CALIBRATION OF A CONDENSER MICROPHONE

MICROMETEOROID SENSOR

by

Robert L. Evans

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SUMMARY

A detailed calibration study of a 2-in. dia. open area condenser microphone micrometeoroid impact sensor is presented. The calibration results show that the sensor responds linearly to incident particle momentum in the design range of $10^{-5}$ to $10^{-7}$ dyne-secs. Both drop-tests and hypervelocity impact tests have been made. Velocities up to 7 km/sec have been achieved using an electrostatic dust particle accelerator.

A mathematical analysis of the diaphragm vibration mechanism has been successful in predicting the type of waveform and the operating modes of the sensor.

It is possible that this type of sensor, when coupled with a time-of-flight sensor now developed at the NASA Goddard Space Flight Centre may form a very useful and sensitive gauge for measuring the properties of micrometeoroids.
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\( A_{nm} \)  constants
\( a \)  maximum diaphragm radius, particle radius
\( B_{nm} \)  constants
\( C \)  sensor capacitance
\( C_0 \)  initial sensor capacitance
\( C_l \)  \( \sqrt{\frac{S}{\mu}} \)  speed of wave propagation
\( F \)  electric field intensity
\( I \)  meteor luminous power in watts
\( J_n \)  Bessel function of the first kind of order \( n \)
\( L \)  Meteor luminosity
\( M \)  stellar magnitude
\( M_v \)  absolute visual magnitude
\( m \)  particle mass
\( q \)  particle charge
\( r \)  radius from center of diaphragm
\( S \)  tension per unit length of membrane
\( t \)  time
\( v \)  velocity
\( V \)  voltage
\( w \)  membrane deflection
\( \Delta \)  undisturbed plate separation
\( \varepsilon_0 \)  permitivity of free space
\( \theta \)  angular position on membrane
\( \mu \)  membrane mass per unit area
\( \rho \)  mass density
\( \rho_{nm} \)  zeros of Bessel functions
\( \omega \)  characteristic frequency
I. Introduction

With the advent of space travel, there was considerable speculation on the danger of being struck by cosmic dust or micrometeoroids. These microparticles are present in interplanetary space and move at hypervelocities. The energy of such particles can be considerable and can endanger the life of an astronaut walking in space or of a space vehicle. The danger was pointed out by Whipple\(^1\) over a decade ago. Consequently, there was increasing concern and interest in micrometeoroids after the first space flight. This interest still continues and we are slowly learning about micrometeoroids and their orbital properties.

The first direct evidence of the existence of micrometeoroids was obtained from some of the early V-2 rocket launchings in the U.S.A. right after World War II. Some of the early rocket flights were instrumented with piezoelectric crystal transducers to measure skin panel deflections. When the data from these rockets was analyzed, it was noticed that there were several unexplained pulses in the transducer output. It was postulated that these pulses were due to micrometeoroid impacts. Consequently, one of the two experiments on the first U.S.A. satellite, Explorer I, was a micrometeoroid detection experiment\(^2\). The other experiment on Explorer I was a radiation detection experiment. After the initial successes of Explorer I and several sounding rockets instrumented to detect micrometeoroids, many more micrometeoroid experiments were designed both for earth satellites and sounding rockets. Later experiments were also designed and placed on interplanetary satellites.

A further stimulus to the study of micrometeoroids is the desire to know more about the universe, in particular about our own solar system. Astronomers are interested in the total composition of our solar system and for some time have theorized that the zodiacal light is caused by the diffraction and scattering of sunlight by cosmic dust\(^3\). In fact, some of the early work on the determination of the mass distribution of micrometeoroids was based on observations of the zodiacal light.

When it became apparent that micrometeoroids could be a real threat to space travel, several workers began to take a serious look at the actual mechanism of hypervelocity impacts. Some of the most successful of these studies resulted in a two-dimensional computer code for following the histories of both target and projectile after impact\(^4,5\). In the limited experimental velocity ranges available, the theoretical results agreed fairly well with experiment.

A serious difficulty that early micrometeoroid workers encountered was the lack of adequate calibration facilities. In order to accurately calibrate any type of micrometeoroid impact sensor, it is necessary to have a facility capable of launching small projectiles at velocities up to the maximum heliocentric meteoroid velocity of 72 km/sec. There has been a lot of work done in the past few years to develop a launcher capable of simulating meteoroid impact velocities. Many interesting techniques have been developed, including light gas guns, exploding wires, explosive drivers and at UTIAS, an implosion-driven launcher technique\(^6\). One of the most promising of the new techniques is an electrostatic charged particle accelerator modified to shoot small iron particles\(^7\).

A very sensitive type of micrometeoroid sensor is based on the condenser microphone principle. It would appear that these sensors, once calibrated,
could yield valuable information on micrometeoroid momenta and influx rates. Experiments utilizing these sensors could be designed for both near-earth sounding rocket measurements and for longer duration satellite measurements.

This report presents a brief review of micrometeoroid research to date. Later sections describe the condenser microphone sensor in detail, and presents the results of the calibration of such a sensor.

II. Micrometeoroid Research to Date

1. Micrometeoroids and Cosmic Dust

Since the dawn of history, man has observed meteors or "shooting stars" as they are popularly called. The first recorded account of a meteor sighting appears in Chinese and Japanese records of 180 B.C. Throughout early history there are such records as "stars falling like a shower", and similar accounts.

Today, by general agreement, the word "meteor" is applied to the bright flash of light accompanying a solid particle entering the earth's atmosphere. The reddish visible light is due to the radiating plasma associated with a high-speed particle entering the atmosphere. The solid particle creating the meteoric light is known as a meteoroid. Most meteoroids are vaporised by the extreme heat generated by atmospheric entry and hence never reach the earth's surface. If the meteoroid is massive enough, however, to survive the atmospheric entry and falls to the ground, the particle on the earth's surface is called a meteorite. It can also happen on the other hand, that the particle is so small that its ratio of surface area to mass is sufficiently large for the particle to be able to radiate away all the heat generated by atmospheric entry. If this happens, the particle falling to earth is termed a micrometeorite and the particle travelling through space is called a micrometeoroid. The diameter of these particles, depending on density of course, is roughly less than 100 microns.

If we consider meteoroids to be members of the solar system, the maximum heliocentric velocity they may have is the velocity for a parabolic orbit which is about 42 km/sec. The average velocity of the earth in its orbit about the sun is approximately 30 km/sec, so that the maximum geocentric meteoroid velocity is obtained for a head-on collision between earth and the meteoroid, and is 72 km/sec. The minimum geocentric velocity of a meteoroid would occur for a particle initially at rest at a large distance from earth. This particle would obtain the earth escape velocity of 11.2 km/sec in falling towards the earth. The range of geocentric meteoroid velocities then is between 11.2 and 72 km/sec.

The origin of these micrometeoroids, or cosmic dust particles as they are sometimes called, is still open to question. Several theories have been proposed to explain the presence of cosmic dust in our solar system and no one theory seems to be adequate. Perhaps a synthesis of all these theories is required to explain the existence of cosmic dust.

One of the most interesting of these theories describes cosmic dust as being of cometary origin. Comets are thought to be made up of ices of oxygen, hydrogen, nitrogen, ammonia and several other gases, as well as some solid material. Some of this solid material is thought to appear as dust particles imbedded in the conglomerate of ices. As the comet nears the sun in its orbit,
some of the ices are melted, releasing some of the entrapped dust particles. Initially this dust forms part of the comet's tail which streams out from the comet away from the sun due to the action of the solar wind and solar radiation pressure. The theory supposes that as the comet moves away from the sun, some of this dust released by the sun's melting action is left behind in the solar system.

Another prominent theory suggests that some meteoroids and cosmic dust may be the result of collisions or a grinding action amongst members of the asteroid belt. The asteroid belt is a region located between the orbits of Mars and Jupiter where thousands of fragments are located. Some of the largest of these fragments are sometimes considered to be minor planets and are given names. Ceres, for example, is approximately 480 miles in diameter.

For many years, astronomers have been observing meteoroids and plotting their radiants in order to learn more about our solar system. Several observational techniques have been used, the simplest method being an observer making a visual sighting. Several trained observers are often used, stationed a few miles apart. Each observer carefully notes the meteor path in relation to the star background and marks this information as well as the time of the sighting down on his chart. When the result of all observers are compared, the radiant or path in the sky of the meteor can be determined by triangulation.

Visual sightings are not possible for meteors fainter than magnitude+5, which is about the limit for the human eye. The stellar magnitude scale, which is over a hundred years old is expressed by the relation:

\[ M_1 - M_2 = 2.5(\log_{10} L_2 - \log_{10} L_1) \]  

where \( M_1 \) and \( M_2 \) are the magnitudes associated with stars or meteors having luminosities given by \( L_1 \) and \( L_2 \) respectively. Opik\(^{10}\), has defined an absolute visual magnitude scale, given by

\[ M_V = 6.8 - 2.5 \log_{10} I \]  

where \( I \) is the luminous power radiated in watts.

For meteors fainter than magnitude+5, other observational techniques are used, including photographic, radio and radar techniques. Time exposures of the night sky are usually made from two locations separated by some distance using the photographic technique. By comparing the meteor trails on the two photographic plates with the star background, the meteor radiant can be fairly accurately obtained.

Radio and radar techniques are based on a different principle from the visual and photographic techniques. While visual and photographic methods make use of the actual luminous power radiated by the tail of plasma behind the meteoroid, radio methods make use of radio signals reflected off the ionization column.

These techniques can accurately track a meteor which would not be seen by the human eye or even recorded on a photographic plate. Accurate paths of magnitude +10 meteors have been obtained with radar installations and echoes of meteors down to magnitude +15 have been recorded. Table 1 taken from Whipple\(^1\)
gives the mass vs visual magnitude relationship for meteors adopted by Whipple and other prominent meteor workers. It can be seen from this table that the faintest meteor observable by radar, i.e. magnitude +15, corresponds to a particle mass of a few milligrams. Micrometeoroid particles which we are interested in have masses of the order of $10^{-11}$ grms and corresponding visual magnitudes of the order of +30. It is obvious that particles this small require another method of observation and leads into a discussion of direct methods of micrometeoroid detection.

II. 2. Types of Micrometeoroid Sensors

With the advent of rockets and satellites, it has become practicable to make direct measurements of the concentration of cosmic dust in our solar system. As was mentioned in the Introduction, the first direct evidence of the presence of micrometeoroids was found accidently. The first rocket to detect such particles was USAF V-2 #31 launched on December 8, 1949. This rocket had been instrumented to monitor acoustic noise in the rocket skin during the flight. The instrumentation was a piezoelectric crystal bonded to the rocket skin. Dubin, a NASA investigator, suggested that the peculiar pulses registered by the equipment were due to impacts with micrometeoroids. The same type of pulses were detected on several other early V-2 rockets.

After these initial indications of the presence of cosmic dust, many sounding rockets carried instrumentation specifically designed to monitor micrometeoroid impacts. Most of the sounding rockets carried the crystal microphone type of sensor. This sensor usually makes use of a small piezoelectric crystal bonded to a metallic sounding board. When a particle impacts on the sounding board, a disturbance is transmitted through the board to the piezoelectric crystal, which then emits a typical ringing signal. The initial amplitude of this ringing signal is taken as the characteristic measurement for the impacting particle. Gorjup has done a rather extensive calibration of a crystal microphone type sensor. Unfortunately, however, he was not able to achieve particle velocities in the hypervelocity regime required for micrometeoroid simulation.

Pressurized cell type of detectors have been used on some micrometeoroid experiments. These consist of very thin annealed beryllium-copper cells filled with helium. When a cell is punctured by a micrometeoroid impact the helium leaks out, actuating a pressure switch which records the impact. These cells are detectors rather than sensors in the sense that they simply indicate a puncture by a micrometeoroid rather than measure any particle parameters. They are also one shot devices, in that only one puncture can be recorded. For this reason, many cells are used in an array mounted on the satellite.

Two types of resistance change impact detectors were flown on Explorer XVI. The first type consisted of a thin stainless steel cover plate attached to the outside of a continuous gold film grid. A puncture in the stainless steel cover plate will result in breakage of the gold grid and hence a change in resistance across the grid circuit. The copper wire card detector developed by Secretan at NASA's Goddard Space Flight Center is very similar. These detectors consist of many windings of 1 to 3 mil copper wire wound on a melamine card. A micrometeoroid impact breaks the wire opening the circuit and causes a change in resistance which is used to signal the impact. Both of these detectors are similar to the pressurized cell detector in that no further
information can be obtained after the initial impact.

Another type of sensor used on Explorer XVI is the cadmium sulfide cell type. This sensor consists of a very thin film of aluminum which has been vapour deposited on a thin mylar sheet, below which is a light sensitive cadmium sulfide cell. After being penetrated by a micrometeoroid, the mylar film allows a small amount of sunlight to pass through to the cadmium sulfide cell. The signal from the cell, of course, is dependent on the amount of light reaching it and hence on the size of the impact hole. When calibrated then, this device more nearly becomes a sensor than the resistance change or pressurized cell detectors.

An interesting type of micrometeoroid sensor has been under development at UTIAS for some time. This sensor utilizes strain gauges imbedded in a block of viscoelastic plastic. The strain in a viscoelastic plastic for a given stress is dependent on strain rate. This property results in a variation in the speed of wave propagation with stress through the plastic. By encapsulating several strain gauges and noting the time of arrival of the stress wave at each one, an idea of the momentum of the impacting particle can be had. At this stage of development, however, this sensor is not as sensitive as other types.

What would appear to be a very promising type of sensor is being developed by Computing Devices of Canada Ltd. This sensor utilizes photomultiplier tubes to look at the light flash radiated during a hypervelocity impact. Although this basic idea has been used by other people to estimate the energy at impact, the Computing Devices of Canada concept appears to be the most sophisticated to date. Their sensor uses nine photomultiplier tubes and nine narrow band filters to look at certain emission lines of the impact flash. By carefully choosing the filters to monitor target emission lines, background lines and other selected lines, much information about the mass velocity and particle composition can be obtained. Observation of the shape of several time resolved target lines yields information about the mass and velocity of the impact, and comparison of all emission line spectra gives clues as to the composition of the particle itself. This sensor is particularly appealing because with one sensor, most of the particle parameters of interest, as well as an idea of the particle composition can be obtained.

Probably the most ambitious and sophisticated sensor to date to be successfully flown on a satellite is the sensor developed at the NASA Goddard Space Flight Center under the direction of Otto Berg. This sensor uses a conventional piezoelectric crystal microphone, but also has an ingenious grid system to measure the particle velocity and the velocity vector. Figure 1, taken from Ref. 16, shows the sensor schematically. As a particle passes through the very thin front film a small amount of its energy is used to create a plasma at the film. Electrons are collected on the positively biased grid giving a negative pulse and ions are collected on the negatively biased film giving a positive pulse. A similar situation occurs at the second grid and film array placed on the crystal microphone resulting in a positive and negative pulse, and a signal from the microphone. The pulses from the front and rear film and grid arrays are used to start and stop an electronic clock, respectively, yielding a time-of-flight measurement of the particle velocity. The microphone signal is processed in the usual manner to yield particle momentum. Fig. 2, again taken from Ref. 16, shows how the film and grid arrays are formed from four vertical and horizontal strips. By noting at which vertical and horizontal strip the
signal originates on both the front and rear arrays, the velocity vector can be determined. Results from this sensor flown on Pioneer 8, have enabled Berg et al to plot the orbits of individual micrometeoroids\(^{16}\). These results will be presented in the next section.

II. 3. Results of Cosmic Dust Measurements

Alexander et al\(^{17}\) have written a review which summarizes many of the direct measurements of micrometeoroid flux to date. Fig. 3, taken from their report shows the results of many U.S. satellite measurements, the Oklahoma State University rocket results, as well as some satellite and rocket measurements made in the Soviet Union. All the results shown plotted, except the Soviet results, have been corrected for earth shielding of the sensors and the measurements normalized to a solid viewing angle of \(\frac{4\pi}{10}\) steradians. It is not clear whether the Soviet results were corrected for earth shielding, so the results were reported as given. Alexander et al then drew an average cumulative mass distribution curve through the points, as is shown in Fig. 3. The shaded upper portion of the curve indicates the large degree of uncertainty in flux measurements for particle masses smaller than about \(10^{-10}\) gms. Also shown on this plot are the results of the Venus Flytrap experiment, a rocket experiment which purported to trap micrometeoroid particles and return them to earth. The particles were then counted and the mass distribution in space estimated. In making the calculations for the preparation of Fig. 3, Alexander et al assumed a mean particle speed of 30 km/sec, which is the approximate mean value between the two theoretical velocity limits of 11.2 and 72 km/sec.

Brownlee et al\(^{18}\) have reported on a very interesting micrometeoroid experiment on board the Gemini 12 manned spacecraft. This experiment used semitransparent metallic films of both gold and copper deposited on transparent slides. These slides were exposed to the micrometeoroid environment for a total time of 6 hrs. and 24 mins. during the Gemini 12 mission. When the slides were returned to earth they were scanned by both optical and electron microscopes in search of micrometeoroid impact craters. The copper slide was not successful, due to contamination, but the gold one was successfully scanned. Both the optical scan and electron microscope scan revealed no impact craters on the gold slide. The minimum crater detection limit was 0.75 microns. Since no craters were found, it was possible to statistically derive an upper limit to the micrometeoroid flux in the two ranges scanned. For the optical scan, an upper limit for the cumulative flux of \(3.1 \times 10^{-2}\) particles m\(^{-2}\) sec\(^{-1}\) down to a mass of \(10^{-12}\)g and for the scanning electron microscope an upper limit of \(4.3\) particles m\(^{-2}\) down to \(1.8 \times 10^{-14}\) g was found. An average meteoroid velocity of 20 km/sec was used for the calculations. Figure 4 adopted from Brownlee et al compares these results with the average cumulative flux curve of Alexander et al. The figure show that the two upper limits are significantly lower than the curve given by Alexander et al. Brownlee points out that due to the fact there is no apparent source of error in this method, the previous direct measurements are open to serious question.

The results from the micrometeoroid sensor developed by Berg et al\(^{16}\), at the NASA Goddard Space Flight Center and described in the previous section, although very limited so far, have been most impressive. As mentioned in the description of the sensor, this device measures the particle's momentum and velocity and obtains an estimate of the velocity vector. The angular reso-
olution of the sensor is $\pm 27^\circ$ due to the physical arrangement of the experiment. With all the particle parameters determined, Berg has been able to plot orbits for micrometeoroids. To date, orbits for four such particles have been determined. Figure 5, taken from Ref. 16, shows the orbit of a particle detected on March 11, 1968. The spacecraft Pioneer 8 is shown in a heliocentric orbit closely following the earth. The two dotted lines give the two limiting particle orbits based on the $\pm 27^\circ$ angular resolution of the sensor. The nominal particle trajectory is shown solid. It is very interesting to note that so far, all particles observed have been in heliocentric orbits, and all have been in the ecliptic plane. Table 2 lists the parameters of all four particles detected to date.

The Soviet Union has been fairly active in micrometeoroid detection, although they have not published extensively in the open literature. A brief review of Soviet research in this area is given in Ref. 19. Table 3, (Ref. 19) lists the Soviet experiments up to 1966. The first rocket measurements reported were taken in May 1957, some eight years after the initial indication of cosmic dust particles by a U.S. rocket.

The first satellite experiment reported was on Sputnik 3 launched in May 1958. Nearly all the Soviet experiments have been based on a piezoelectric crystal microphone, similar to the U.S. microphone systems. According to the results, the Soviet experiments do not appear to be quite as sensitive as the most sensitive U.S. ones. The most sensitive microphone records particles down to about $2 \times 10^{-9}$ gms.

In comparing U.S. and Soviet results, one must be careful to determine what particle velocity has been assumed. Initially, both groups used 40 km/sec as an average meteoroid velocity, while later on U.S. investigators moved to 30 km/sec. and the Soviet group chose 15 km/sec. Berg's recent velocity measurements (Table 2), make the latter figure seem more reliable. From some of their results, the Soviets as well as some American workers, have concluded that there is some kind of dust belt (or belts) around the earth. They also postulate that this may be true for other planets.

However, according to a study by Nilsson20, much of the data from crystal microphone sensors is in serious doubt due to spurious sensor signals triggered by thermal gradients. Recent measurements indicate that the micrometeoroid flux in space is most likely at least two orders of magnitude lower than it was previously thought21. These results indicate that the high concentration of dust in the vicinity of earth needed to support the dust belt theory is probably not present, and puts the theory in some doubt.

III. The Condenser Microphone Sensor

1. Description

The results obtained with the crystal microphone impact sensor have been often criticized in the past, chiefly because of their tendency to emit erroneous signals due to thermal stress. Recently, these "creak" effects have been blamed for the seemingly high impact results for the cumulative micrometeoroid flux reported by many experimenters. In order to produce a more sensitive impact sensor and one which is not subject to thermal creak effects, the condenser microphone type of sensor was developed. The two sensors used in the
present calibration study were developed and manufactured by the Ling-Temco-Vought Inc. Research Center, Anaheim, California. One of these sensors is seen in Fig. 6.

The sensor consists basically of two capacitor plates, one fixed and one moveable, and an amplifier unit. A schematic of the sensor is shown in Fig. 7. The fixed capacitor plate is circular and centrally located. It is separated from the case by an insulator. The moveable plate is a very thin (.00014 in.) stainless steel circular diaphragm clamped at the edges. The diaphragm tension can be adjusted by turning the clamping nut which stretches the diaphragm over a tensioning ring. The distance between the two capacitor plates is .0025 ± .0005 in. All material is stainless steel except for the ceramic insulator.

The capacitor sensor has a polarizing voltage of +350 V dc across it, and is AC coupled to the amplifier section through C1. The amplifier is a three-stage design. The first stage utilizes a field-effect-transistor to give a high input impedance to minimize the input current. The second and third stages consist of a common emitter-emitter follower cascade to further amplify the signal. The amplifier power required is approximately 1.6 ma at +25 Vdc.

In operation, a microparticle strikes the diaphragm, distorting it and hence changing the inter-plate spacing. This change in spacing changes the sensor capacitance and as the applied voltage is kept constant an output signal is produced according to the relation \( i = \frac{\partial C}{\partial t} \). This signal is then amplified and is ready to be displayed on an oscilloscope or fed into a telemetry system on board a spacecraft. After being struck by the microparticle the diaphragm vibrates at its natural frequency. Due to damping caused by bending of the diaphragm, the signal appears as a decaying periodic wave. Typical signals, caused by tapping on the sensor case are shown in Fig. 8. The actual mechanism of diaphragm vibration is discussed more thoroughly in the next section.

III. 2. Diaphragm Vibration Mechanism

It was noted above that the exterior plate of the capacitor sensor is a clamped circular membrane. In order to understand the operation of the sensor, the equation of motion of the diaphragm is solved to determine the possible signal waveforms. If, from this analysis the observed waveform can be reconstructed, then the vibrational modes of the sensor are known. The solution for the dynamics of a clamped circular membrane is a classical problem which has been dealt with by several authors22,23,24.

The equation of motion for a vibrating circular membrane in polar coordinates is given by 23,

\[
Cl \left( \frac{\partial^2 w}{\partial r^2} + \frac{1}{r} \frac{\partial w}{\partial r} + \frac{1}{r^2} \frac{\partial^2 w}{\partial \theta^2} \right) = \frac{\partial^2 w}{\partial t^2}
\]

where \( w = \) membrane deflection
\( r = \) radius from centre of membrane
\( \theta = \) angular position on membrane
\( t = \) time
\( Cl = \frac{\rho}{\mu} \) speed of wave propagation
\( S \) = tension per unit length of membrane  
\( \mu \) = membrane mass per unit area

Using the method of separation of variables, assume a solution of the form:

\[
 w(r, \theta, t) = R(r) \Theta(\theta) f(t) \tag{3.2} 
\]

A general solution of Eq. 3.1 is then given by\(^23\),

\[
 w(r, \theta, t) = \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} \left[ w_{nm}^{(1)}(r, \theta, t) + w_{nm}^{(2)}(r, \theta, t) \right] \tag{3.3} 
\]

where \( w_{nm}^{(1)} \) and \( w_{nm}^{(2)} \) are the two characteristic vibrations:

\[
 w_{nm}^{(1)}(r, \theta, t) = J_n \left( \frac{\omega_{nm}}{c_1} r \right) \cos n\theta \left[ A_{nm}^{(1)} \cos(\omega_{nm} t) + B_{nm}^{(1)} \sin(\omega_{nm} t) \right] \tag{3.4} 
\]

\[
 w_{nm}^{(2)}(r, \theta, t) = J_n \left( \frac{\omega_{nm}}{c_1} r \right) \sin n\theta \left[ A_{nm}^{(2)} \cos(\omega_{nm} t) + B_{nm}^{(2)} \sin(\omega_{nm} t) \right] \tag{3.5} 
\]

\( J_n \) is a Bessel function of the first kind of order \( n \). The constants \( A_{nm}, B_{nm} \) are determined from initial conditions and the \( \omega_{nm} \) are the characteristic frequencies. For \( n = 0 \) the characteristic vibrations are independent of angle \( \theta \) and \( w_{nm}^{(2)} = 0 \). Because the change in capacitance of the sensor is only proportional to average displacement of the diaphragm, we are only interested in circular modes of vibration, as all other modes will not yield any net diaphragm displacement. Non-circular vibrational modes displace equal areas of diaphragm above and below the equilibrium position, resulting in no net average diaphragm displacement (see Ref. 25 for a clear illustration of these modes). The only solutions of interest, therefore, are those independent of \( \theta \), or solutions for which \( n = 0 \). The nodal lines of the characteristic vibrations \( \omega_{0m} \) are circles. The fundamental characteristic frequency is:

\[
 \omega_{01} = \frac{c_1}{\alpha} \rho_{01} = 2.404 \frac{c_1}{\alpha} \tag{3.6} 
\]

where \( a \) is the outer radius of the diaphragm and \( \rho_{01} \) is the first zero of \( J_n \). The zeros of Bessel functions may be found in any standard work on Bessel functions\(^26\).

We can now assume \( B_{0m} = 0 \), as the second term in Eq. 3.4 will only change the phase of the signal and will not affect the waveform itself. The deflection of the diaphragm at any radius is now given by:
\[ w(r,t) = \sum_{m=1}^{\infty} J_0 \left( \frac{\omega_{om}}{C_1} r \right) A_{om} \cos(\omega_{om} t) \]  

although in practice it is usually only necessary to include the first few terms, as higher modes are damped out by bending stresses in the diaphragm. In order to obtain the actual capacitance change of the sensor, Eq. 3.7 should be integrated over the radius of the diaphragm. The capacitance is given by:

\[ \frac{1}{C} = \frac{1}{C_0} \left[ 1 - \frac{2}{\Delta} \int_0^a w \, r \, dr \right] \]

where \( C_0 \) is the initial capacitance of the undisturbed sensor, equal to 50 picofarads, and \( \Delta \) is the undisturbed plate separation. Solutions for the sensor capacitance, using Eq. 3.7 in Eq. 3.8 were programmed on a digital computer for several vibrational modes. It was found that the observed sensor signal was almost perfectly reconstructed by using the first two modes in Eq. 3.7. Using these first two modes, Eq. 3.8 becomes

\[ \frac{1}{C} = \frac{1}{C_0} \left[ 1 - \frac{2}{\Delta} \left\{ \int_0^a A_{01} \cos(\omega_{01} t) J_0 \left( \frac{\omega_{01}}{C_1} r \right) r \, dr \right. \\
+ \left. \int_0^a A_{02} \cos(\omega_{02} t) J_0 \left( \frac{\omega_{02}}{C_1} r \right) r \, dr \right\} \right] \]

In order to carry out the integration in Eq. 3.9, the Bessel functions were put in series form, according to the relation

\[ J_n(x) = \sum_{n=0}^{\infty} \frac{(-1)^n \left( \frac{x}{2} \right)^{2n}}{(n!)^2} \]

and integrated term by term. The integrated series were found to converge after the first few terms. For convenience in the calculations, and because of the difficulty of measuring the diaphragm tension, the constant \( C_1 \) was taken to be \( \Delta = 1 \). The solution then appears as a function of non-dimensional time. The constants \( A_{01} \) and \( A_{02} \) are determined by the initial membrane deflection and here were chosen to be equal to 0.001 in., a representative value of the actual maximum deflection of 0.0025 in.

Figure 9 shows the computer-plotted results for sensor capacitance as a function of nondimensional time. The capacitance can be seen to fluctuate around the undisturbed sensor capacitance of 50 picofarads. The sensor signal is actually proportional to the first time derivative of capacitance, according to the relation \( i = V \frac{dc}{dt} \). The first derivative of capacitance is shown plotted in Fig. 10. Comparison of Fig. 10 with Fig. 27 shows the computed waveform to be qualitatively a very good replica of the actual sensor signal waveform. The sensor is apparently operating primarily in the first two circular vibration modes, as any additional terms were found to distort the wave shapes.
IV. Drop Test Calibration

1. The Drop Test Technique

Dropping small beads of known mass has been a long-standing technique for calibrating momentum sensitive devices such as microphone impact sensors. The bead can be accurately weighed or measured and once the drop height is known, the final velocity can be simply calculated (viscous drag is negligible for small particles\(^{12}\)) from the energy relation:

\[
\frac{1}{2} m v^2 = m g h
\]

Thus the momentum of the impacting particle is known and once a value for the coefficient of restitution has been found, the momentum transfer to the sensor can be determined. For the purpose of the present study, a value of \(e = 0.8\) has been used, as suggested by Gorjup\(^{12}\).

The beads used for the present calibration study were "Superbrite" brand glass beads manufactured by the 3-M Co. These beads are manufactured by the Reflective Products Division and are intended for use in paint for road signs, projection screens and the like. These beads have good sphericity but have a wide size distribution. This makes it necessary to carefully measure the diameter of each glass bead under a measuring microscope. This is naturally a very tedious process. However, no better method of obtaining a calibrated supply of small spherical beads has been found. Several size ranges of beads were obtained, and, the smallest beads which could be successfully handled had an approximate diameter of 200 microns.

Because of the extreme damping effect of air trapped between the sensor capacitor plates and also because of a danger of electrical breakdown in air between the plates, it was necessary to perform the drop tests in a vacuum chamber. The chamber consisted of a standard bell jar, a special base plate with electrical lead-throughs, and a stand to hold the sensor, and bead dropper. A schematic of the bell jar, pumping apparatus and vacuum instrumentation is shown in Fig. 11. Figure 12 shows an overall view of the bell jar and base-plate with the bead-dropping apparatus inside.

IV. 2. The Bead Dropping Mechanism

In order to drop the beads individually in the vacuum chamber it was necessary to construct a special remotely operated Bead Dropping Mechanism. This machine was similar in construction but simpler than one suggested by L. Secrerton of NASA's Goddard Space Flight Center\(^{27}\). A cross-section of the mechanism is shown in Fig. 13.

The bottom plate is constructed of two pieces of steel. The bottommost plate has one hole drilled in it for the passage of beads and then is surface ground. A steel ring is then attached to this plate to locate the upper plate. The upper plate is made of brass and has 24 holes drilled in it at the same radius as the lower hole. This plate is placed in the locating ring and is turned by a worm gear and Hurst model DA synchronous motor. The lower plate is attached to a mounting block and the upper one turns inside it at approximately 1/4 rpm. In operation, beads are loaded one at a time in the holes in the upper slot and
as the plate is rotated they fall one at a time through the lower hole. The motor leads are taken through the electrical lead to a reversing switch and start-stop button. The mechanism can then be remotely controlled from outside the vacuum chamber. Figure 14 shows a closeup picture of the Bead Dropping Mechanism.

IV. 3. Experimental Procedure

The drop tests proceeded in several series of runs with about one dozen beads selected for each series. The first step was to measure the diameter of each of the beads using an E. Leitz Wetzlar microscope and place each bead in a separate small pill bottle with the diameter written on a piece of tape on the bottle. Before each measurement the beads were checked for sphericity and those that did not meet the requirements were rejected. After about a dozen measurements eye fatigue became apparent. Therefore this number was selected as a suitable one to work with. The beads were picked up and handled with a drawing compass needle to which the beads stuck by electrostatic attraction. When experiments were not in progress the needle and beads were kept in a dessicator to eliminate as much moisture as possible.

The next step was to load each bead individually into the bead dropping machine, carefully noting on a sheet of paper what diameter bead was in each hole. The loaded bead dropper was then mounted on the stand with the sensor mounted underneath it. The bottommost hole of the dropper was centered over the sensor diaphragm and the distance from the diaphragm to the bead mechanism adjusted to 2 cm. Figure 15 shows the bead dropper and sensor mounted on the base plate. After electrical connections were made, the bell jar was placed over the assembly and the vacuum chamber evacuated to a pressure less than one torr.

The output from the sensor was first taken to a Hewlett-Packard model 465A amplifier before being fed to a Tektronix type 555 dual-beam oscilloscope. The signal was fed to both beams of the oscilloscope, one set on a slow sweep rate to show the decaying nature of the signal and the other on a fast rate to show details of the first few cycles. A schematic of the electrical hookup is shown in Fig. 16. The oscilloscope traces were recorded with a Polaroid camera attachment and stapled to a data sheet on which was noted all the pertinent data. During the analysis of the runs the momentum was determined by means of Eq. 4.1 and the signal was measured from the oscilloscope picture.

A great deal of difficulty was encountered with the beads sticking to the bead dropper, due to either electrostatic attraction or excessive moisture. If a bead simply stuck to the upper plate, the plate was rotated to its next position and the next bead allowed to fall. If, however, a bead became stuck and jammed between the two plates, the series of runs had to be abandoned and a new set of beads measured and loaded in the dropper. Approximately 1 out of 3 beads loaded in the dropper was dropped successfully. It is seen that there is still a need to develop a simple and effective bead-dropping mechanism.

V. Hypervelocity Calibration

1. The Electrostatic Dust Particle Accelerator

As was mentioned in the Introduction, the lack of suitable hypervelocity launchers is a serious handicap in any type of micrometeoroid impact calibration
program. A very interesting technique for the acceleration of microparticles to hypervelocities has been recently developed by the Space Technology Laboratories of TRW Systems Inc. This technique accelerates charged microparticles to high velocities in an electrostatic field. TRW Systems have developed a modification kit to enable a standard 2 million volt van de Graaff generator to accelerate charged carbonyl iron particles.

The key problem is to obtain single microparticles with a high electrostatic charge, which can then be injected into a high-voltage accelerating field. Vermeulen has done a theoretical and experimental study of the contact charging process which is used in this method of acceleration. The energy of a charged particle in an electric field is given by,

\[ \frac{1}{2} m v^2 = q V \]  \hspace{1cm} (5.1)

where \( q \) is the charge on the particle and \( V \) the accelerating potential.

For a sphere,

\[ m = \frac{4}{3} \pi a^3 \rho \]  \hspace{1cm} (5.2)

where, \( a \) is the particle radius and \( \rho \) the mass density.

The charge on a spherical particle can be found from

\[ q = 4\pi a^2 \varepsilon_0 F \]  \hspace{1cm} (5.3)

where \( \varepsilon_0 \) is the permitivity of free space and \( F \) is the field intensity at the particle surface due to the charge it carries.

Combining Eqs. (5.1) (5.2) and (5.3), we find

\[ v = \left( \frac{6 \varepsilon_0 V F}{a \rho} \right)^{1/2} \]  \hspace{1cm} (5.4)

which gives the particle velocity in terms of the particle surface field intensity in the accelerating potential.

It can be shown that the charge on a negatively charged particle is limited by electron-field emission, while for a positively charged particle it is limited by inter-atomic forces. For negatively charged particles, the surface field strength limit is about \( 10^9 \) V/m, while for positively charged particles it is about \( 2 \times 10^{10} \) V/m. Vermeulen has shown that it is possible to approach these surface field strengths by contact charging carbonyl-iron microparticles.

Figure 17 taken from Ref. 7 shows the relationship between velocity and particle radius for several values of accelerating voltage. The surface field strength for this plot was taken to be \( 2.5 \times 10^9 \) volts/meter.

Figure 18 shows a schematic of the particle injector developed by TRW Systems to contact charge microparticles and introduce them into a van de Graaff
generator. Carbonyl-iron particles are placed in the chamber marked A in Fig. 18. This chamber also contains the charging electrode and a hole just above it to admit dust particles. The injector unit is separated from the van de Graaff accelerator tube by an insulator and the charging electrode and dust container are kept at a potential of 4.5 kV by the high voltage power supply. To operate the system, the pulser is triggered and a negative pulse is applied to the tongue. This pulse attracts some of the dust and a cloud of particles is formed inside the chamber. A few of these particles find their way through the hole in the dust chamber and are exposed to the electric field between the dust chamber and the electrode C. The particle is accelerated back and forth across the gap between A and C exchanging charge each time it strikes either the chamber or the electrode C. Electrode C is shaped so that the field tends to move the particle towards the axis of the accelerator. Eventually, a particle will find its way onto the charging electrode B, where the strong electrostatic field strength gives the particle the maximum charge possible. The particle will then be repelled and if accurately aligned will pass through the hole at C and through the control hole D. After passing through hole D the highly charged particle is under the influence of the 2 million volt van de Graaff potential.

The fact that the particle is charged makes it relatively easy to provide a detection system. A simplified schematic of the type of detector used by TRW Systems is shown in Fig. 19. This detector consists basically of a cylindrical drift tube mounted coaxially inside a grounded shield. As a charged particle enters the detector it will induce on it a voltage proportional to the particle charge. The duration of the signal will be equal to the time of flight of the particle through the detector. With this type of instrumentation both the particle charge and velocity can be readily determined from one signal. Several of these detectors can be used to monitor the particle parameters at various positions in the accelerator barrel.

V.2 The NASA Accelerator

The NASA Goddard Space Flight Centre microparticle accelerator uses a TRW Systems Particle Modification Kit to convert a High Voltage Engineering Corporation 2-million volt van de Graaff generator to accelerate carbonyl-iron particles. The complete accelerator consists of the van de Graaff generator, the particle injector, an accelerator barrel enclosing the charge and velocity detectors and other associated electronics. Most of the electronics have been developed by Labco Scientific of Stillwater, Oklahoma. Two views of the accelerator are shown in Fig. 20.

The accelerator barrel and the test chamber are evacuated to provide a space simulation chamber and to eliminate drag on the particles as much as possible. The test chamber consists of several sections which can be joined together to accommodate a test package of approximately 1 cubic foot. In addition to charge and velocity detectors there is a set of deflection plates in the accelerator barrel. In operation, charge and velocity limits for a particle are set on the detection system electronics. The detectors measure the charge and velocity of a particle coming down the barrel and compare these measurements with the limits set. If the particle parameters are not within the specified range, a pulse is applied to a deflection plate just as the particle reaches it. This pulse deflects the particle from the experiment centre-line and prevents it from proceeding through the small hole in the end of the barrel into the test chamber.
The dust particles used to simulate micrometeoroids are carbonyl-iron particles of a few microns or less in diameter. Carbonyl-iron Fe(CO)\textsubscript{5} is a particularly pure source of iron. The dust particles used for these experiments are available from the General Aniline and Film Corporation, Dyestuff and Chemical Division, Linden, New Jersey. Figure 21 shows a microphotograph at a magnification of 1000X of some of these particles.

V. 3. Experimental Procedure

For the NASA particle accelerator calibration the sensor was placed in one section of the test chamber, and the facility was evacuated. Electrical feed-throughs in the chamber permitted the +350 Vdc polarizing voltage and the +25 Vdc power to be fed into the sensor and the signal to be fed out to an oscilloscope. The signal was fed to both channels of a Tektronix type 555 oscilloscope, the top trace being set on a fast sweep rate and the lower trace on a slow sweep rate to note the decaying form of the signal. In each case the signal was fed through a type 0 Operational Amplifier unit set to give an additional gain of 100 to the signal before it was displayed on the scope.

Once a sufficient vacuum had been achieved and all power and instrumentation turned on, the desired charge and velocity measurements were set on the accelerator electronics. When a particle within the proper range had been fired, the particle charge and velocity were read out on paper tape. To take an experimental run, the accelerator was triggered and as soon as the printer was heard to operate, the oscilloscope camera shutter was opened. The high persistence of the Oscilloscope screen allowed the signal to be photographed a few seconds after the oscilloscope sweep had triggered. If the signal looked to be of the proper form, all the data was recorded, and the oscilloscope photograph was stapled to the data sheet.

VI. Experimental Results and Discussion

1. Drop Test Results

Bead drop testing can only give an approximate calibration of a hypervelocity particle impact sensor owing to the fact that the impacts are elastic while hypervelocity impacts are inelastic. In the present study due to the difficulty in handling beads smaller than 200 microns in diameter, the lower limit on momentum was of the order of 10\textsuperscript{-3} dyne-sec. for the drop tests. The design momentum range of the sensors is 10\textsuperscript{-5} - 10\textsuperscript{-7} dyne-sec., so that the drop tests were actually two orders of magnitude above the design momentum range of the sensors. For these reasons the drop tests were mainly used to give an indication of the type of sensor response to be expected and to get some appreciation of sensor operation. Consequently, only the hypervelocity calibration results can provide accurate data.

Some typical drop test sensor signals are shown in Fig. 22. The top trace is on a slow sweep rate of 10 msec/div and the lower trace on a fast sweep of 0.5 msec/div. The top trace shows the decaying nature of the signal and the lower trace the typical waveform as would be expected from the theoretical considerations of Section III-2. The top trace also shows a low frequency impressed on top of the waveform, which is due to vibrations present in the
laboratory. Although care was taken to vibration isolate the sensor, this problem could not be completely overcome. This no doubt contributed to the data scatter. Also, the top trace can be seen to repeat about half way along. This is caused by the bead striking the diaphragm a second time after its initial rebound.

The calibration results for the drop tests are shown in Fig. 23. The momentum range covered by these tests is necessarily quite small. The lower limit on impact momentum was determined by the smallest bead which could be successfully dropped and a low upper limit was imposed by a desire to avoid damage to the sensor. As can be seen in Fig. 23, the sensor response is linear with momentum up to $10^{-3}$ dyne/sec which is two orders of magnitude greater than the sensor upper design limit.

VI. 2. Hypervelocity Calibration Results

Hypervelocity impacts are distinct from very low speed impacts in that they are inelastic. Although the particle flows in the crater it generates a considerable amount of debris which may be thrown out from the crater. This high-speed ejecta may make the actual momentum transfer several times higher than the incident particle momentum. The accommodation coefficient is the factor by which the incident particle momentum must be multiplied to obtain the final momentum transfer. Because of the uncertainty in determining the accommodation coefficient, all hypervelocity results are plotted in terms of incident particle momentum.

The calibration runs were done at velocities between 2 and 7 km/sec, using the NASA Goddard Electrostatic Dust Particle Accelerator. Figure 24 shows some of the impact craters on the sensor diaphragm. These craters are typical of the inelastic hypervelocity impacts. The sensor signal showed the same form generally as the drop-test signal except that the slow sweep signal did not exhibit the low frequency component attributed to laboratory vibrations. Some typical hypervelocity impact signals are shown in Figs. 25a and 25b. The top trace in each case has a horizontal sweep rate of 0.5 msec/div and shows details of the first few cycles of the signal. The lower trace has a horizontal sweep rate of 50 msec/div and shows the decaying nature of the signal. The top trace again shows the same type of wave-form as was expected from the theoretical considerations of Section III-2.

The first set of calibration runs was done by selecting three narrow velocity limit bands and then varying the incident particle momentum. Figure 26 shows the results of these runs. The response of the sensor is seen to be linear with momentum and a straight line has been visually fitted to the data. An initial least squares analysis of some of the data indicated a visual fit to be just as good an indication of the data trend, so all plots were visually fitted. The fact that within the experimental scatter, one line can be fitted to the data indicates that within the velocity range used, the sensor signal is insensitive to velocity and responds linearly to momentum. Figure 26 is the calibration curve for sensor S/N 4A, the first of two sensors calibrated.

Figure 27 is a calibration curve for the second sensor, S/N 5A, and again the sensor indicates a linear dependence on momentum. Figure 28 shows the results of a series of runs designed to find the lower threshold of operation of the sensor. The plot again shows a good linear response with momentum, but
the three points grouped in the lower part indicate that the sensor should probably not be used for particle momenta less than $10^{-6}$ dyne-sec, because of the low signal to noise ratio below this value. It should be noted that this cutoff point is rather arbitrary and further work should be done on a flight instrument to firmly establish a reliable lower momentum limit. The next set of runs were done at velocities slightly higher than the ones previously used. The velocity range used was $5-7$ km/sec. Figure 29 shows the results of these runs for both sensors, S/N 4A and S/N 5A. The curves exhibit very good linear dependence on momentum and indicate the different sensitivities of the two otherwise identical sensors. This varying sensitivity between identically manufactured sensors indicates the necessity of individually calibrating each sensor before flight.

A whole series of runs were taken with the sensor set off-center behind the accelerator barrel to determine the radial sensitivity variation of the sensors. For these runs sensor S/N 4A was used and runs were taken with the sensor on-center, and $1/4''$, $1/2''$ and $3/4''$ off-center. Figure 30 shows the results of all these runs with straight lines visually fitted to the data. Only one line could be reasonably drawn through both sets of data for $1/2''$ and $3/4''$ off-center impacts. Figure 31 has been derived from Fig. 30 and indicates the radial variation in sensitivity of the sensors for three different incident momentum levels. The curves show that the sensitivity decreases with increasing radius of impact. The dropping-off is most pronounced in the $1/4''$ to $1/2''$ off-center range and no further drop-off could be detected after a radius of $1/2''$. The maximum decrease in sensitivity for all 3 momentum levels is about 40%.

VI. 3. Discussion

The results of the current calibration studies indicate that the condenser microphone sensor responds linearly to incident particle momentum. The type of information obtained with this sensor is of the same form as with the crystal microphone sensor. The signal appears as a decaying oscillatory signal, much the same as for the crystal microphone. In actual spacecraft applications, this signal has to be pulse height-analyzed before it is telemetered back to a ground station. It was not possible to perform a detailed error analysis on the experimental data. This is a result of the uncertainty in the accuracy of information on particle velocity and mass obtained directly from the electrostatic dust particle accelerator. It is probably reasonable to assume, however, that these accuracies were within the experimental error in measuring the signal amplitude from oscillographs, which was of the order of 5%.

The condenser type sensor, however, has several advantages over the crystal microphone. The crystal microphone sensitivity is determined by the characteristics of the piezoelectric crystal itself. The condenser system, on the other hand, can be "tuned" when manufactured to virtually any particle momentum, by varying the diaphragm thickness, tension and the interplate spacing. The lower limit of sensitivity of this type of sensor would be determined by manufacturing capability. This would mean that it would be possible to build a sensor to investigate any portion of the micrometeoroid mass spectrum desired.

Although the sensitivity of the sensor decreases with increasing radius from its center, this does not appear to be nearly as prominent as it is in the crystal microphone. Gorjup$^{12}$ reported a decrease in sensitivity by a factor of from 3 to 4 from the center to the outer radius of the piezoelectric
crystal sensor. The maximum sensitivity decrease of the condenser microphone sensor is only about 40%, as can be seen in Fig. 31. Consequently, its use for space flight would be more desirable. An advantage of the crystal microphone, however, is that it can be used with a sounding board of large area, while the effective area of the condenser sensor is the area of the diaphragm. This means that to record the same number of micrometeoroid events, the condenser sensor would have to be exposed to the meteoroid hazard for a longer time.

In the past the micrometeoroid flux results obtained with crystal microphones have been criticized as being too high. The consistently high results obtained with crystal sensors have been attributed to thermal effects. The large temperature variations encountered by a satellite evidently give rise to spurious signals which are mistaken for actual micrometeoroid encounters. This thermal stress effect has been blamed for the excessive cosmic dust flux measurements which were the basis of theories postulating dust clouds or belts about the earth.

The condenser microphone sensor should not give spurious signals due to thermal stress effects. It is possible, however, that there may be a change in sensitivity of the sensor due to temperature changes. A varying temperature could conceivably cause the diaphragm to expand and contract, thereby altering its tension and the sensitivity of the sensor. The extent of this thermal effect, if any, should be investigated before it is used on a spacecraft.

The electrostatic Dust Particle Accelerator is an attractive facility for the calibration of micrometeoroid sensors. So far, this has been the only means of successfully obtaining hypervelocities for particles of appreciable size. Theoretically, for a 2 MV accelerator, the maximum particle velocity should be about 20 km/sec for a 0.1 micron radius particle (Fig. 18). During the calibration runs, the highest observed particle velocity was about 9 km/sec. However, because of the small particle size, the incident momentum was too low to register a readable sensor signal. The highest particle velocity for a particle of above threshold particle momentum was about 7 km/sec. In order to calibrate sensors at real micrometeoroid velocities it would be desirable to have a facility capable of accelerating particles of approximately one micron in diameter to velocities up to 50 km/sec. Unfortunately, such a facility is not yet available.

VII. Conclusions

This report has presented some background information on micrometeoroid research and a detailed calibration study of a Condenser Microphone Micrometeoroid Sensor developed by Ling-Temco-Vought Inc. The calibration results show that the sensor responds linearly to incident particle momentum in the design range of $10^{-5}$ to $10^{-7}$ dyne-seconds. A mathematical analysis of the diaphragm vibration mechanism has been successful in predicting the type of waveform of the sensor. Calibration results also show a radial variation in sensitivity of the condenser microphone sensor, although this variation does not appear to be as large as for the piezoelectric crystal type sensor.

The condenser microphone type sensor should appeal to micrometeoroid researchers because of the fact that it can be "tuned" during manufacture to a variety of momentum ranges. The lower limit on sensitivity is simply determined by manufacturing capabilities. The sensor is also attractive owing to the lack
of thermal "stress" effects which are thought to cause erroneous signals in the current piezoelectric crystal microphone sensors. The condenser microphone, however, could have a sensitivity which varies with temperature due to expansion and contraction of the diaphragm. The extent of this effect, however, should be determined in a pre-flight thermal check-out of the sensor.

Both, bead drop-test and hypervelocity particle accelerator calibrations, have been done. It has been found that for the very low momentum range of the sensors used, drop-test calibrations are not useful other than for determining the operating characteristics of the sensor. The smallest beads which could be successfully dropped resulted in an incident momentum two orders of magnitude above the upper operating limit of the sensor. The fact that Electrostatic Dust Particle Accelerators are available which are able to accelerate micron size particles to hypervelocities makes these extremely attractive facilities for micrometeoroid sensor calibration.

This type of sensor, when coupled to the time and direction of flight sensors now developed at the NASA Goddard Space Flight Center may well form a very useful and sensitive gauge for determining scientific data such as micrometeoroid mass, momentum, energy, velocity, direction and its heliocentric orbit.
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**TABLE 1**  MASS TO VISUAL MAGNITUDE RELATIONSHIP (REF. 1)
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TABLE 2 COSMIC DUST PARTICLE PARAMETERS (REF. 16)
ROCKETS | SATELLITES | SPACE PROBES
---|---|---
May 24 1957 212 | Sputnik 3 May 15 1958 | Luna 1 Jan. 2 1959
Aug. 25 1957 212 | | Luna 2 Sept. 12 1959
Aug. 31 1957 212 | Electron 1/2 Jan. 30 1964 | Luna 3 Oct. 4 1959
Aug. 2 1958 212 | | Luna 12 Oct. 22 1966
Aug. 13 1958 212 | | Venera 1 Feb. 12 1961
Aug. 27 1958 451 | | Mars 1 Nov. 1 1962
Sept. 19 1958 473 | | Zond 2 Nov. 30 1964
Oct. 4 1958 110 | | Zond 3 July 18 1965
Oct. 10 1958 110 | | Venera 2 Nov. 12 1965
Oct. 31 1958 473 | | Venera 3 Nov. 16 1965
Dec. 23 1958 110 | | 
Dec. 25 1958 110 | | 
July 2 1958 212 | | 
July 10 1958 212 | | 

TABLE 3 SOVIET MICROMETEOROID EXPERIMENTS (REF. 19)
FIG. 1  THE BASIC SENSOR (REF. 16)
FIG. 2 FILM AND GRID SCHEMATIC (REF. 16)
FIG. 3 AVERAGE CUMULATIVE MICROMETEOROID MASS DISTRIBUTION FOR THE VICINITY OF EARTH (REF. 17)
FIG. 4 GEMINI 12 FLUX ESTIMATES (REF. 18)
FIG. 5 DUST PARTICLE ORBIT FOR MARCH 11, 1968 (REF. 16)
FIG. 6 THE CONDENSER MICROPHONE SENSOR
FIG. 7 CONDENSER MICROPHONE SENSOR SCHEMATIC
FIG. 8 TYPICAL SENSOR SIGNALS
FIG. 9 CALCULATED MEMBRANE CAPACITANCE
FIG. 10 \( \frac{dC}{dt} \) AS A FUNCTION OF TIME
FIG. 11 SCHEMATIC OF BELL JAR AND VACUUM SYSTEM
FIG. 12  THE DROP TEST APPARATUS
FIG. 13 CROSS-SECTION OF BEAD DROPPING MECHANISM
FIG. 14 THE BEAD DROPPING MECHANISM
FIG. 15  BEAD DROPPER WITH MOTOR DRIVE AND SENSOR MOUNTED ON BASE PLATE
FIG. 16 EXPERIMENTAL SCHEMATIC
FIG. 17  THEORETICAL PERFORMANCE OF ELECTROSTATICALLY ACCELERATED IRON MICROSPHERES (REF. 7)
FIG. 18 PARTICLE INJECTOR SCHEMATIC
FIG. 19 VELOCITY AND CHARGE DETECTOR SCHEMATIC
FIG. 20 TWO VIEWS OF NASA ACCELERATOR
FIG. 21 MICROPHTOGRAPHHS OF CARBONYL-IRON PARTICLES SHOWING SPHERICITY OF APPROXIMATELY 1 MICRON DIA. PARTICLES (x 1,000)
FIG. 22 SOME TYPICAL DROP TEST SENSOR SIGNALS

TRACE A 10 msec/div — 5 volts/div
TRACE B 0.5 msec/div — 2 volts/div
FIG. 23 DROP TEST CALIBRATION RESULTS FOR SENSOR S/N 4A
FIG. 24 SOME TYPICAL HYPERVELOCITY IMPACT CRATERS ON SENSOR SURFACE GENERATED BY APPROXIMATELY 1 MICRON DIA. CARBONYL-IRON PARTICLES (x 1,000)
FIG. 25a SOME TYPICAL HYPERVELOCITY IMPACT SENSOR SIGNALS

( Amplifier gain of 100 )

1. m = \(5.64 \times 10^{-11}\) gms, \(v = 3.22\) km/sec, 
   \(mv = 1.81 \times 10^{-5}\) dyne-secs

2. m = \(3.84 \times 10^{-11}\) gms, \(v = 2.60\) km/sec, 
   \(mv = 9.9 \times 10^{-5}\) dyne-secs

TRACE A 0.5 msec / div — 0.1 volts / div

TRACE B 50 msec / div — 0.1 volts / div
FIG. 25b  SOME TYPICAL HYPERVELOCITY IMPACT SENSOR SIGNALS ( 1. \( m = 1.34 \times 10^{-11} \) gms, \( v = 3.10 \) km/sec, \( mv = 4.17 \times 10^{-5} \) dyne secs \\
2. \( m = 3.39 \times 10^{-11} \) gms, \( v = 2.20 \) km/sec, \( mv = 7.5 \times 10^{-5} \) dyne-secs )
FIG. 26 MICROMETEOROID SENSOR S/N 4A CALIBRATION FOR THREE VELOCITY RANGES
FIG. 27 MICROMETEOROID SENSOR S/N 5A CALIBRATION
FIG. 28 MICROMETEOROID SENSOR S/N 4A THRESHOLD CALIBRATION
FIG. 29 HIGH VELOCITY CALIBRATION OF BOTH SENSORS

( v=5-7 km/sec )
FIG. 30 OFF-CENTER RUNS FOR SENSOR S/N 4A
FIG. 31 SENSITIVITY VARIATION WITH RADIAL DISTANCE FOR SENSOR S/N 4A
A detailed calibration study of a condenser microphone micrometeoroid impact sensor is presented. The calibration results show that the sensor responds linearly to incident particle momentum in the design range of 10^{-5} to 10^{-7} dynes/second. Both drop-tests and hypervelocity impact tests have been made. Velocities up to 7 km/sec have been achieved using an electrostatic dust particle accelerator. A mathematical analysis of the diaphragm vibration mechanism has been successful in predicting the type of waveform and the operating modes of the sensor. It is possible that this type of sensor, when coupled with a time-of-flight sensor now developed at the NASA Goddard Space Flight Center, may form a very useful and sensitive gauge for measuring the properties of micrometeoroids.