PREPRINT INSTRUMENT SOCIETY of AMERICA
19th Annual ISA Conference and Exhibit • October 12-15, 1964, New York
Preprint Number 16.1-4-64

125

INSTRUMENTATION FOR INVESTIGATING THE PHYSICAL PROPERTIES OF THE LUNAR SURFACE

by Alfred G. Beswick

NASA Langley Research Center
Langley Station, Hampton, Va.

Presented at the 19th Annual ISA Conference and Exhibit

New York, New York
October 12-15, 1964

[redacted]

INSTRUMENTATION FOR INVESTIGATING THE PHYSICAL PROPERTIES OF THE LUNAR SURFACE

by Alfred G. Beswick
Electronic Engineer
NASA Langley Research Center
Langley Station, Hampton, Va.

ABSTRACT

One of the problems confronting the current effort to explore the moon is the physical condition of the lunar surface, particularly with regard to its bearing strength with respect to spacecraft landings. Researchers at the Langley Research Center have found that a good idea as to the hardness, bearing strength, and penetrability of the lunar surface can be gained from analysis of the deceleration time history resulting from the impact of deceleration measuring instruments, i.e., impact accelerometers. The accelerometers are embodied in a structure called a penetrometer which also houses a radio telemeter. The penetrometer thus has the capability of transmitting the impact information to a remote receiver. The instrumentation concepts and details of two types of penetrometers are described. Typical applications of how such instrumentation might be employed to investigate lunar or planetary surface conditions with various spacecraft are presented.

INTRODUCTION

One of the problems confronting the current effort to land upon and explore the moon is the determination of the moon's surface character with regard to spacecraft landings and post-landing locomotion of exploratory vehicles and personnel. In the past, investigators have been able to ascertain the large-scale characteristics of the moon, such as the size and distribution of mountains and craters, by the use of a variety of earth-based radio and optical techniques and instrumentation. However, to the present time, no direct measurements of the small-scale features, such as texture, and topographical detail on a dimensional scale of interest to man's movement on the surface, have been possible. The casual observer can find descriptions in contemporary literature which estimate that the lunar surface hardness may range from the hardest of rocks to the finest of dusts. Such a literature search would also reveal that there is a general agreement among most observers that whatever the surface material may be, on a small scale it is of uniform character over the entire lunar disk. Further, the surface material appears to be of very low gross density, and very low reflectivity, which suggests the possibility of a structure similar to oceanic coral, for example. The lack of positive information on the load supporting capability of the lunar surface is due to the inability of earth-based instrumentation to measure such quantities with the required resolution.

Presently planned and scheduled missions incorporate photographic and other survey techniques which should do much to provide greatly improved knowledge of the small scale topographical features of the lunar surface. However, results from such missions may not provide the necessary information regarding characteristics of the surface such as its hardness and load supporting capability.

BACKGROUND RESEARCH

The Langley Research Center of the National Aeronautics and Space Administration has been interested in the problem of obtaining a measure of the load supporting capability, or bearing strength, of the lunar surface for some time. One of the outgrowths of this interest is a research program to find suitable means of performing such measurements. This endeavor has shown that certain of the physical characteristics of a typical earth surface material, such as its hardness and penetrability, can be determined by analysis of the deceleration signature produced by the impact of suitably instrumented projectiles upon the material. The impact measuring instrumented projectiles have been designated "penetrometers." The LRC research program has also shown that there is a relationship between the hardness and penetrability characteristics of a terraneous-like material and its static load bearing strength. Knowledge of the complete impact acceleration time history of a penetrometer can indicate the physical composition of the material, that is, whether it is granular, such as gravel or sand, or powdery, such as various dust media. Configurations of hard rock, such as granite, or brittle, frangible structures such as lava or coral can be identified with good accuracy with the penetrometer technique. Results from the penetrometer impact research programs to date show that the penetrometer technique can provide useful information on the bearing strength of the lunar surface from the point of view of the spacecraft landing-gear structure designer.

Some results of the Langley impact studies are presented in reference 1. This report shows that sufficient information can be derived from the acceleration time histories of impacts upon

[redacted]

earth materials to adequately define the nature of the materials. In the case of a remote surface, such as that of the moon, impact acceleration time histories can be compared with impact acceleration time histories developed by the same, or similar, instruments impacted on earth materials to characterize the unknown target surface material, to a first order at least, in terms of known earth materials.

INSTRUMENTATION REQUIREMENTS

Figure 1 presents a few typical acceleration time history waveforms, as developed by penetrometers used in the LRC impact tests. The significant features of these waveforms are as follows: duration time, maximum acceleration, time required to reach maximum acceleration, the number and location of acceleration peaks, tail-off characteristics, and the overall shape of the waveform. The important features of these typical information signals with respect to the instrumentation requirements are the acceleration range and pulse-duration range - these quantities define the instrumentation dynamic-amplitude and frequency-response requirements.

In the investigation of a remote surface such as that of the moon, a penetrometer instrument must not only have the capability of transducing the physical process of the impact event to a usable information signal, but must also be capable of relaying the information signal to a location where it can be utilized. In present concepts of penetrometer deployment essentially two information relay techniques are under consideration; interconnecting cable and radio telemetry. From an instrumentation viewpoint, interconnecting cable systems are typically less complex than radio telemetry; however, the cable systems have limitations associated with deploying the cable while maintaining instrument orientation during flight and impact. Even though these problems be solved, or reasonably under control, dispersion ranges for space vehicle applications appear to be limited by practical cable lengths and weights. Although radio telemetry techniques for relaying information signals are more complex, and in some respects may not offer off-the-shelf technology for penetrometer applications, such techniques are devoid of many of the problems of trailing cable information transmission systems, and simultaneously can provide greater experimental flexibility of the impact penetrometer instrument.

LRC has undertaken the development of penetrometer instruments having radio telemetering capability. The instrumentation requirements for a radio telemetering penetrometer instrument can be divided into two major areas: (a) acceleration sensing and transducing, and (b) the radio telemetry system, and its power supply, signal conditioning, antenna and support structure.

a. Acceleration Sensing

The requirements of the acceleration sensing and transducing components are defined by parameters of the information signal derived from the impact as shown in figure 1. These parameters naturally have a strong dependency on the impact velocity, which in turn, is dependent upon the maneuvering capability of spacecraft from which the penetrometers are deployed. Therefore the acceleration sensor must be capable of performing adequately throughout the range of impact velocities likely to be encountered as a result of limitations in space vehicles maneuverability. In the LRC studies impact velocities from 20 to 300 feet per second have been considered as a fairly broad range of capabilities for spacecraft maneuvering. A second factor, associated with, but not entirely dependent on the limitations of spacecraft maneuverability, is the orientation of the penetrometer during the impact process. The ideal penetrometer is omnidirectional so that impact decelerations measured are equal regardless of the angle of impact or impact attitude of the penetrometer. Such omnidirectional capability thereby infers a spherical penetrometer. It can be shown that the impact accelerations measured by an omnidirectional penetrometer have significance despite impact angles relative to the target surface which may be encountered due to local surface slopes, or penetrometer trajectories. However, for this application, omnidirectional acceleration sensing is unfortunately not off-the-shelf technology.

In figure 1, it was shown that the time duration of acceleration time histories may range from a 250-microsecond essentially half sinusoid waveform, produced by an impact with a hard, elastic material, to a 200-millisecond asymmetrical, although still unipolar, waveform produced by encounters with very soft materials. It is probable that the longer duration signals will contain intervals where the waveform amplitude is changing rapidly. Since the duration of all impact information signals are within these limits, it is evident that the penetrometer instrumentation must be capable of encompassing the frequency range, 2000 to 2.5 cycles per second.

Because of the unknown load supporting capability of the lunar surface, a wide dynamic range of acceleration amplitude response, possibly encompassing three orders of magnitude, is required. The wide range requirement imposes some difficulty. For example, if a penetrometer is deployed from a space vehicle so that it impacts the target surface at a velocity higher than 100 feet per second, extremely high shock loadings can result if a hard solid surface is encountered - shock loadings approaching 100,000 earth "g" are possible. However, for penetrometer applications presently being considered the information signal quality, or resolution, can be allowed to degrade as shock loadings increase.

The reduction of required resolution results from the lessening of the exactness with which it is necessary to know the load supporting capability of a target surface after it has been established that its support capability exceeds a given threshold value; or, in other words, it is much more important to know the probability of typical spacecraft loads to cause sinking to dangerous depths in a soft material, than to know how much stronger a target surface may be above an established threshold value. The apparent allowable deterioration of data quality above a certain threshold suggests the possibilities of providing some form of impact limiter on the penetrometer - a crush-up outer structure for example. The use of impact limiting structure has several advantages in addition to providing shock protection for instrumentation components. The impact limiter is a mechanical form of acceleration dynamic range compression - very wide acceleration range response is not required of the acceleration sensor. Further, the impact limiting structure can be made very light in weight, thus reducing the gross density of the penetrometer and increasing its surface area to mass ratio, hence improving its sensitivity to low-density target materials.

b. Radio Telemetry

A block diagram of instrumentation which might be employed in a penetrometer equipped with a radio telemeter is shown in figure 2. Following the omnidirectional acceleration transducer and signal conditioning circuitry are the basic telemetry components required of a penetrometer. These components are a radio transmitter-modulator, an antenna, and a power supply system.

A number of interesting requirements exist for the transmission of data with minimum communication link distortion to even moderate distances of a few miles. Adequate radio-frequency power output is naturally an important criterion. Frequency stability is equally important. Since amplitude modulation imposes extremely difficult conditions upon attempts to communicate during an impact process, acceptable alternative modulation techniques not requiring unduly complex modulation drive are frequency modulation, or possibly phase modulation. Single-channel frequency modulation by direct deviation of the transmitter carrier signal is an acceptable technique. Thus, frequency stability becomes of paramount importance. Frequency stability as achieved by use of the conventional piezoelectric quartz crystal frequency controlling element is impractical for the high shock levels that may be encountered. Thus a self-excited transmitter having high short-term frequency stability is required. Forunately, most missions envisioned for penetrometer applications do not require long transmission intervals - transmitting times will usually be measured in seconds. Thus it appears reasonable to try to build miniature ruggedized radio transmitting equipment capable of remaining within a few thousandths of a percent of a given operating frequency for a few minutes.

A second requirement of the telemetry system of an omnidirectional penetrometer is an omnidirectional transmitting antenna. Again, several factors unique to operation during an impact process define its desired operating criteria. The requirement that the radiation pattern of such an antenna be omnidirectional implies a lossy antenna; other factors affecting its performance during an impact process indicate further antenna inefficiency. For example, the antenna comes into contact with and may become partially or completely immersed in the material it impinges upon, yet it is required that penetrometer performance including data transmission not be grossly affected by this circumstance. Contact with a medium other than that of free space causes severe electrical loading effects on an antenna. The drastic antenna impedance changes resulting from such electrical loadings can cause severe shifting of the transmitter operating frequency, as well as detuning and inefficiencies of the antenna. One of several possible approaches to minimizing these problems is two sided: (a) to operate the antenna capacitively detuned, and (b) to isolate the transmitter output from its oscillator to the greatest practical extent.

A third requirement of a penetrometer is that it contain its own power supply. Since the penetrometer must be ruggedized for the possible high shock loading situation, it is desirable that the power supply be an integral part of the penetrometer instrument structure. The requirement that the complete penetrometer instrument be electrically tested for proper operation and determination of its operating characteristics, and calibrated by impact upon various earth materials, calls for a rechargeable battery type power supply. Such a battery must be capable of performing adequately throughout the maximum anticipated shock loadings while providing the required electrical power without appreciably disturbing other electrical functions.

All components of the penetrometer's telemetry system must be capable of performing during all impact conditions which may be encountered, without inserting undue distortion into the impact acceleration information signal. The range of impact conditions may include high levels of shock loadings, to many thousands of earth "g" ranges possibly, as well as effects resulting from immersion into some media it may encounter. The high shock loading condition may be the simpler problem, since both impact limiting and shock protection structures can be employed, and at the same time, it is allowable for information quality to degrade at high shock loadings, as previously noted. Telemetry system antenna performance during immersion into a terraneous-like media is an important consideration, which is at present under intensive investigation. Early results from these studies indicate the feasibility of reasonable operation during immersion up to a few penetrometer diameters, and the studies are now being directed toward the numerical definitions of performance characteristics.

Figure 3 summarizes penetrometer instrumentation requirements and considerations just discussed.

INSTRUMENTATION DESCRIPTION

In order to determine the practicality of performing direct measurements of the load supporting capability of the surface of the moon and the planets with the penetrometer technique, a number of applicable hardware items are being developed under the auspices of LRC. Some of this hardware will now be described.

a. Omnidirectional Acceleration Sensing

One of the most interesting and challenging aspects of the instrumentation requirements of an omnidirectional penetrometer is the omnidirectional acceleration sensor.

A number of approaches to satisfying the omnidirectional acceleration sensing requirement are conceivable; some of them have been investigated to the extent of hardware testing in the LRC program. Included were spherical fluid filled sensors, which sense fluid pressure changes produced by applied acceleration forces; concentric spherical capacitors, which sense capacitance changes caused by displacement between the capacitor plates produced by acceleration forces; concentric resistors, essentially similar to the concentric capacitors except that the sensed quantity is the resistance change caused by the applied stress of the acceleration forces; systems of spherically distributed strain gages, and several configurations of piezoelectric crystal acceleration sensors. The latter category seems to offer the best promise of fulfilling the requirements of a penetrometer mission, with the least amount of development. However, of the several concepts of spherically confined fluid sensors considered for penetrometer applications, at least one type has been constructed and tested sufficiently to demonstrate adequate omnidirectionality for a penetrometer. Testing of this device demonstrated the considerable difficulties inherent in fabricating such devices to perform within desired limits, with regard to both consistently repeatable omnidirectionality and the accuracy of acceleration measurements. Further, the frequency-response and dynamic range requirements previously described do not seem to be readily attainable with fluid filled devices.

Concentric capacitor systems that were explored suffered from difficulties of obtaining and maintaining true concentricity while simultaneously allowing adequate displacement to provide usable values of capacitance variation. It was also found very difficult to maintain proper electric field distribution while providing electrical lead feed through the spherical capacitor plates. The spherical capacitor sensor also inherently becomes more sensitive with increasing acceleration forces, which is opposite to the desired condition of signal amplitude compression at high impact levels. Concentric resistors, and distributed strain-gage systems do not conveniently provide wide range capabilities, and further may require undesirably high drive currents and/or null balance circuitry, and attendant complexities.

Conventional piezoelectric crystal acceleration sensing devices seem to have a number of advantages compared to other techniques. As a class, these devices have very wide dynamic ranges, 4 decades and more are usually available. A wealth of technology in the use of the devices as acceleration sensors has been built up in recent years. They can be self-generating, and can be manufactured in very small size, lightweight, and a variety of configurations. Triaxial versions of such devices are commercially available and are attractive as the acceleration sensing element of an omnidirectional acceleration sensor, with the resultant of the three-axis system determined by associated electronic operations. However, piezoelectric devices are charge generators, and as voltage signal sources, have very high internal impedance; further, this source impedance is, in effect, frequency dependent - as frequency decreases, the effective source impedances increase. The high source impedance factor places severe demands on the signal conditioning circuitry required to treat their output signals; although these demands can be met.

A considerable effort has been underway in recent months to develop piezoelectric omnidirectional acceleration sensing devices suitable for use in an omnidirectional penetrometer. In general, the development effort has been along two paths, (a) electronic circuitry capable of providing the square root of the sum of the squares of the signals from each of the three axes of a conventional triaxial piezoelectric accelerometer, and (b) the development of various configurations of piezoelectric material which approximate sphericity. Among the latter are included spherical piezoelectric crystal elements and spherically distributed arrays of linear piezoelectric crystal elements. Each of the latter techniques seems to have potential and studies are currently aimed at determining which has the highest potential.

Figure 4 is a photograph of a typical conventional triaxial piezoelectric accelerometer, a pair of piezoelectric hemispheres, and a hollow piezoelectric sphere; all of which are under study as possible acceleration sensing elements of an omnidirectional acceleration sensing system.

b. Penetrometer Radio Telemetering Considerations

Given a solution to the developmental problem of omnidirectional acceleration sensing, and assuming that the solution employs some form of piezoelectric crystal, whose signal conditioning requirements are satisfactorily met, further problems unique to radio telemetering penetrometers require solution. Among these problem areas are the radio transmitter itself, its power supply system, and the omnidirectional transmitting antenna. Considering the transmitter first, its fundamental requirements are adequate radio-frequency power, frequency stability commensurate with the mission requirements, adequate performance during the high shock loadings it may encounter, and small size and weight. Present-day transistor technology is such that adequate radio-frequency power output is not a problem at the frequencies and short transmission ranges of interest to a penetrometer mission. Nominal radio-frequency power outputs of 100 milliwatts at 250 megacycles are readily achieved in the units illustrated in figure 5. However, the frequency stability required under the various conditions of operation a penetrometer may encounter is a more critical problem area.

The requirement for operation during high shock loadings appears to eliminate conventional frequency stabilizing elements such as quartz crystals. Thus, the transmitter utilizes a self-excited oscillator as its frequency determining element. The oscillator is coupled to a buffer, or isolation, amplifier, and then to a final power amplifier. The three stages of the transmitter are designed as unilaterally as is practical; RF signal progression through the three stages is coupled by attenuating pads, and interstage shielding is employed so as to minimize unwanted feedback. The transmitter is entirely encapsulated in a solid epoxy resin medium. The intimacy between the epoxy medium and all components of the transmitter minimizes instabilities encountered during high shock loadings, although such instabilities cannot be completely suppressed during the very high shock loadings. However, the data quality degradation allowable at the higher shock loadings reduces the demand upon transmitter shock stability under these circumstances. Frequency instabilities associated with power supply voltage variations are minimized by employing a simple solid-state regulator. Transmitter frequency instability caused by variations of antenna impedance changes as the penetrometer impinges upon various target materials is minimized by the proper antenna electrical configuration and the unilateralization of the transmitter itself. The fundamental frequency of a typical transmitter model used in the LRC studies will be changed less than ±0.05 percent when its output terminal is reconnected from its normal 50-ohm termination, to either a short circuit or an open circuit. The small size and mass of the transmitter, and its encapsulation in a material of low thermal conductivity, do not allow ready elimination of internally generated heat and although the power dissipated is moderate, thermal frequency instability effects exist. A number of techniques can be used to minimize thermal instability effects, such as temperature compensating elements, very long pre-deployment warmup time, and relatively short operational performance time. The use of high transmitter carrier frequency deviation ratios and wide bandwidth communication can also be employed to override frequency instabilities with signal deviation large in comparison to the instability deviation.

The transmitting antenna configuration of an omnidirectional penetrometer also presents a number of unique factors for consideration. One of the most important is that the radiation pattern of the transmitting antenna be essentially omnidirectional. An additional requirement is that the omnidirectional antenna be coupled to an instrumentation system contained within the antenna structure and the entire device be physically small. The small size suggests that the antenna probably cannot be resonant at the operating frequency. The antenna and instrumentation system is further expected to operate reasonably well during severe shock loadings, and also during immersion in media other than free space. One technique of satisfying the above problems is to operate the antenna system capacitively detuned and to provide the antenna with a dielectric covering preventing ohmic contact with surrounding media. If the coating is thick enough to aid in minimizing the added capacitance loadings presented by the contacted media, then an antenna system of reasonably satisfactory performance in terms of recovering the desired impact data results. In the LRC investigations, it has been found that spherically shaped antennas at about 250 megacycles can be driven so that radiation patterns are omnidirectional within a few decibels. Figure 6 is a photograph of a wire mesh hemisphere pair operated as an antenna sphere in early tests, and an orthogonal loop omnidirectional antenna configuration presently being studied. The antenna spheres were coated with dielectric shells and quite good operation was attained during impact tests, in terms of the usability of the recovered data.

It seems likely that most mission applications of the penetrometer technique will require that the penetrometer instrument have a low overall density; specific gravity may be on the order of 1/2 gram per cubic centimeter, for example. Since the basic penetrometer device discussed up to now must be compact and rugged, it may be considerably more dense than 1/2 gram per cc. Thus an additional outer shell of very light material of considerable thickness is implied.

Such a lightweight outer shell can also serve as a shock absorber or impact limiting structure, and thus relieve some of the problems imposed by high impact velocities on hard target surfaces. However it does not seem likely that the impact limiter structure could also house an antenna structure, due to the severe mechanical deformations which it may undergo.

c. Interim Unidirectional Acceleration Sensing

Due to the lack of an established technology capable of fulfilling the omnidirectional acceleration sensing requirements, an interim unidirectional acceleration sensing technique has been employed. This technique, with trailing cable transmission links, was used in the study of impact response characteristics of terraneous materials described at the beginning of this paper and shown in figure 1. The technique employs a uniaxial piezoelectric crystal accelerometer mounted in a suitable manner within a projectile. The accelerator output upon impact can be transmitted to recording equipment by trailing cable connection or applied to a self-contained radio telemeter and radioed to the recording equipment. In either case, the use of a piezoelectric element, and its attendant high effective source impedance requires signal conditioning circuitry to transform impedance levels to lower values. In the case of radio telemetry signal transmission, a further requirement of the signal conditioning was signal amplitude range selection, since the telemetry employed had a practical limit to its amplitude range capability.

The interim unidirectional penetrometer demands proper orientation of the acceleration sensing element at impact for accurate knowledge of its performance. This limitation is of little consequence in laboratory investigations where impact attitude can be easily controlled; however, in instrumented space vehicle explorations such control may be considerably more difficult to achieve. Further, the use of a unidirectional device cannot account for the effects of unknown local surface slopes which it may encounter. Omnidirectional instruments eliminate or reduce the magnitude of this latter problem and for these reasons, the principal effort of the LRC development effort has been directed toward producing an omnidirectional penetrometer. However, a number of successfully operating unidirectional penetrometers have been constructed and utilized in the LRC investigations.

d. Unidirectional Penetrometer

The objective of the unidirectional penetrometer investigation at LRC was twofold; one, to demonstrate the feasbility and practicality of the radio telemetering penetrometer concept without waiting for development of the omnidirectional technology and, secondly, to provide a penetrometer of greater flexibility and utility than the counterpart trailing wire type. A sectioned view of a typical unidirectional penetrometer is shown in figure 7. The uniaxial acceleration sensor employed is a conventional piezoelectric accelerometer. The antenna system employed is essentially a vertically oriented dipole, in which the metallic body structure of the penetrometer is one-half of the dipole element. The antenna is isolated from ohmic contact with impacted media by the separation its dielectric housing provides. The transmitter module employed and shown in figure 7 is essentially as was previously described and shown in figure 5. The power supply system is a series-connected string of miniature nickel cadmium rechargeable battery cells capable of 50 milliamperes at minus 15 volts for 15 to 20 minutes. A transistor series regulator maintains constant voltage to the transmitter during its operating time, and also incorporates overcharge protection and protection against the application of reversed polarity external power. The impedance matching signal conditioning circuitry employs field effect transistors. These penetrometers do not employ any range compression technique and dynamic "g" range is limited to slightly less than 2 decades. However, the sensitivity level can be decreased by adding shunt capacitance to the output of the piezoelectric crystal accelerometer, thus permitting higher impact velocities. The basic structure of the penetrometer is an epoxy resin filled with randomly oriented fiberglass roving. Fiberglass cloth wrappings are inserted in certain regions for increased strength. The epoxy formula is adjusted by adding flexing agents so as to provide high impact strength without allowing permanent or excess dynamic deformation during impact. Since the unidirectional penetrometer requires impact attitude orientation, the unidirectional application of shock forces can be exploited to provide some shock protection to components.

The unidirectional penetrometers shown here have met their development objectives and prove very useful in the continuing impact research and test programs. In terms of the capabilities of present-day space vehicles maneuverability, unidirectional penetrometers have limited applicability because of the requirement of controlled impact orientation. Thus, deployment techniques are more complex than is required for omnidirectional penetrometers; in effect, simpler instrumentation is gained at the expense of more complex deployment systems and possible reduction of the probabilities of attaining desired experimental goals.

Figure 8 presents some comparative views of impact acceleration time histories, illustrating the performance of telemetering unidirectional penetrometers compared to trailing wire unidirectional penetrometers, both impacted into the same media at the same velocities.

FUTURE WORK

The main effort of future work is to complete the development of the omnidirectional penetrometer. The effort is aimed toward attaining a penetrometer compatible with a variety of missions and spacecraft with minimum modification. An effort will be made to extend the transmission range capabilities of penetrometers beyond the present limit of a few miles to considerably longer ranges, approaching 100 miles, for example. It is also planned to develop suitable receiving equipment, designed specifically for handling the unique form of typical penetrometer signal transmissions with maximum efficiency while retaining compatibility with the various spacecraft in which such receiving equipment might be housed.

In conclusion, the following figures illustrate how penetrometers described herein might be employed with presently conceived lunar and planetary exploration programs. Reference 2 discusses penetrometer applications to these mission concepts in more detail.

Figure 9 shows the penetrometer concept applied to a Ranger vehicle. The first sequence depicts the Ranger spacecraft in its cruising mode during earth-moon traverse, nearing the moon. Prior to the next sequence, the Ranger transfers from the cruising mode to its terminal maneuver phase as it draws close to the moon. The spacecraft now becomes oriented so that its longitudinal axis is directed along a lunar radius. In the next sequence, a solid-propellant retro-rocket motor has fired, and separated itself and the penetrometer payload capsule from the main frame of the Ranger spacecraft. The Ranger spacecraft main frame continues on to the lunar surface at undiminished velocity, and crashes. The spent retro-rocket motor is separated from the payload capsule after burnout and falls away. The payload capsule is now a few thousand feet above the lunar surface. At this time, as shown in the next view, a smaller secondary retro-rocket motor contained within the payload capsule is ignited, and serves to sustain the payload capsule essentially hovering above the surface. The several penetrometers of the payload capsule are deployed during secondary retro-rocket burning, and fall to the lunar surface. The penetrometer fall time is about 30 seconds for a typical deployment altitude of 3,000 feet. The secondary retro-rocket burns out in nominally 10 seconds, and then the payload capsule itself begins falling. During its fall, the penetrometers impact upon the surface, as shown in the last sequence and radio the acceleration signals they develop upon impact to the still aloft, but falling, payload capsule. The payload capsule contains the necessary components to accept the penetrometer impact data, process it as needed and retransmit it to earth at power level and data format appropriate for such a transmission, prior to its own impact upon the surface.

Figure 10 depicts a penetrometer application to the Surveyor family of soft landing spacecraft. Telemetering penetrometers could be deployed from the Surveyor during the final stages of its landing approach as shown in the figure, and the impact data relayed to earth by suitable relay equipment aboard the still aloft, descending spacecraft. This figure also shows how penetrometers might be deployed from a Surveyor spacecraft after a sucessful landing. Use of the penetrometer technique could enlarge the area within which measurements of surface characteristics could be made. In the latter application it seems likely that either radio telemetering or trailing wire type penetrometers could be deployed.

Figure 11 shows how a penetrometer mission might be deployed from a nonlanding Apollo spacecraft in orbit about the moon. In such a case, a penetrometer payload package, not unlike that previously described for a Ranger mission, is ejected from the parent Apollo spacecraft and by means of suitable guidance and propulsion mechanisms is brought into position with respect to both the lunar surface and the parent Apollo spacecraft, so that penetrometers can be deployed. The impact signals could possibly be transmitted directly from the impact site to the Apollo, or relayed as before, via the penetrometer payload package. The impact information could then be stored aboard the Apollo for later analysis, or retransmitted to earth.

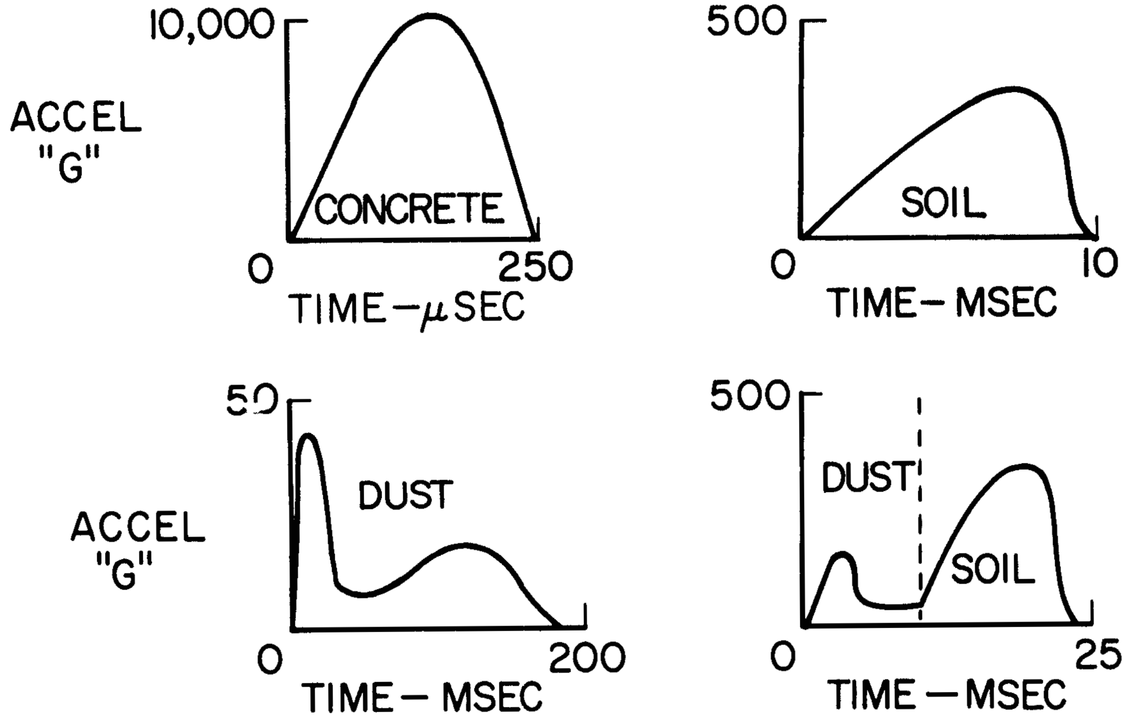
Figure 12 depicts the utilization of penetrometers as an aid to the manned landing phase of the Apollo program. In this application, the penetrometers are deployed from the Lunar Excursion Module to directly aid the astronauts in certifying a specific landing site.

Figure 13 shows a possible configuration of a penetrometer experiment on a Mars exploratory mission. In this case, a surface exploratory package programed to penetrate the Martian atmosphere is ejected from a fly-by space vehicle. Penetrometer deployment after the main entry was essentially complete could be accomplished with the aid of aerodynamic stabilizing and velocity controlling devices, such as parachutes.

REFERENCES

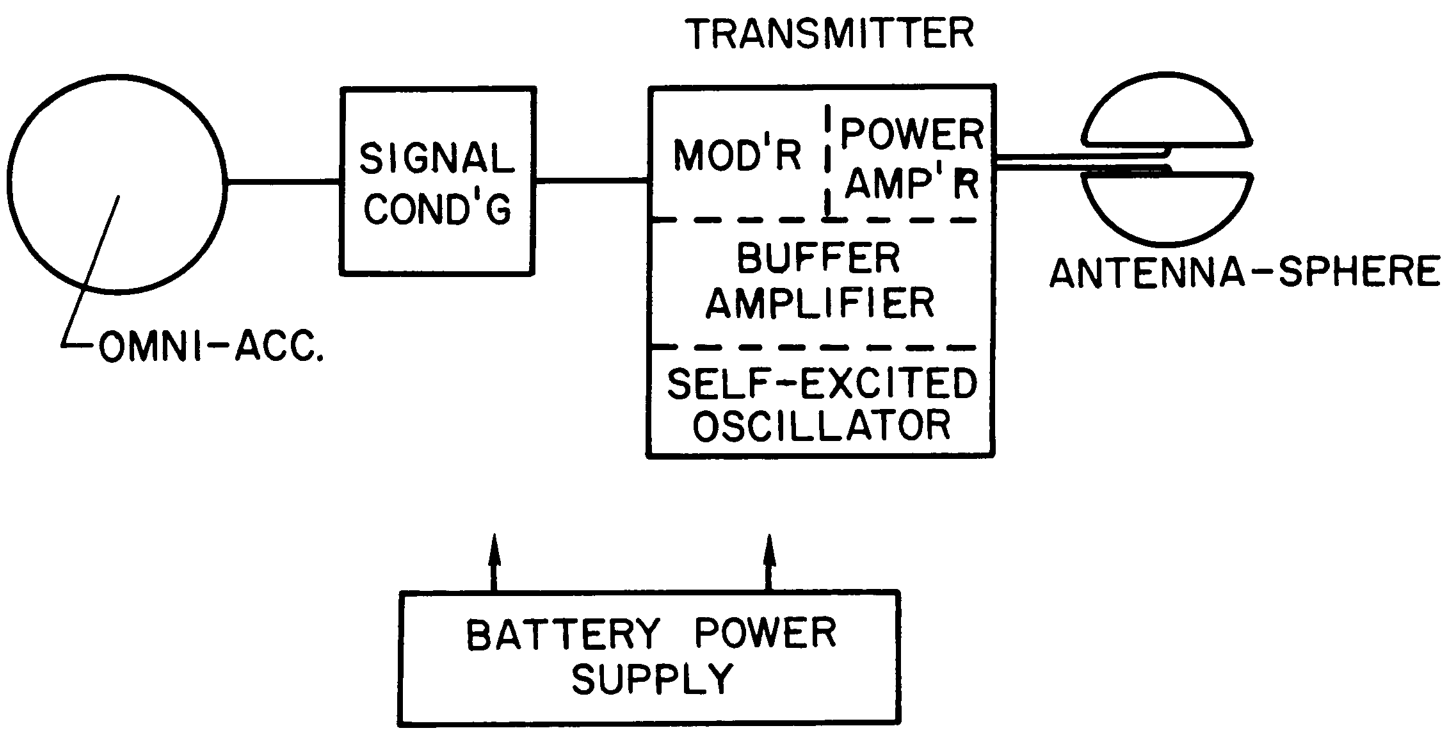
(1) McCarty, J. L., and Carden, H. D., Impact Characteristics of Various Materials Obtained by an Acceleration-Time-History Technique Applicable to Evaluating Remote Targets, NASA TN D-1269, 1962.

(2) McCarty, J. L., Beswick, A. G., and Brooks, G. W., Application of Penetrometers to the Study of Physical Properties of Lunar and Planetary Surfaces, NASA TN D-2413, 1964.



NASA

Figure 1.- Typical impact acceleration time histories.



NASA

Figure 2.- Instrumentation for telemetering penetrometer.

A. ACCELERATION SENSING AND TRANSDUCING

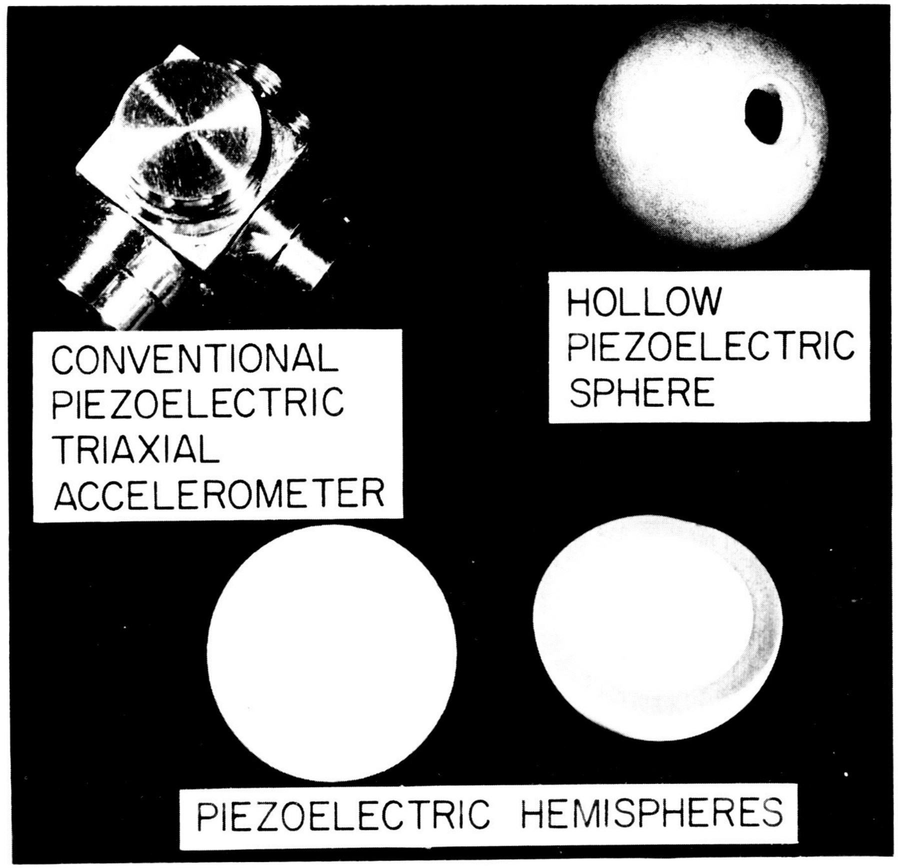
1. FREQUENCY RESPONSE, 2.5 TO 2000 CPS
2. AMPLITUDE RANGE, 3 DECADES
3. AMPLITUDE LEVEL, UP TO MANY THOUSAND "G"
4. MECHANICALLY RUGGED
5. OMNIDIRECTIONAL
6. MECHANICAL AND/OR ELECTRICAL RANGE COMPRESSION, IMPACT LIMITING

B. RADIO TELEMETRY

1. RADIO FREQUENCY POWER, 100 MW, MIN
2. RF STABILITY
3. SIMPLICITY
4. RUGGEDIZATION, SHOCK STABILITY
5. SELF - CONTAINED POWER SUPPLY
6. OMNIDIRECTIONAL ELECTRICALLY STABLE ANTENNA
7. ANTENNA PERFORMANCE DURING CONTACT AND /OR IMMERSION

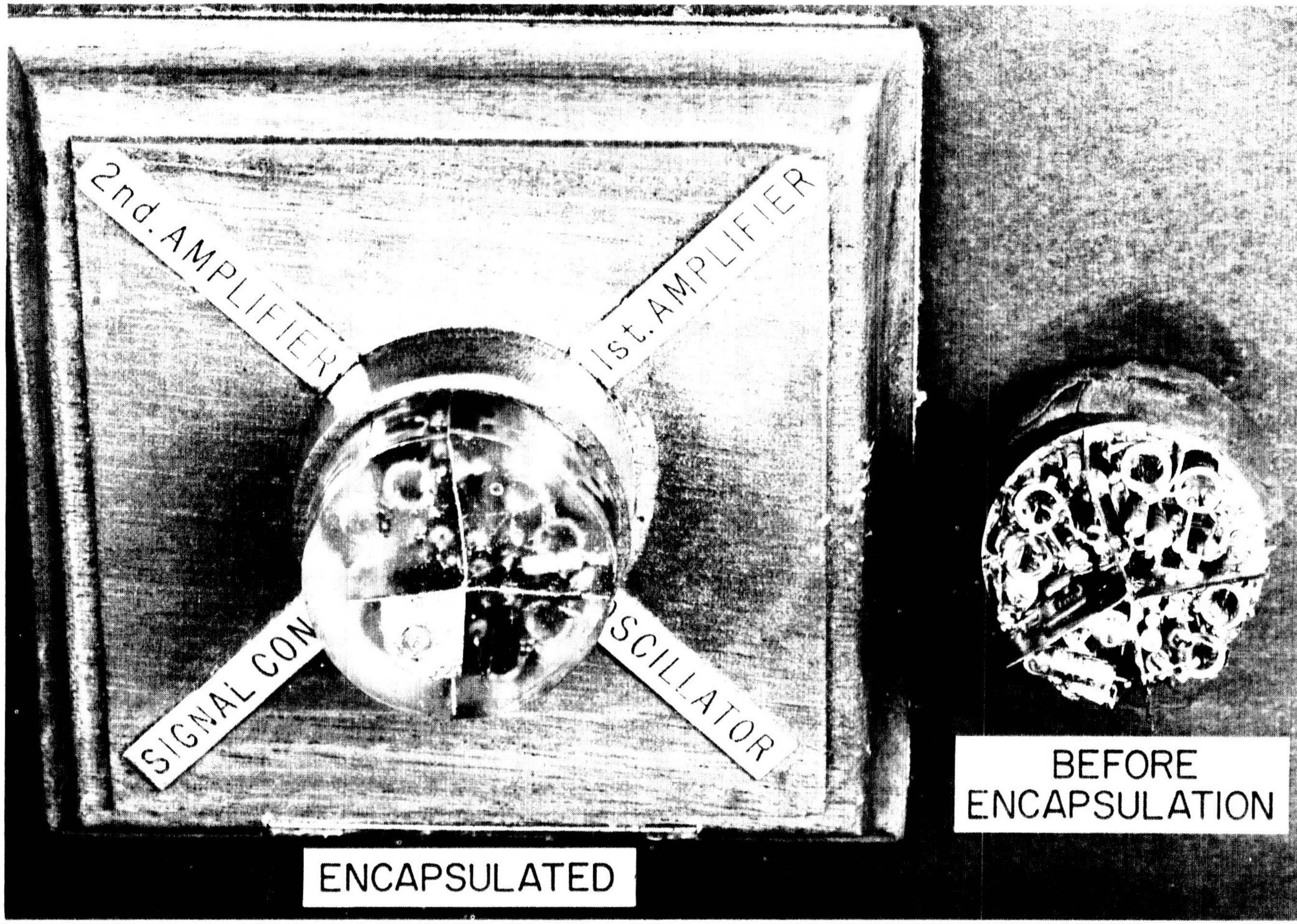
NASA

Figure 3.- Penetrometer instrumentation considerations.



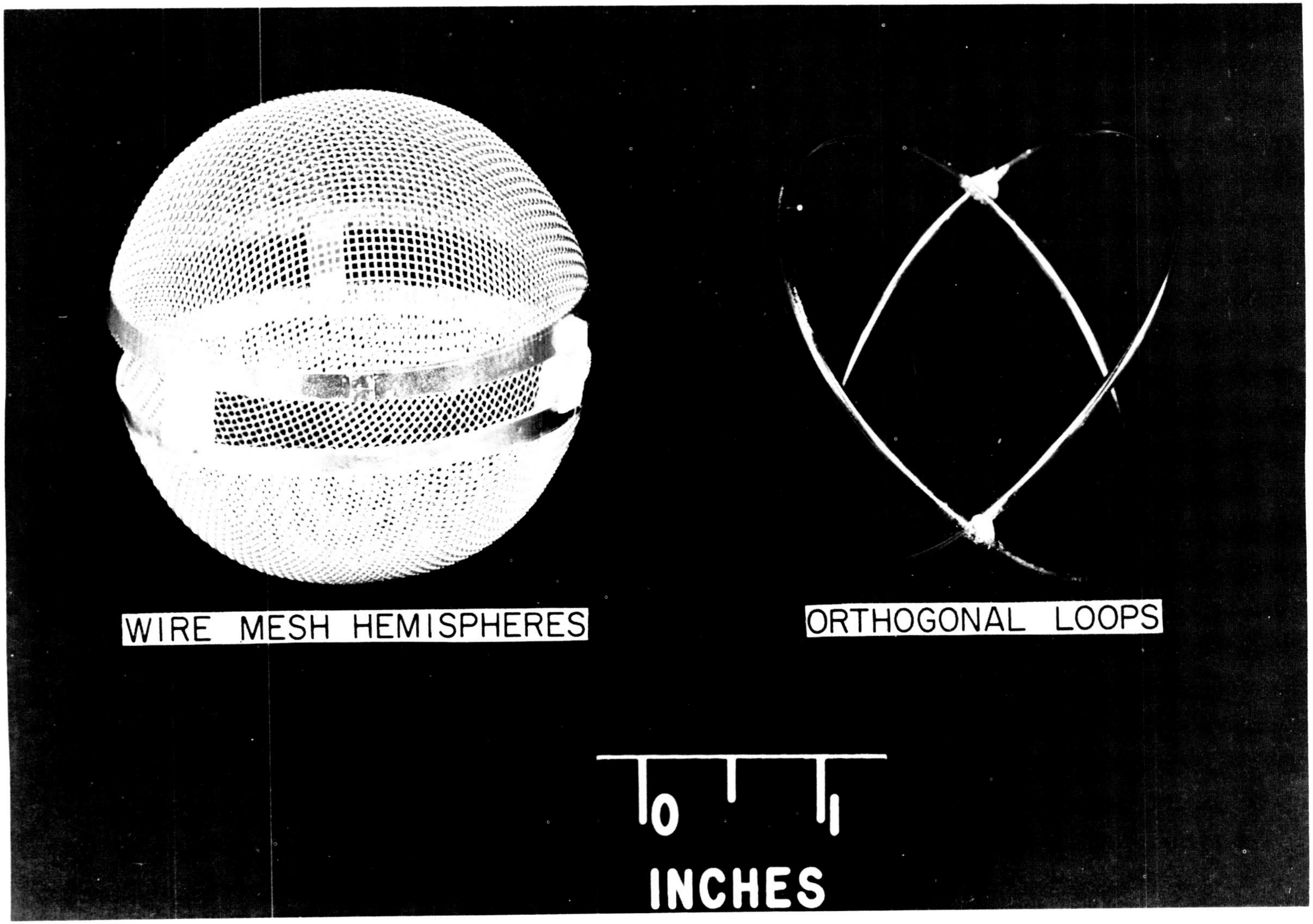
NASA

Figure 4.- Possible omnidirectional acceleration sensing elements.



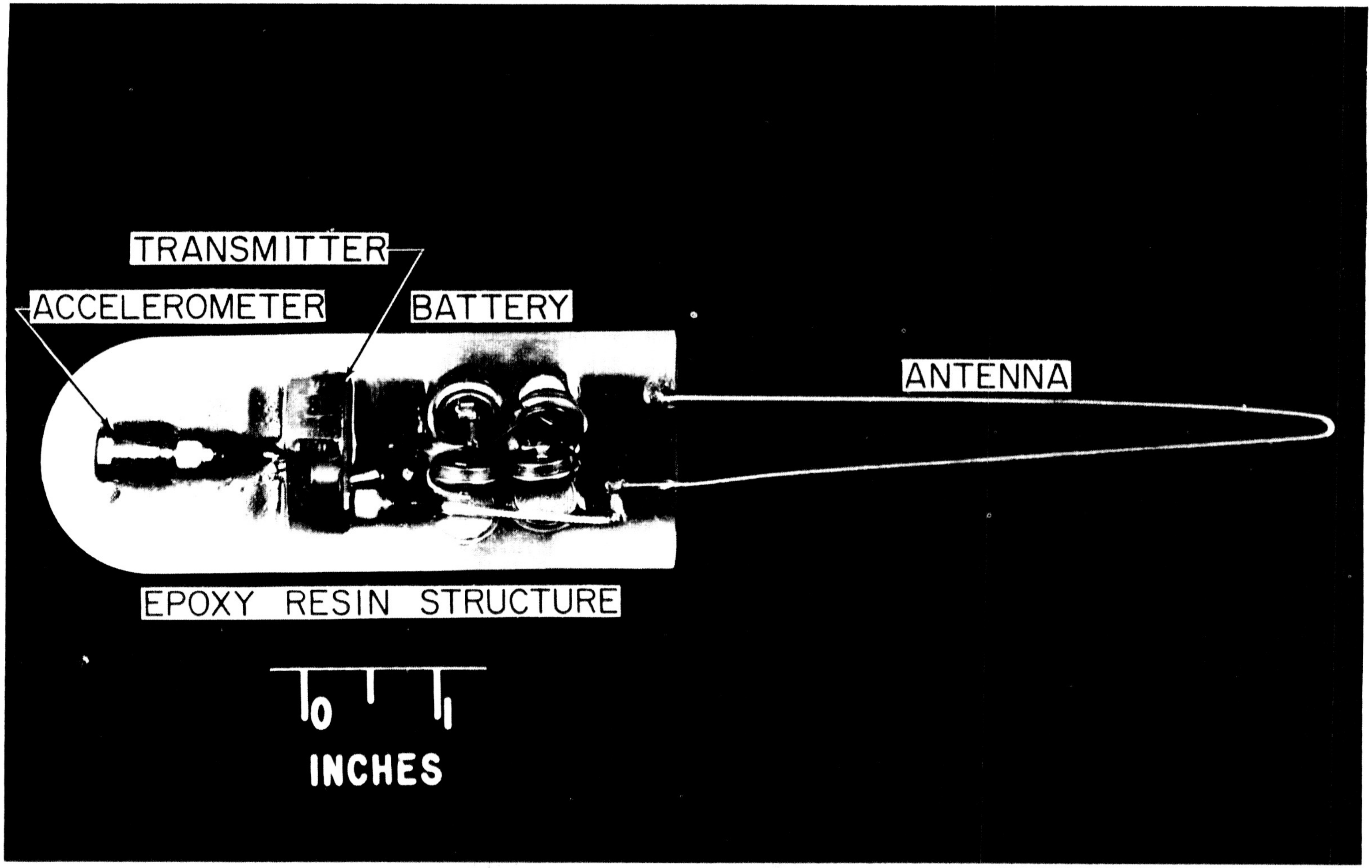
NASA

Figure 5.- Penetrometer transmitter.



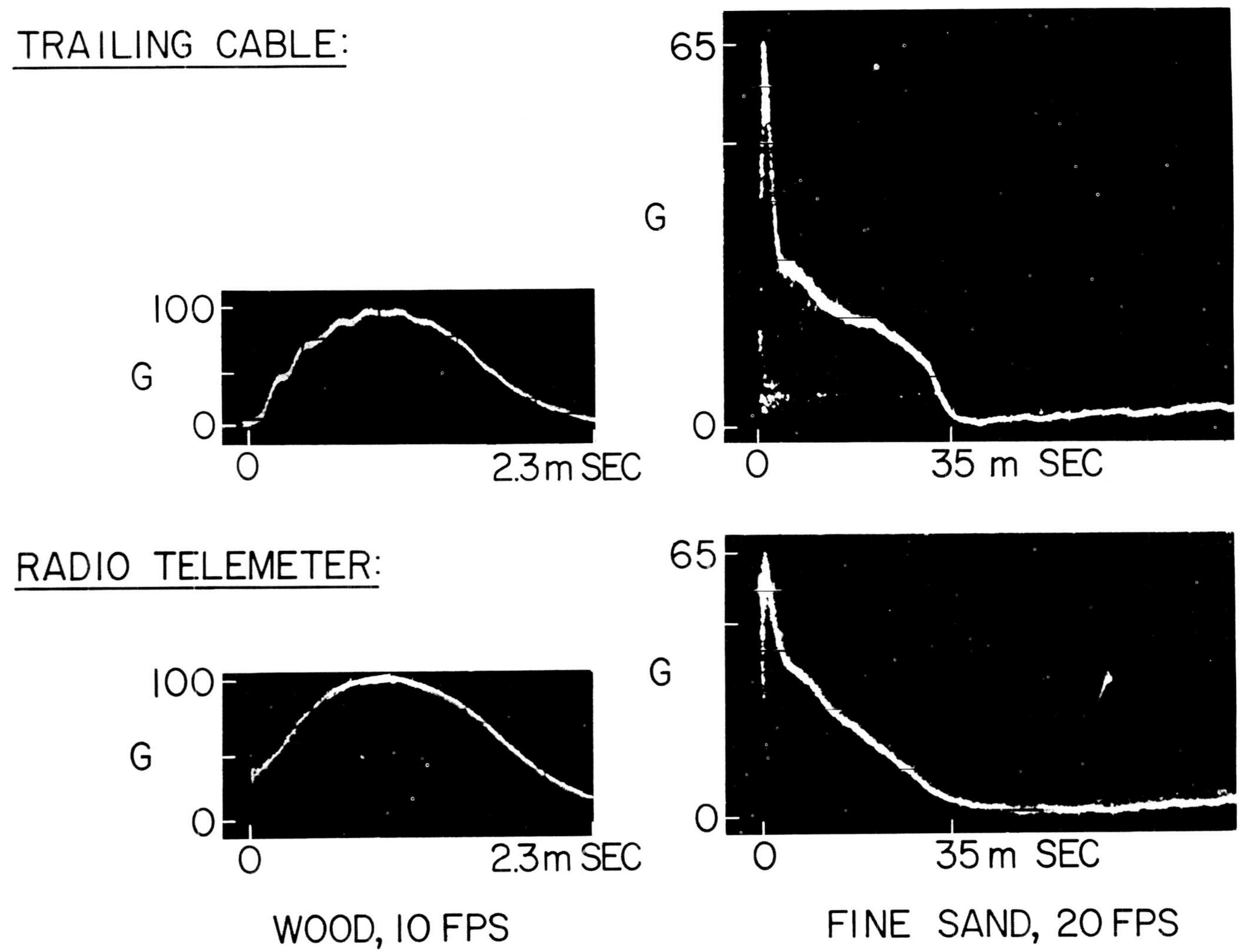
NASA

Figure 6.- Possible omnidirectional transmitting antennas.



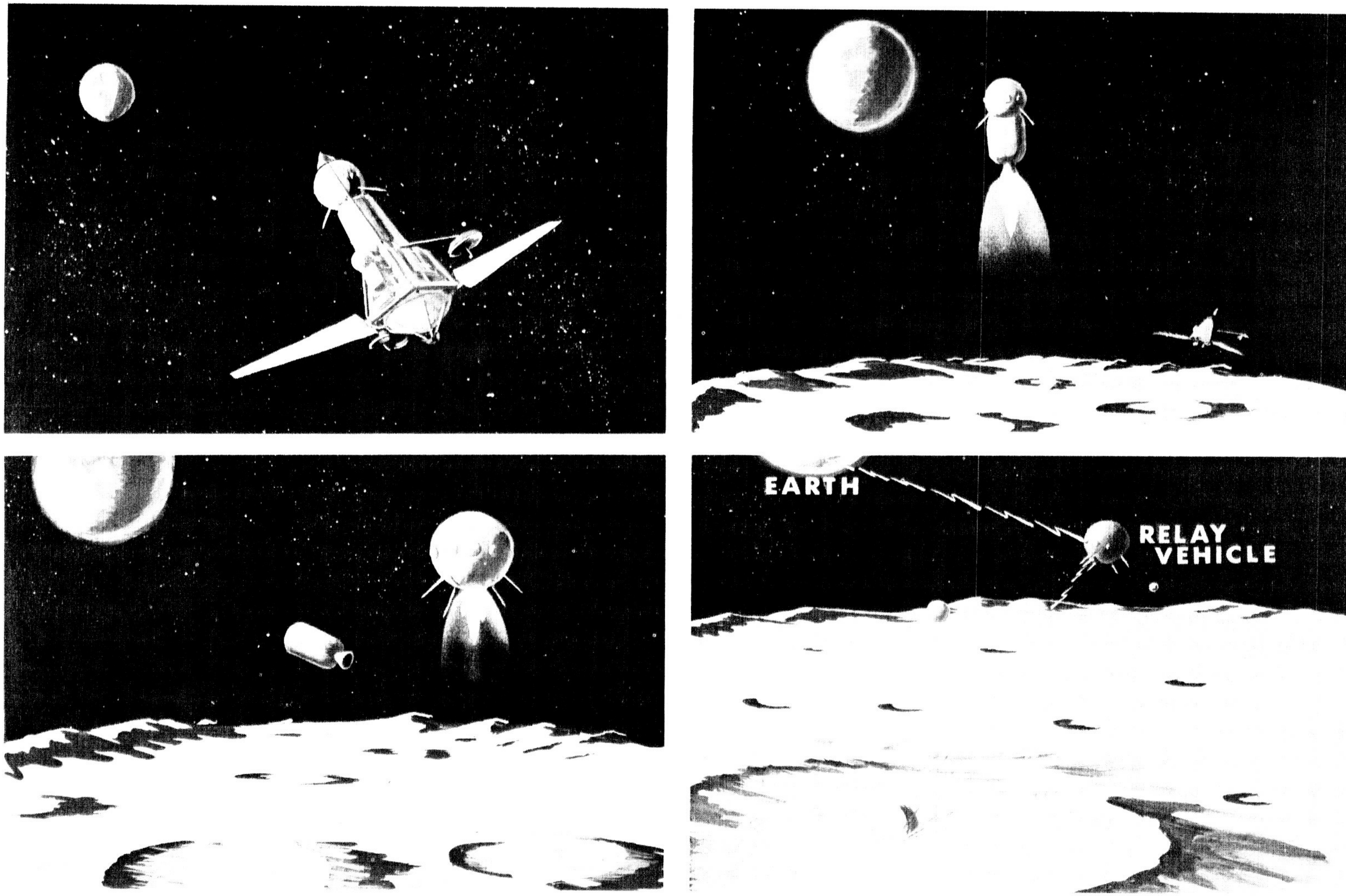
NASA

Figure 7.- Unidirectional penetrometer.



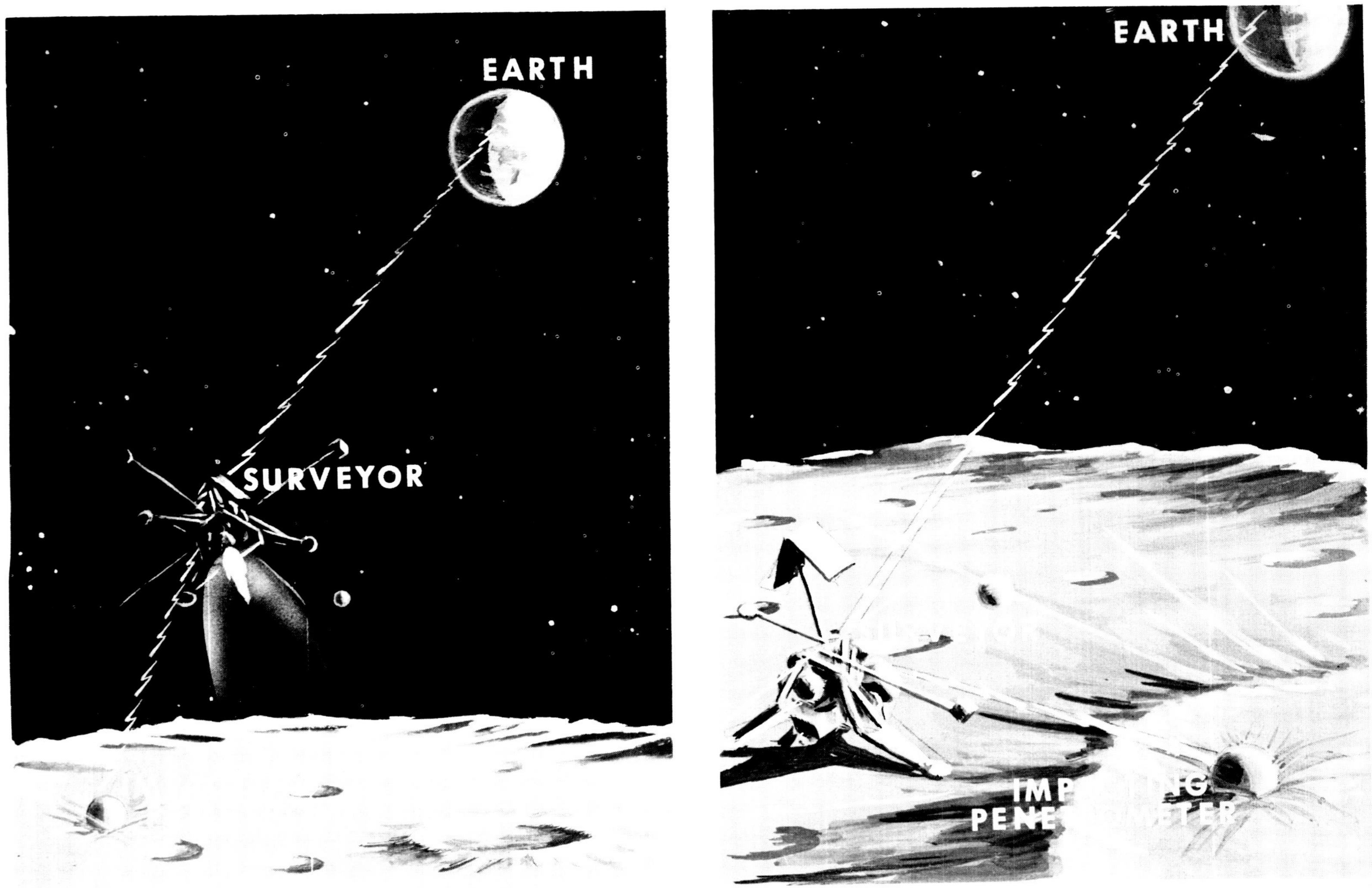
NASA

Figure 8.- Comparison of penetrometer waveforms.



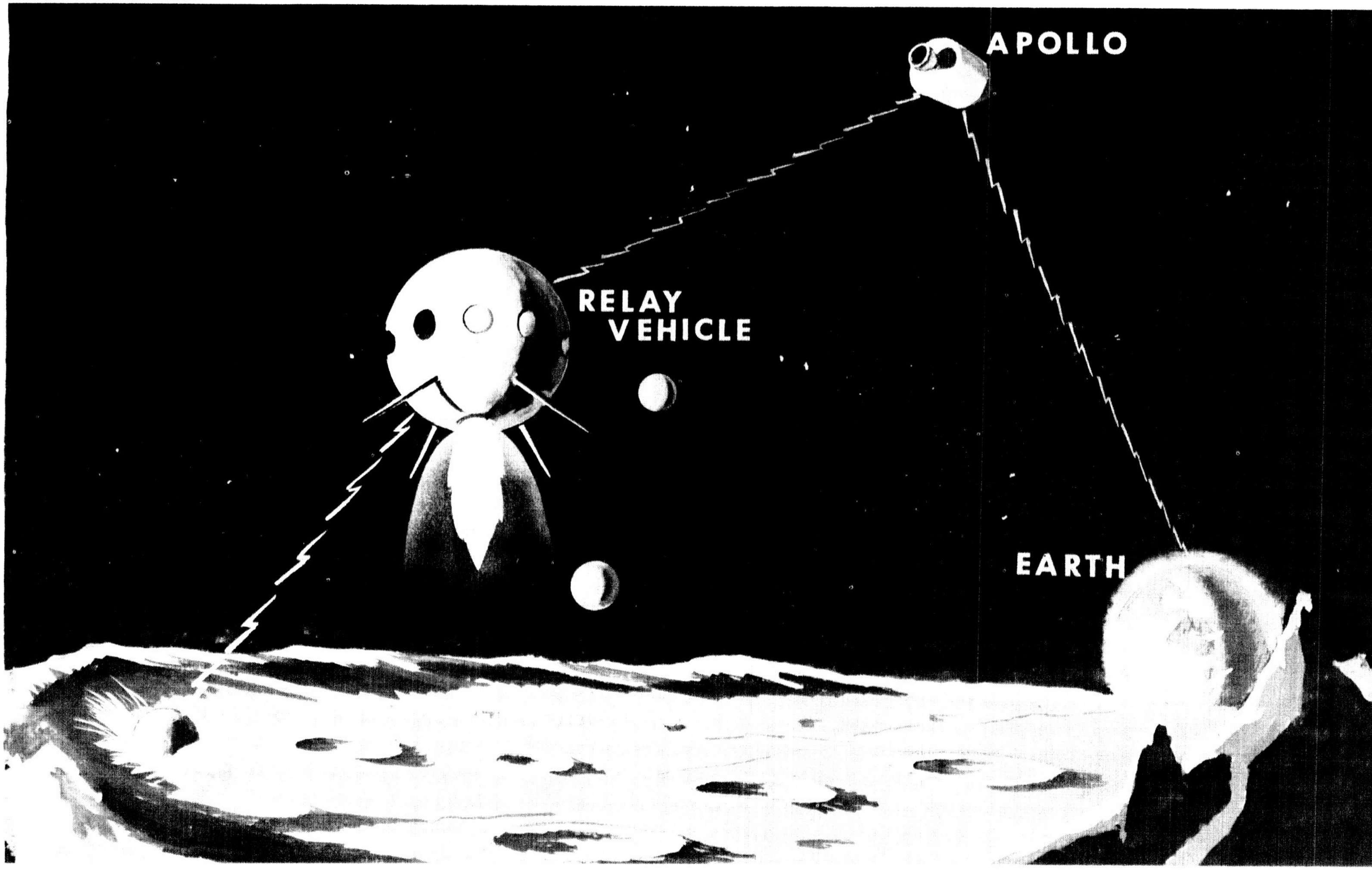
NASA

Figure 9.- Possible application of penetrometer technique to a Ranger mission.



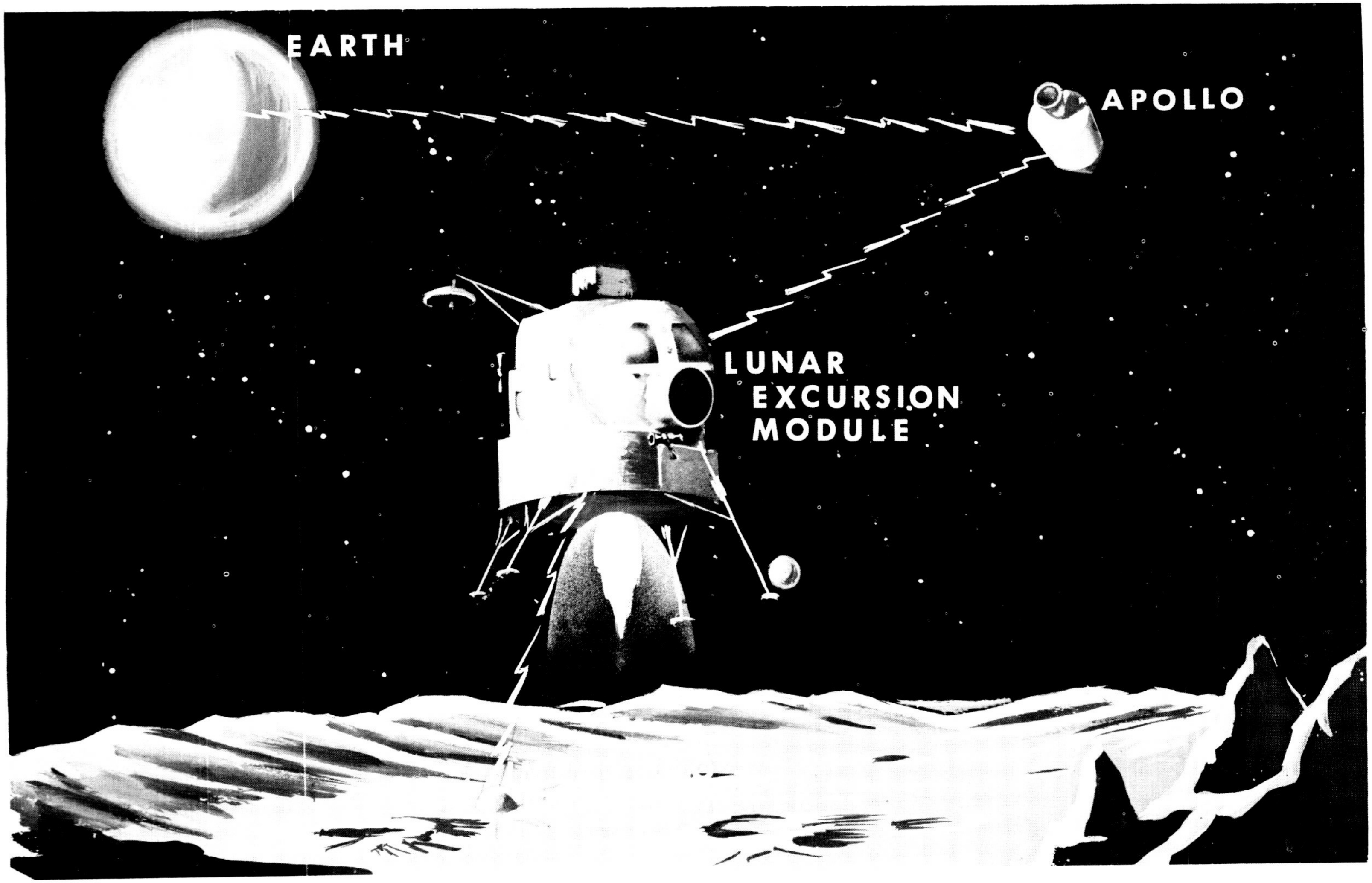
NASA

Figure 10.- Penetrometers deployed by Surveyor.



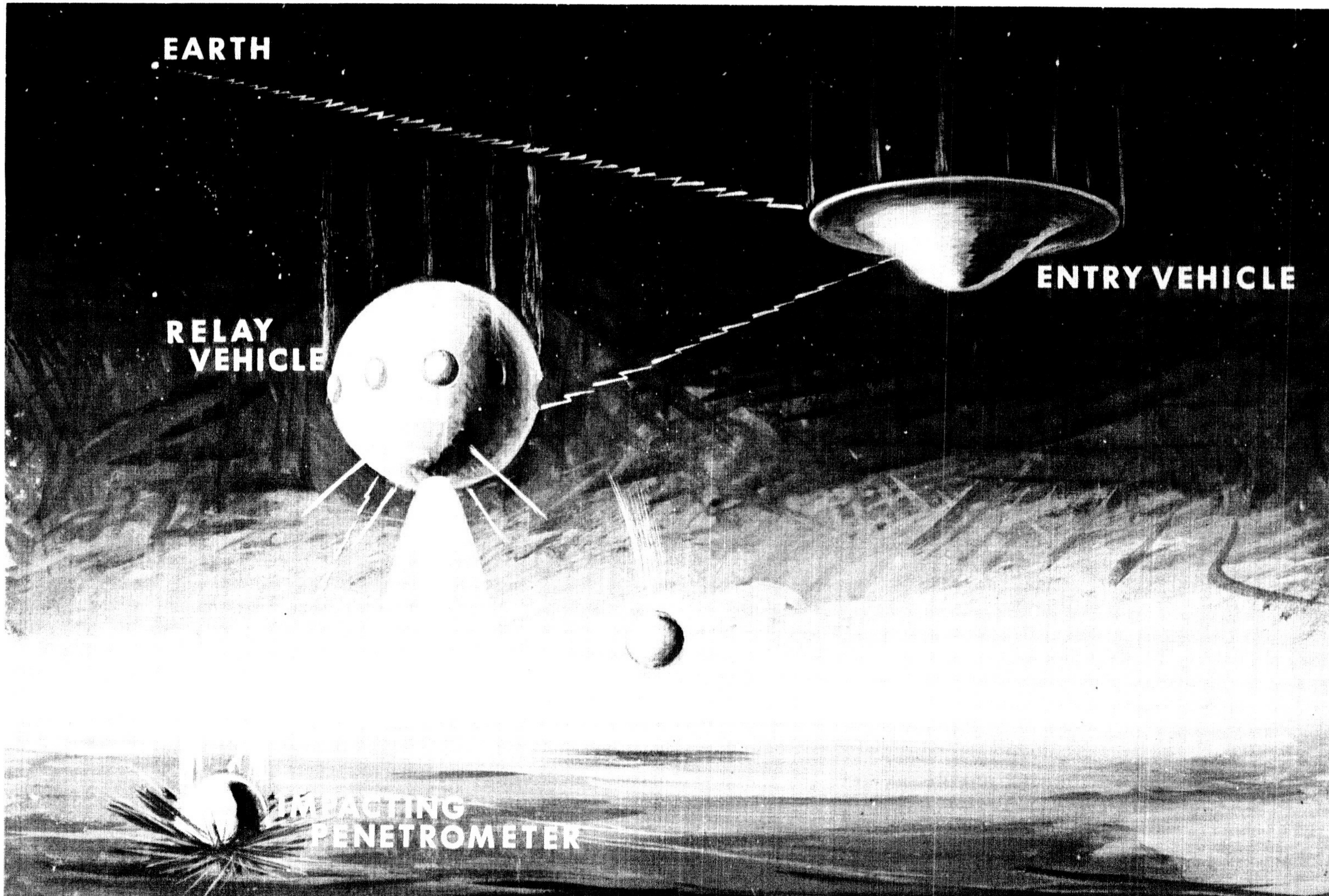
NASA

Figure 11.- Application of penetrometer technique to Apollo reconnaisance mission.



NASA

Figure 12.- Utilization of penetrometers by the Apollo lunar excursion module.



NASA

Figure 13.- Penetrometer deployed from a Mars exploration mission.

NASA-Langley, 1964