0 VOLT/MICROBAR (0.1 N/m^2)

FREQUENCY	SENSITIVITY (dB)		
	MIN.	NOM.	MAX.
100	---	-58.0	---
1000	-60.0	-57.0	-54.0
10000	---	-53.5	---

OUTPUT IMPEDANCE: 2000 TO 6000 OHMS
(3500 OHMS NOMINAL).

Figure 8. Electret detector type BT-1834 sensitivity.

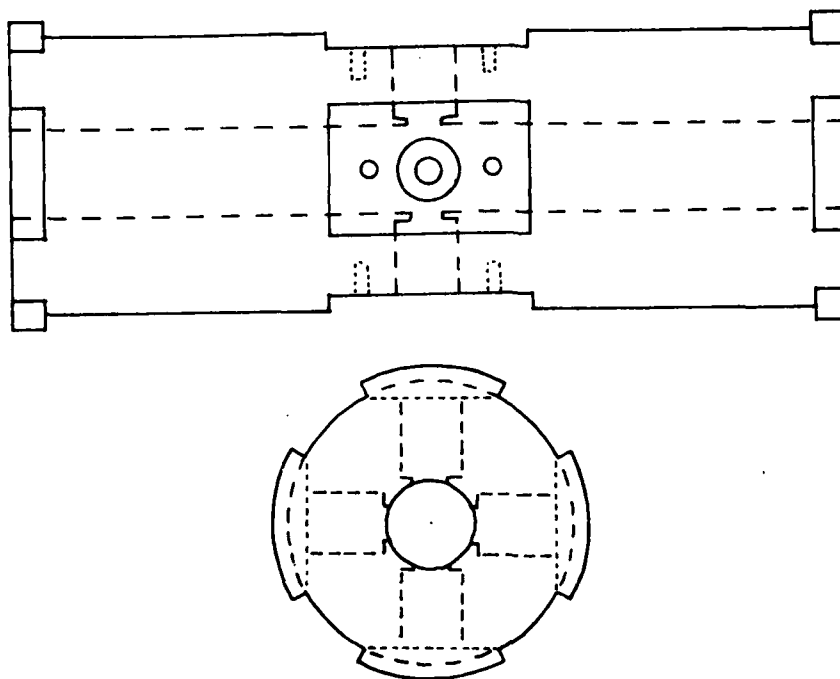


Figure 9. HF/CO₂ pulsed spectrophone using four electret detectors.

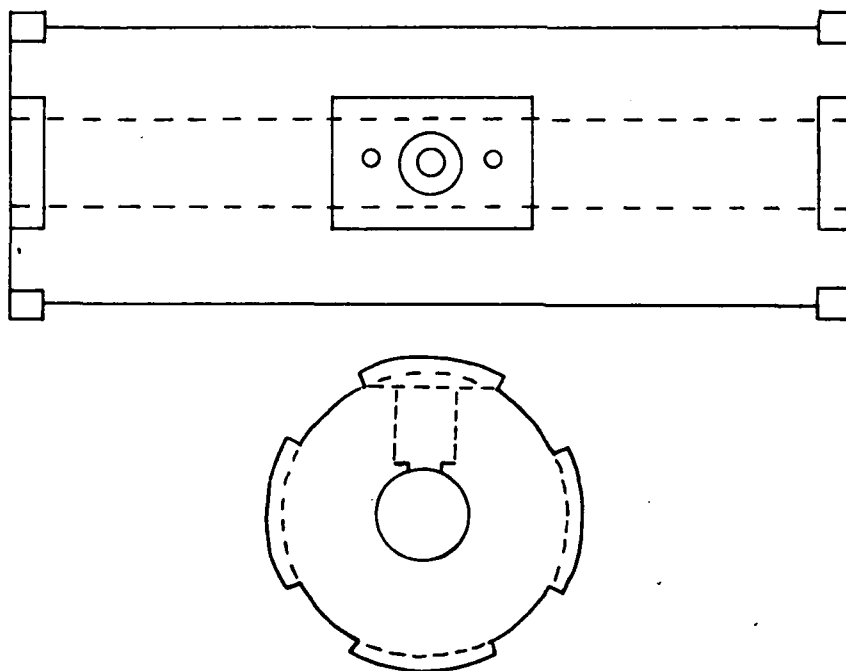


Figure 10 Intracavity near-millimeter wave laser spectrophone using one electret detector.

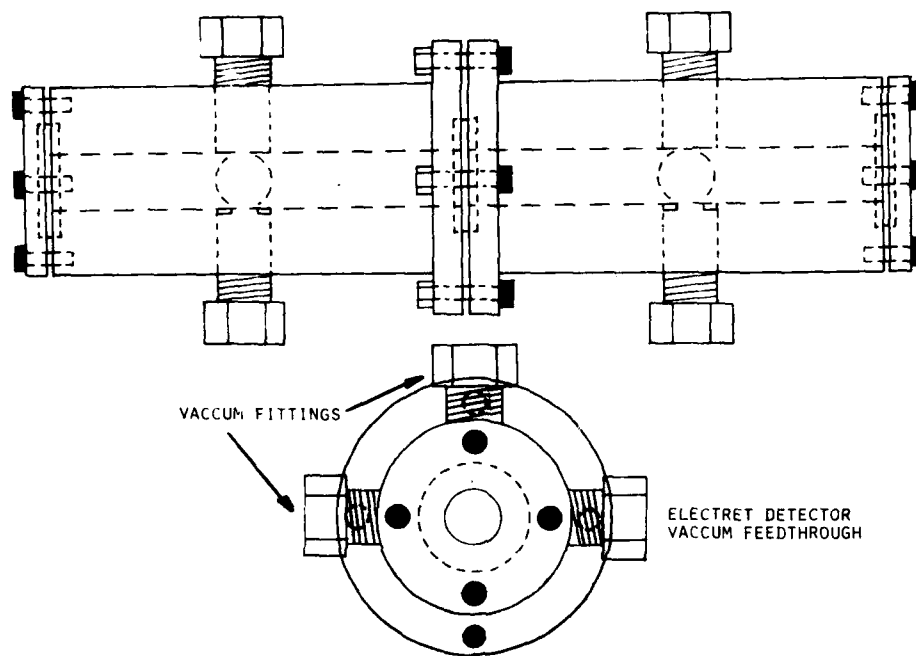


Figure 11. Differential type spectrophone using two delectret detectors.

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