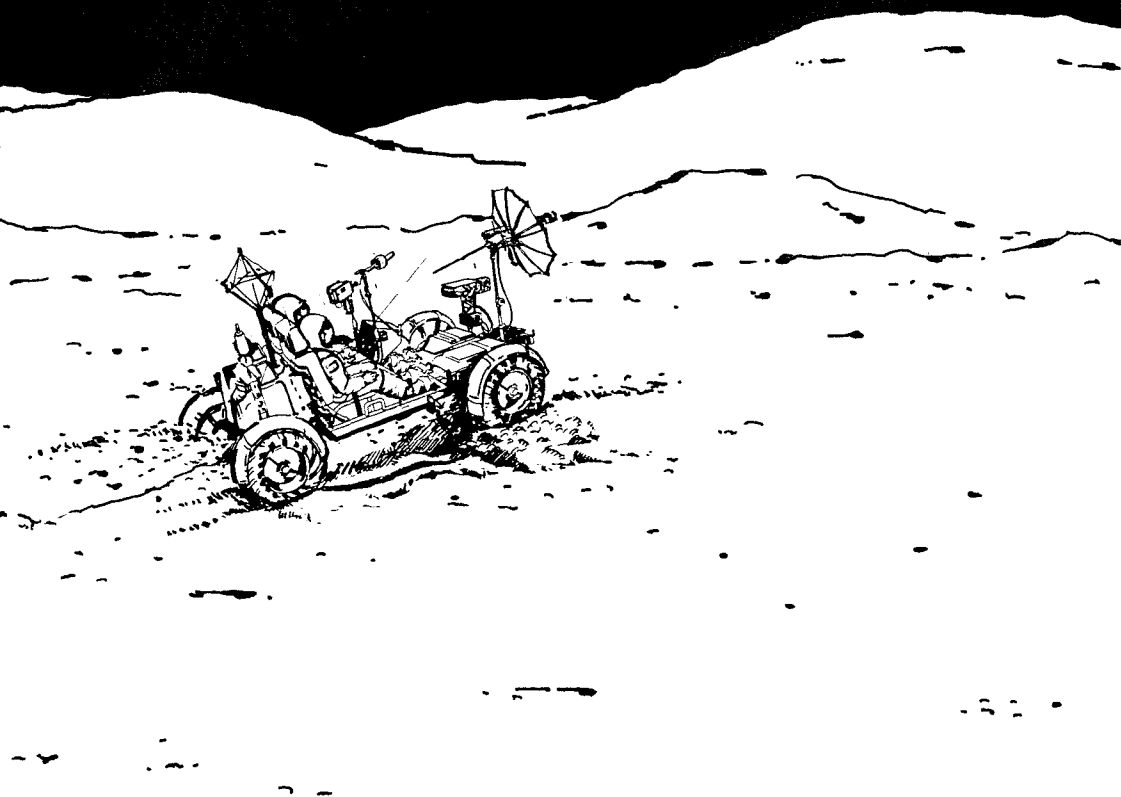


An introduction to

**SEP**

Surface  
Electrical  
Properties  
experiment

**APOLLO XVII**



APOLLO XVII  
LUNAR SURFACE ELECTRICAL PROPERTIES EXPERIMENT  
Conceived and Developed at the  
MASSACHUSETTS INSTITUTE OF TECHNOLOGY  
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Raytheon Company, Equipment Division

**A BRIEF INTRODUCTION  
TO THE SURFACE ELECTRICAL  
PROPERTIES EXPERIMENT**

by  
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August 1972

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## INTRODUCTION

One of the experiments to be done on the Moon by the Apollo 17 astronauts uses radio waves to “see” down into the Moon, possibly as far as a few kilometers.\* We will look for layering in the Moon’s rocks and soils. We will look for large boulders that are completely buried and so hidden entirely from the astronauts’ eyes and also from telescopes. We will even look for water although we do not really expect to find any subsurface water. And finally, we will measure the electrical properties of the Moon. We expect to study a large portion of the landing site. Our experiment will be carried on each traverse made during the second and third EVAs (Extra Vehicular Activity).

The SEP experiment is extremely important for many reasons. First, the values of the electrical properties of the Moon’s outer few kilometers of rock and soil measured in situ for the first time may help interpret observations already made with both earth-based radar and with bistatic radar. (For an elementary discussion of bistatic radar and some preliminary results see On the Moon with Apollo 16—Guidebook to the Descartes Region, EP 95, available from Government Printing Office, Washington, D.C., \$1.00.) Secondly, SEP will provide data that are needed to interpret the observations to be made with an Apollo 17 orbital experiment, the Lunar Sounder. In that experiment, the times required for radio waves to penetrate the Moon, be reflected, and return to the surface of the Moon are measured. Yet rather than times, Lunar scientists are really interested in depths which are obtained by the simple procedure of multiplying the travel times by the speed. And SEP measures the speed with which radio waves travel in the Moon. Thirdly, SEP will provide background data that will be useful for many years. Undoubtedly, the major exploration of the other planets as well as the continued exploration of the Moon will be done remotely using radio waves. Thus the experience, as well as the data, gained with SEP on the Moon, will be invaluable in the future study of planets. Fourthly, we expect to learn much about the Apollo 17 landing site. Visual observations made both by the astronauts and with cameras are restricted to the very surface of the Moon. Yet SEP can “see” to depths of a few kilometers. Thus, SEP will extend to depth those visual observations made at the surface. But even more importantly, SEP can see features at depths that do not reach the surface.

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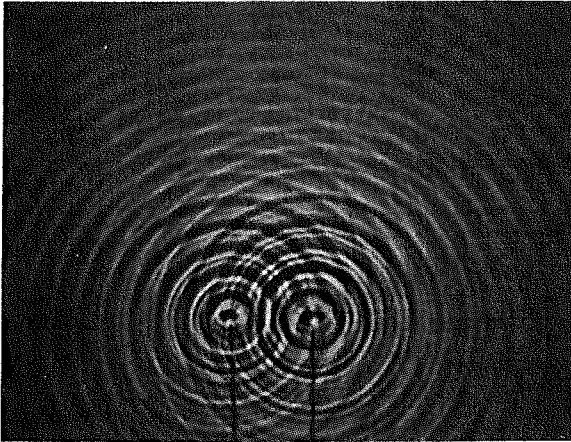
\*A kilometer is about 0.6 miles. A meter is 39 inches, slightly more than 1 yard.

## THE TECHNIQUE

The basic principle of SEP, interferometry, is a familiar one in science, engineering, and technology. It involves only the interference of two or more waves to produce a "synthetic wave". For example, the pattern produced by the two sets of waves on the surface of water when two pebbles are dropped into a pond at the same time, but separated by a few feet, is an interference pattern (see Fig. 1). So is the pattern produced in a bathtub by the combination of (1) original waves caused by dropping a small object into the water and (2) reflected waves from one side of the bathtub. A third example from everyday life of interference phenomena is the beautiful colors associated with a thin film of oil floating on water. Light waves interfere, in this example, to produce the various colors.

In SEP, the waves are radio waves, similar to those used in commercial radio broadcasting and in television. We use a radio transmitter and antenna to launch a radio wave on the Moon's surface. See Fig. 2 for a view of the transmitter, Fig. 3 for one of the receiver, and Fig. 4 for the arrangement to be used on the Moon. Part of the energy in the wave travels in the Moon, just below the surface. Part travels just above the Moon's surface with the speed of light. The part that travels beneath the surface is slower. Therefore, near the surface of the Moon these two waves interfere to produce a wave that is sometimes called "beat frequency wave" or a "synthetic wave". By detecting and measuring the properties of this interference wave, we can determine two things about the Moon: (1) the speed of radio waves in the subsurface and (2) the ease of propagation of radio waves in the Moon. This second property is termed attenuation and it is determined by measuring the strength of the interference wave at several distances from the transmitter. (Actually, these measurements are made continuously and automatically as the Lunar Rover moves along.)

In addition to the two waves that we have discussed, another wave may also be present. Energy is radiated by the transmitting antenna downward into the Moon. If layers exist in the subsurface, then part of this energy is reflected back towards the surface (path 3 in Fig. 4) where it then interferes with the other two waves. This additional interference makes the analysis of the data more complicated but it also adds considerable information about the Moon's interior. This additional complexity is small when compared with the gain in information.



*Fig. 1 This is the pattern of two interfering waves as shown by a ripple tank. It is possible to simulate an idealized model of the SEP experiment showing different velocity waves above and below the interface and their interference at the interface. Even a reflecting layer can be included.*

## THE EQUIPMENT

The principles on which the experiment is based are simple. So are the equipment concepts. Indeed the equipment is no more complicated than a good quality, hi-fi FM home receiver. At the same time, do not let us mislead you. Considerable design effort, exacting controls in manufacturing, and extensive testing combine to make this equipment extremely reliable. The environment of the Moon is hostile not only to human life but also to equipment.

On the Moon, the astronauts will set out a small, low power transmitter, shown in Fig. 2, and then they lay on the surface two crossed dipole antennas. Readers who are unfamiliar with dipoles can easily visualize them by realizing that the familiar TV rabbit ears, with both arms extended along the same line, is really just a dipole. The SEP dipoles are longer; they are 70 meters tip-to-tip.

The receiver and receiving antennas, shown in Fig. 3, are also unpacked from the pallet on which they will be carried to the Moon. The astronauts mount both on the Lunar Roving Vehicle (LRV). An artist's sketch of all the equipment set out on the Moon and ready to operate is shown in Fig. 5.

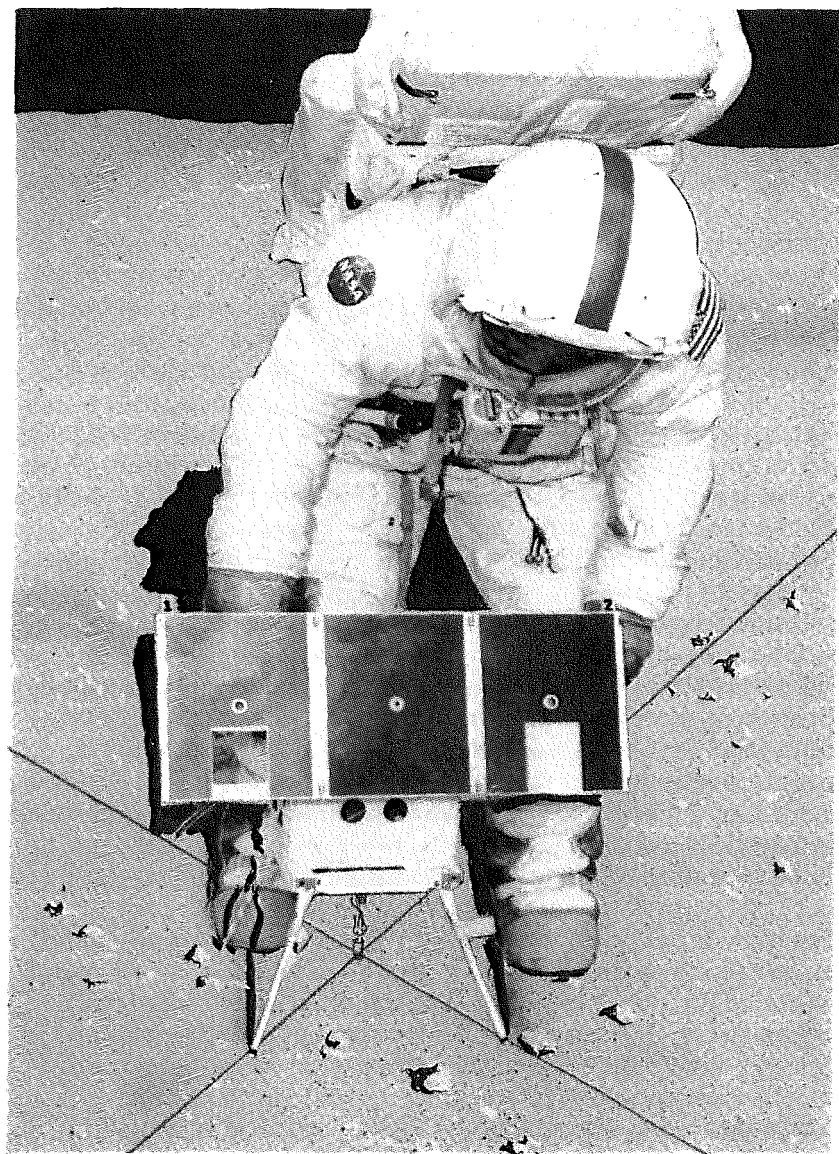
Inside the receiver, there is a tape recorder that is similar to the familiar home portable cassette tape recorder. The data are recorded on magnetic tape. The entire tape recorder, which incidentally carries the awesome official designation of "Data Storage Electronics Assembly" (DSEA), will be returned to Earth so that the data can be analyzed. In addition to our SEP data, information on the location and speed of the Rover, obtained from the Rover's navigation system, are also recorded on the tape.

In addition to the preceding general description of the equipment, some readers may desire a technical description. Those readers not interested in the technical description should omit the rest of this section and flip ahead to Data Interpretation.

## EQUIPMENT DESCRIPTION

The six SEP frequencies are transmitted and received according to the scheme shown in Fig. 6. One frame, which is 38.6 seconds in duration, consists of six 6.4 second subframes that are identical except for the receiver calibration and synchronization process. In Subframe 1, for example, the receiver is calibrated at 32.1 MHz and





*Fig. 2 Astronaut Cernan, who will set up this part of SEP on the Moon, practiced many times on Earth. Shown here is the compact SEP transmitter with its solar panel power source and dipole antennas deployed. The transmitter electronics package is covered on the bottom five sides with a thermal blanket. Because the top of the unit is shaded by the solar panel, the uncovered surface needs only a coat of thermal paint to provide adequate cooling for the enclosed electronics. The balance between heat lost to cold space by radiation and that generated inside the unit by the electronics equipment is very delicate and requires careful thermal design.*

16 MHz and the synchronization signal is transmitted on the N-S dipole and received on the X antenna. In Subframe 2 the receiver is calibrated at 8.1 MHz and 4 MHz while the synchronization signal is transmitted on the E-W antenna and received on the Y antenna. Each experiment frequency sequence is repeated exactly as shown in all six subframes. Each individual experiment frequency is transmitted first on the N-S antenna for 100 milliseconds and then on the E-W antenna for 100 milliseconds. During each 100-millisecond transmission interval, the receiver "looks" at the transmitted signal for a period of 33 milliseconds with each of the three orthogonal (X,Y,Z) receiving loops. In addition to the above, once each subframe the receiver observes environmental noise and records its amplitude.

The receiver acquires the transmitter signal sequence automatically as long as the signal exceeds a given threshold. Synchronization of the receiver is accomplished when both (or either) the 1 and 2.1 MHz signals exceed a given threshold. A block diagram of the SEP receiver is shown in Fig. 7.

The loop antennas are connected sequentially to a low noise amplifier section which amplifies, converts (in frequency) and logarithmically compresses the amplitude of the received signal. A constant amplitude, variable frequency signal (in the band 300 to 3000 Hz) corresponding to the logarithm of the received signal amplitude is recorded on magnetic tape in the DSEA. The DSEA can record nearly 10 hours of data. Upon completion of the experiment, the astronaut removes the DSEA from the receiver, as indicated in Fig. 8, for return to earth.

Signal synchronization, frequency mixing, and antenna switching, etc., are all controlled by the timing section which is in turn crystal controlled for stability. The entire receiver assembly is battery powered using primary cells (cells that cannot be recharged) and is enclosed, except for the antenna assembly, in a thermal blanket (roughly corresponding to a thermos bottle) which has two flaps that may be opened to expose OSRs (Optical Solar Reflectors) which form a thermal radiator for internally produced heat, while reflecting that from the sun to control the internal temperature of the receiver.

The SEP transmitter, shown in Fig. 3 and in block diagram form in Fig. 9, is powered by solar cell panels which are designed to provide a minimum of 10.0 watts output at +15 volts, and 1.10 watts at +5 volts. Each panel is constructed with an aluminum honeycomb substrate utilizing Heliotek bar contact 2 x 2 cm, blue sensitive, N on

P type solar cells. Individual cells are insulated from the aluminum substrate with a Micaply sheet that is covered with a six-mil, micro-sheet cover. The +15 volt source consists of a 6 x 52 cell matrix, and the +5 volt source consists of a 3 x 17 cell matrix. The cells are interconnected utilizing the Spectrolab "SOLAFLEX" interconnect system, which uses silver-plated copper 0.002 inches thick. The cell matrices are connected to the power output cable using 24 gauge, teflon coated stranded copper wire which is bonded to the panel. The power output cable is connected to the Amplifier Module through a Deutsch 7-pin, socket-type connector. Both the +15 volt and +5 volt power sources are shunt regulated by means of a regulator circuit mounted on the back of the right-hand solar panel. The regulator circuit is protected from solar radiation by an OSR in the lower center of the front of the panel. The left-hand panel contains a cutout to permit the closing of the panel over the regulator circuit in the stowed configuration. Like the receiver, the transmitter timing sequence is crystal controlled for stability. Also, separate stable crystal oscillators generate the signals which are radiated by the dipole antennas placed on the lunar surface. Because the antennas are required to radiate energy at six different frequencies they are constructed in sections (Fig. 10) where each section is electrically separated by electrical filters (signal traps). Each section of the antenna is of the proper electrical length for optimum performance. Each dipole, 70 meters long (tip-to-tip), is made of insulated wire between traps which are stored on reels until deployed by the astronaut.

## DATA INTERPRETATION

The SEP experiment is entirely new. The reader may think, "If the experiment is so great for studying the Moon, why has it not been used to study the Earth?" The answer is simple. The Moon is an excellent electrical insulator but the Earth's rocks near the surface are fairly good conductors. Therefore, the radio waves that travel to depths of a few kilometers in the Moon would travel in the Earth only to a few meters. Because the depth of penetration is so limited on the Earth, no use had been made previously of the SEP technique and the method remained undeveloped. Fortunately data interpretation requires only three things: (1) good geophysical insight, (2) understanding of the physics of electromagnetic waves and especially of interferometry, and (3) experience in known test situations. The geophysical insight is provided for the SEP experiment by several members of the SEP team who have interpreted other geophysical data for many years. The background in physics and interferometry

is gained from the formal training of several team members in physics and electrical engineering. And finally, the experience is being gained rapidly by applying the SEP technique to the study of several terrestrial glaciers. Perhaps glaciers seem to be peculiar places to test a lunar experiment. We chose them because ice is an insulator and hence radio waves travel in glaciers much as they travel in the Moon.

Although the principles of interferometry are well known, the application of them to our particular experiment had not been made explicitly. So we have developed our own analysis techniques. In this section, we describe only the simplest schemes. The reader interested in advanced techniques should consult the original articles listed in the bibliography.

In an idealized case in which the interferometer is used on a surface separating two semi-infinite media, an interference is produced by the two waves travelling just above and just below the interface (paths 1 and 2 in Fig. 4) because the velocities of the two waves differ. If the two media are (1) a vacuum and (2) a loss-free dielectric material, the wavelength,  $\lambda_i$ , of the interference pattern is given:

$$\lambda_i = \frac{\lambda_0}{n_1 - 1}$$

where  $\lambda_0$  is the wavelength in vacuum, and  $n_1$  is the index of refraction (see the top curve of Fig. 11). For low loss media, the index of refraction is equal to the square root of the dielectric constant, a parameter commonly used to describe the electrical properties of materials. Typical values of the dielectric constant for several materials are the following:

Water	81
Glacial Ice	3.4
Dry Granite	3 to 4
Porcelain	6 to 8
Plexiglass	2.5
Diamond	5.5
Lunar Rocks	3 to 10
Pyrex Glass	4 to 5

So from the observed interference pattern we determine the value of the dielectric constant of the surface material to depths of about one wavelength for each of the SEP frequencies. And from the dielectric constant, we obtain the velocity of radio waves.

We have mentioned a second electrical property, the attenuation or relative loss. Its value can also be estimated from the observed interference curve. We merely compare the decrease of strength at various distances with the decrease known to occur in a loss-free medium. Free space is the “standard” normally used. The excess loss which is always present (except in free space) is due to the medium itself. The losses, which may be dependent on frequency, are measured in this way at all six SEP frequencies.

If the lunar surface is layered, and these layers have significantly different electrical properties, then the incident radio waves will be reflected as in path 3, Fig. 4. As a result there is superimposed on the first interference pattern another one created by the difference in path length between the direct and reflected wave. Maxima will occur for  $n\lambda_m = 2d \sin \theta$  where  $n$  is an integer 1, 2, . . . , and  $d$  is the depth of the reflecting layer.  $\theta$  is the angle of incidence, and  $\lambda_m$  is the wavelength in the medium. (Strictly speaking, the interference pattern results from the addition of all waves, but the analysis is simpler, and also correct, when the several interference patterns are considered separately.) Incidentally this expression  $n\lambda_m = 2d \sin \theta$  has much broader application. It was first obtained by Sir William Bragg and forms the basis for the interpretation of X-ray diffraction data.

The distance from the transmitter at which the  $n^{\text{th}}$  maximum can be expected, if there is adequate signal from both the direct and reflected waves, is given by:

$$R(n) = 2d \left[ (2d/n\lambda_m)^2 - 1 \right]^{1/2}$$

Roughly speaking, the number of maxima that can be seen as a result of the presence of a reflecting layer at depth  $d$  is

- 1 for  $d > \lambda_m/2$
- 2 for  $d > \lambda_m$
- 3 for  $d > 3\lambda_m/2$

and so on.

The actual interference patterns depend upon several things—whether the receiver is within two wavelengths of the transmitter, losses in the media (technically, loss tangent), the “reflection strength” of the second interface (technically, reflection coefficient), and so on. These interrelationships are indeed complex. In Fig. 11, we show a family

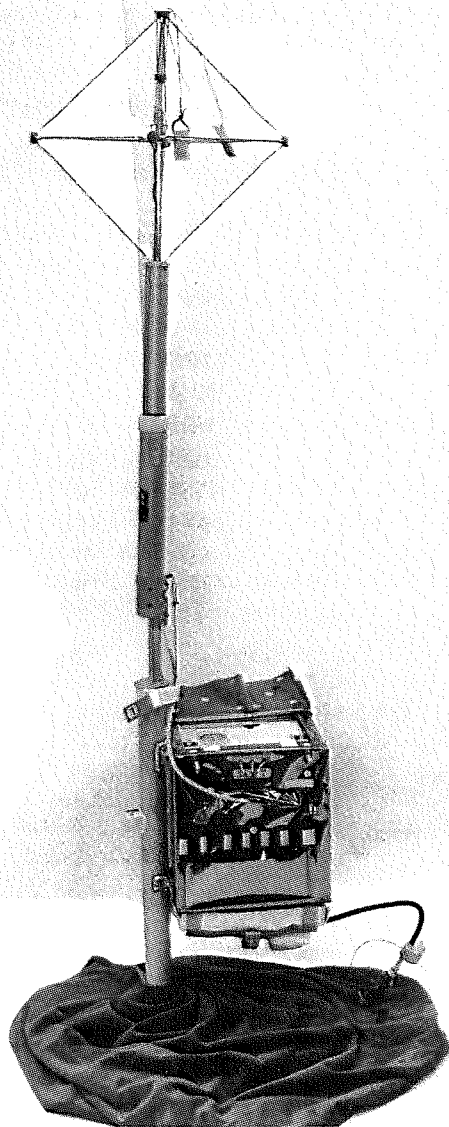


Fig. 3 The SEP receiver electronics including tape recorder and battery are contained in a nine inch box which is completely enclosed in a thermal blanket. Optical solar reflectors, which act as one-way mirrors to release internally generated heat into space and simultaneously reflect sunlight, are shown here with the thermal blanket opened. The three-loop antenna, folded during the journey to the Moon, is shown unfolded as it will be used on the Moon. The astronaut at the end of the experiment removes the tape recorder from the box and brings it back to Earth.

of curves for a model that may be applicable to the Moon. One purpose in showing the illustration is to indicate the additional interferences caused by a reflector. The second purpose is to illustrate the great effect of water. Compare the rest of the family of curves with the thicker top curve. Because the dielectric constant of water is 81 and dry rock is 3–4, small amounts of water have large effects on the interference pattern and can be readily detected.

The transmitting antenna lying directly on the interface between vacuum and the Moon will cause the radiation from the antenna to be concentrated in certain specific directions with profound effects on the interference pattern. In Fig. 12, we show a sketch of the radiation pattern (the distribution in space of the radiated energy) of a dipole antenna on the interface between free space and a medium that approximates the Moon. One of the principal directions of such concentration of energy is approximately along the line of the critical angle for total reflection at the interface. If a reflecting surface exists below the interface, this lobe will be "bounced back" to the surface where a maximum field strength will be observed even in the absence of surface waves sufficiently strong to produce the interference pattern already described above.

Still another phenomenon, scattering, can affect significantly portions of the interference pattern. If there exist in the Moon objects with properties that differ significantly from those of their surroundings and their sizes are comparable to a wavelength, these objects scatter the incident radio waves. Some of the energy in the scattered waves will arrive at the surface of the Moon and interfere with the other waves that we have already discussed. Such scattering bodies in the Moon might be large boulders (10 to 300 meters in size), concentrations of certain minerals, or even voids. At wavelengths large or small compared with the object's dimensions, the nature of the scattering is different. The comparison of interference patterns at different wavelengths will not only indicate the presence of such scatterers, but also will allow us to estimate their size and number.

Let us summarize here this discussion of data interpretation. From the observed interference patterns, we can (1) measure the electrical properties to a depth of a few wavelengths, (2) determine the depth to reflecting interfaces, and (3) detect the presence and determine the characteristics of scattering bodies. Finally, we may even detect the presence of water.

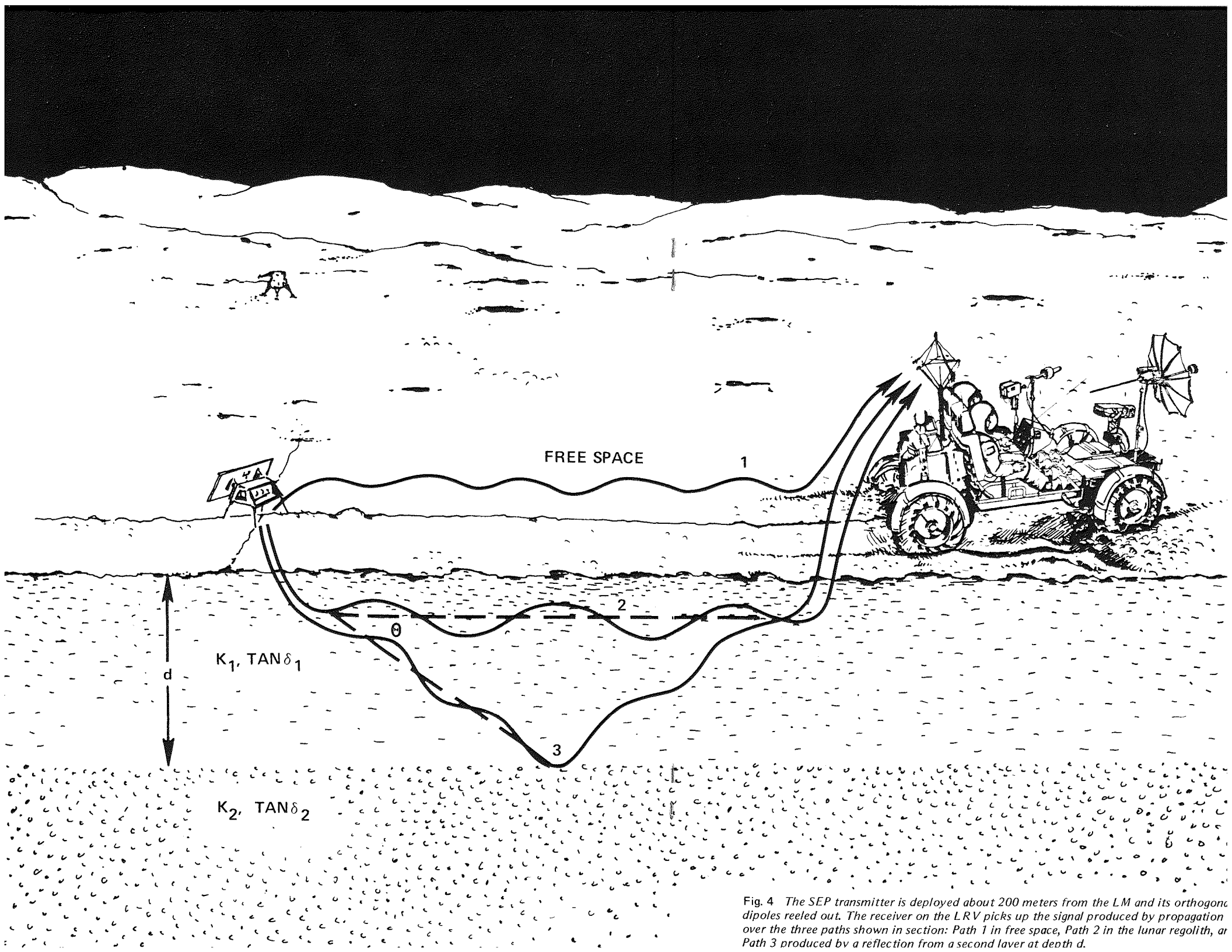


Fig. 4 The SEP transmitter is deployed about 200 meters from the LM and its orthogonal dipoles reeled out. The receiver on the LRV picks up the signal produced by propagation over the three paths shown in section: Path 1 in free space, Path 2 in the lunar regolith, or Path 3 produced by a reflection from a second layer at depth  $d$ .



## GLACIER TESTS

If the SEP technique has not been used on Earth, how can we be sure that it will work on the Moon? Why do we think the methods of data interpretation will give us valid results? These questions and many related ones concerned us greatly in the early stages of designing and building SEP. So we searched for terrestrial analogues on which to test our experiment. All rocks at the surface of the Earth are too conductive and hence the losses are too great for radio waves to travel sufficiently far to provide a suitable test. Laboratory models which have been scaled down in size by factors like 1000 could be studied. Such models have been very useful for certain studies but could not be used to test full scale equipment or experiment concepts. Only two geological environments appeared to be suitable—glaciers and large salt deposits (either the layered tabular bodies, such as occur in the subsurface below Kansas and New York, or the cylindrical bodies, such as occur in Texas and Louisiana). The salt deposits have slightly better values of electrical properties than the glaciers but the geometry of the mines in them is undesirable. Glaciers, on the other hand, have acceptable electrical properties (the losses are slightly higher than we expect for the Moon) but the geometries are ideal.

So we selected several glaciers which had already been studied extensively with other techniques. Various versions of our SEP equipment have now been used for study of the Gorner glacier in Switzerland (in 1968), the Athabasca glacier in Alberta, Canada (in 1970 and 1971), and several glaciers that drain the Juneau, Alaska ice fields (in 1972).

On the Gorner glacier, we used very simple and inexpensive equipment; home-made antennas, a ham operator's receiver, and a laboratory signal generator for the transmitter. We recorded data by hand. We moved equipment literally on our own backs. Daily progress on the glacier was very slow. None of the equipment was automatic. But we proved unequivocally that the experiment concept was valid and we could then proceed with our experiment.

By the second season on the Athabasca glacier, we had built equipment that embodied many of the features that would be used in the actual flight equipment. The electrical aspects of the two sets of equipment were almost identical. Both used the same six frequencies. Both had crossed dipoles for transmitting antennas. Both used loop receiving antennas. And both had similar receivers. We did have an

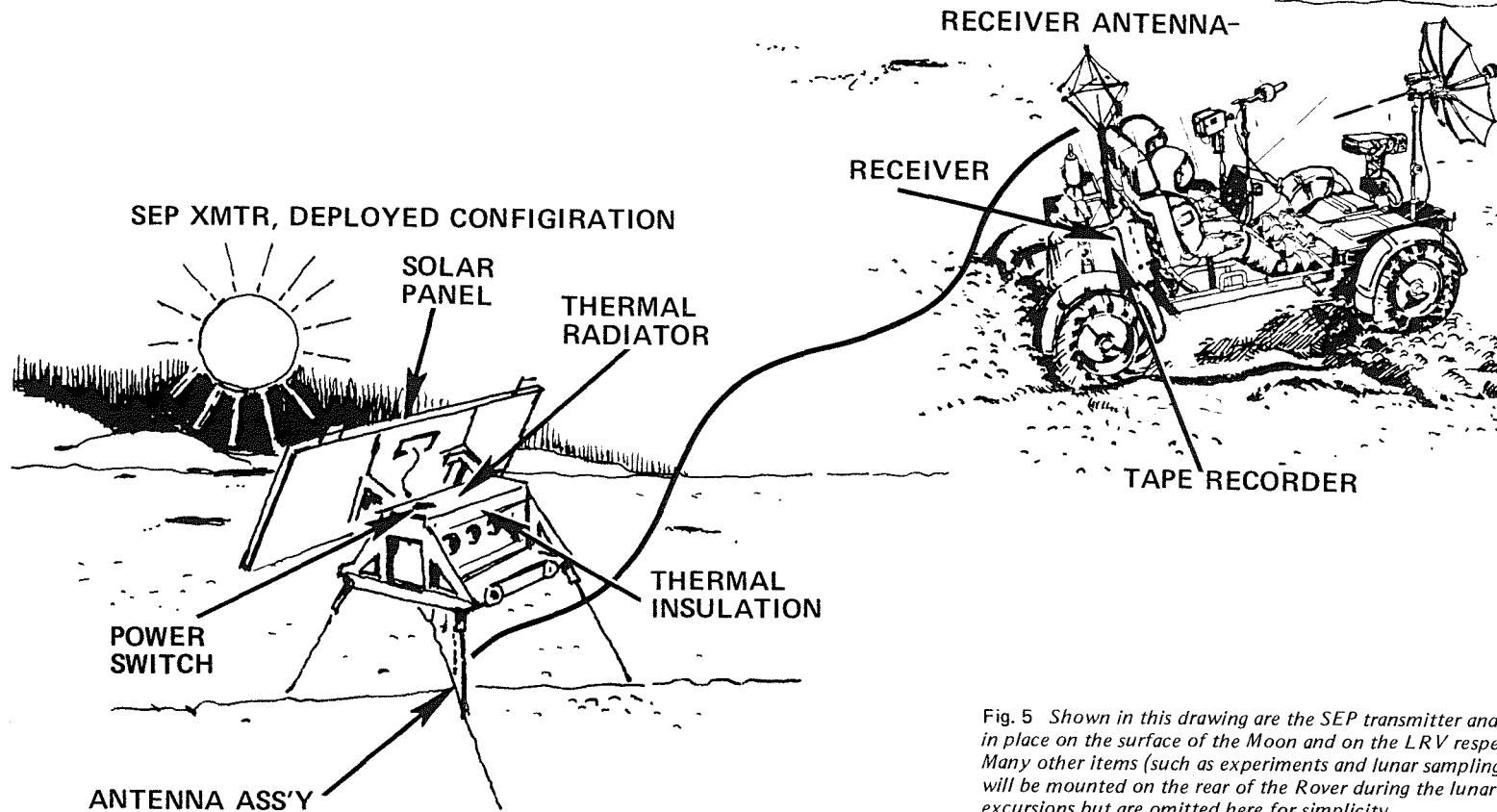


Fig. 5 Shown in this drawing are the SEP transmitter and receiver in place on the surface of the Moon and on the LRV respectively. Many other items (such as experiments and lunar sampling tools) will be mounted on the rear of the Rover during the lunar excursions but are omitted here for simplicity.

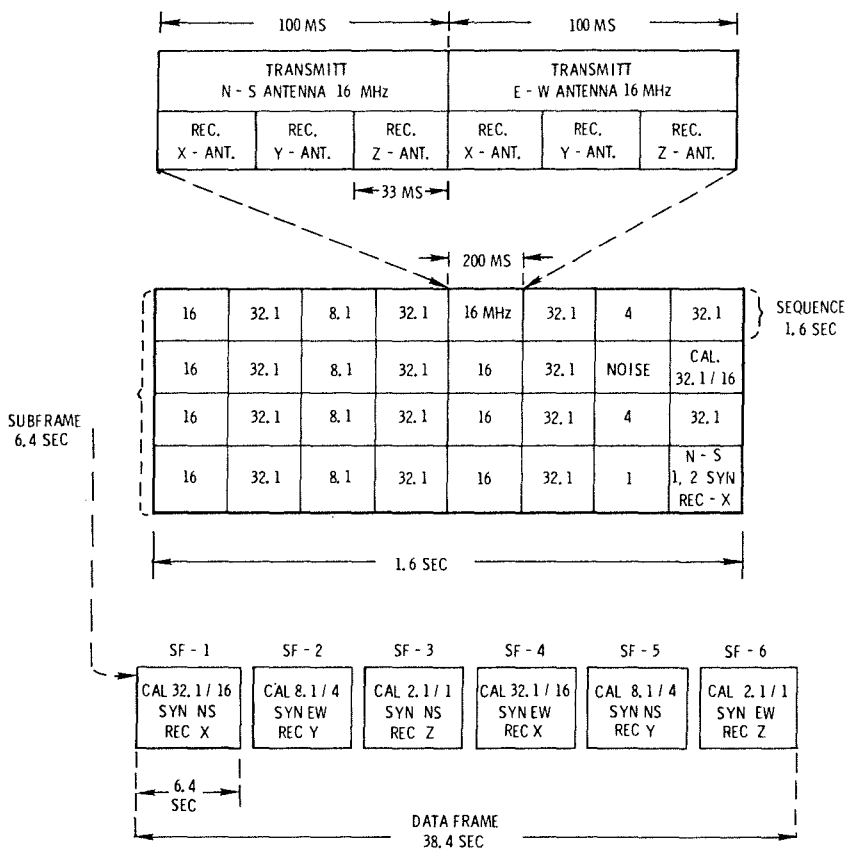


Fig. 6 SEP Data Format

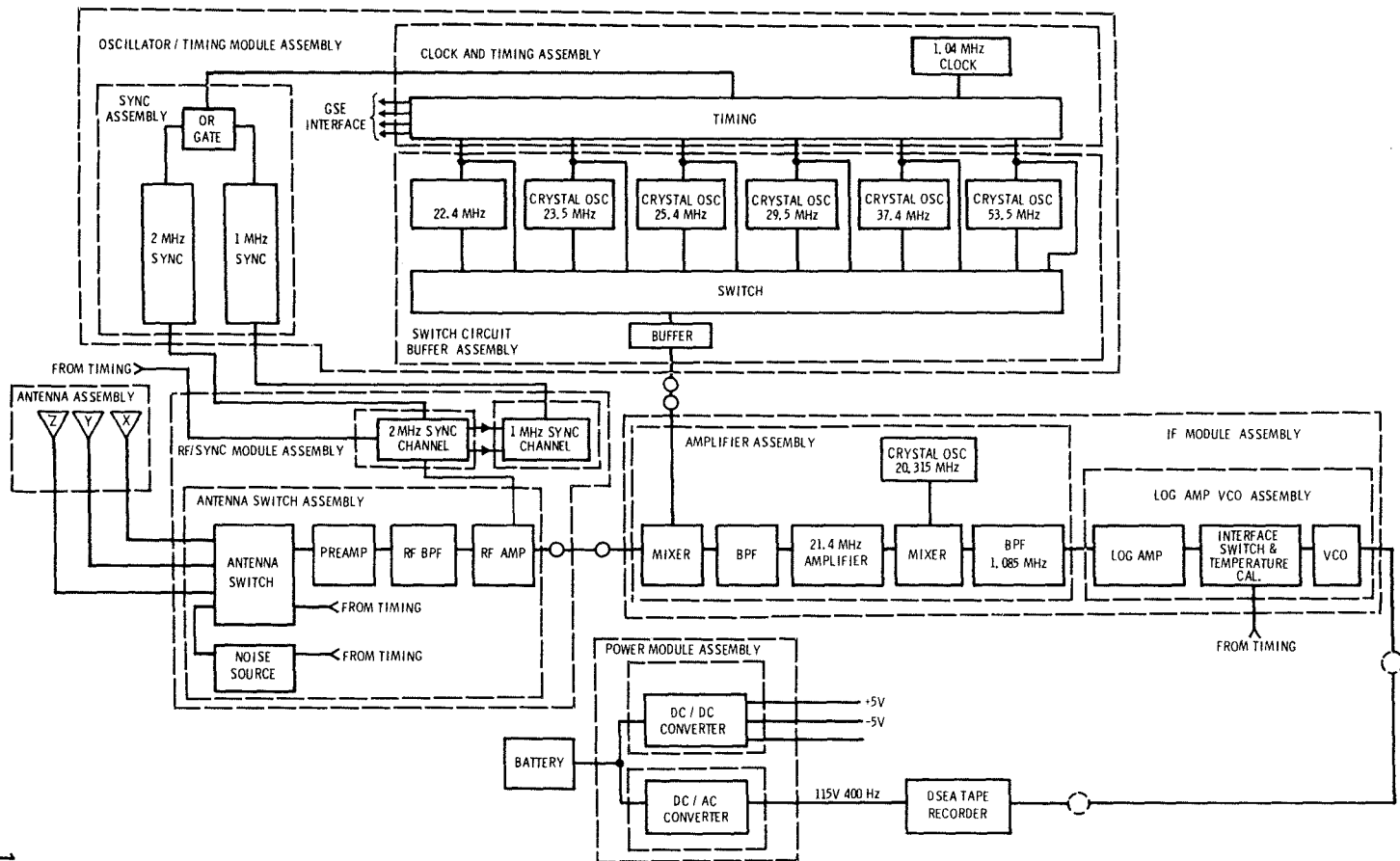
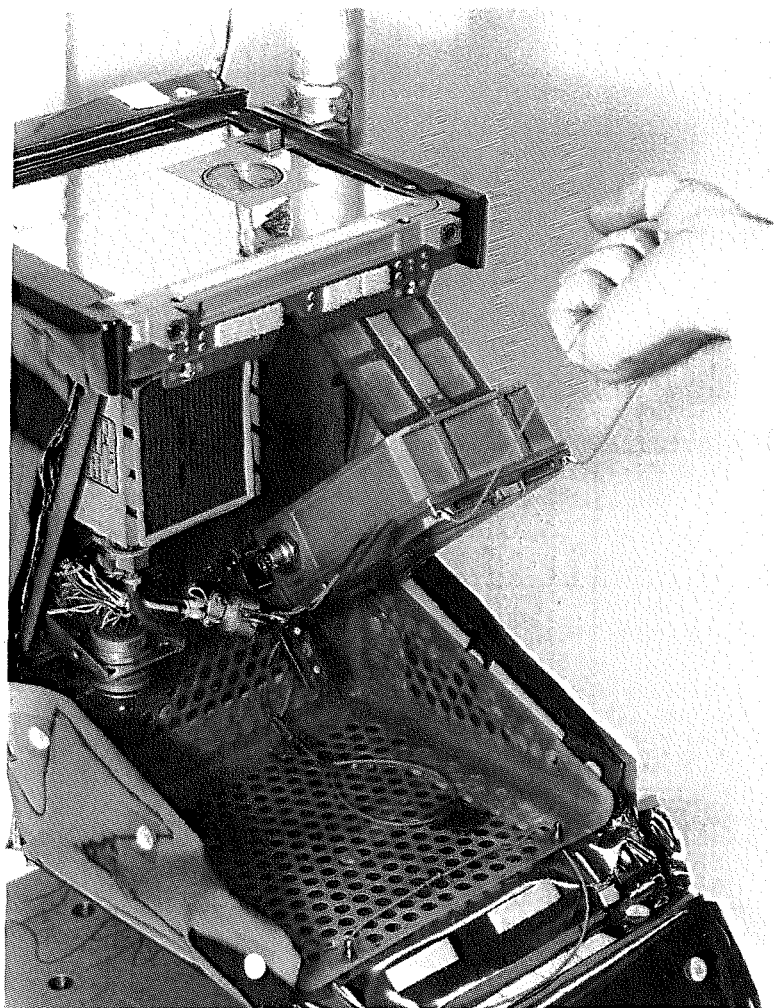


Fig. 7 Block Diagram of SEP Receiver



*Fig. 8 This photograph illustrates how the astronaut will remove the DSEA tape recorder from the receiver at the end of the last EVA for return to Earth.*

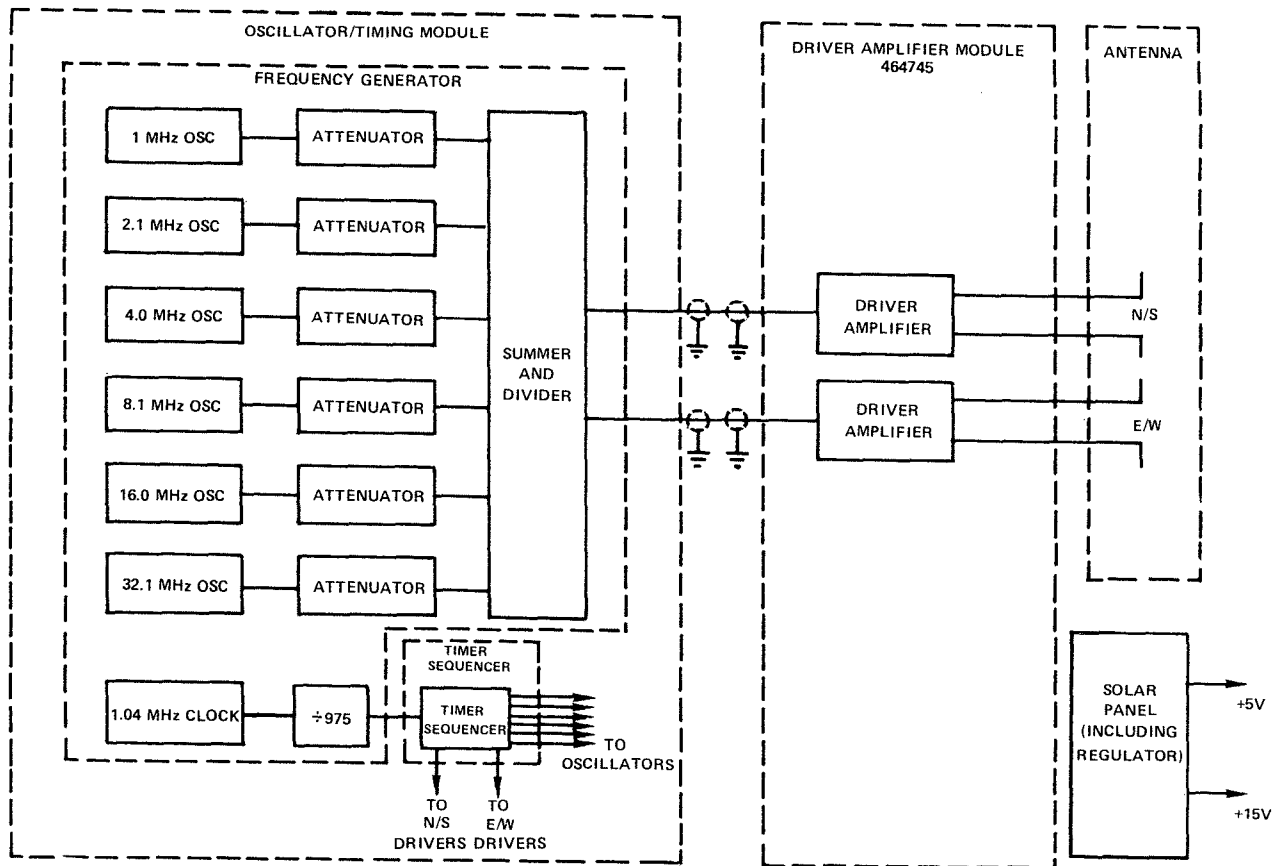


Fig. 9 Block Diagram of SEP Transmitter

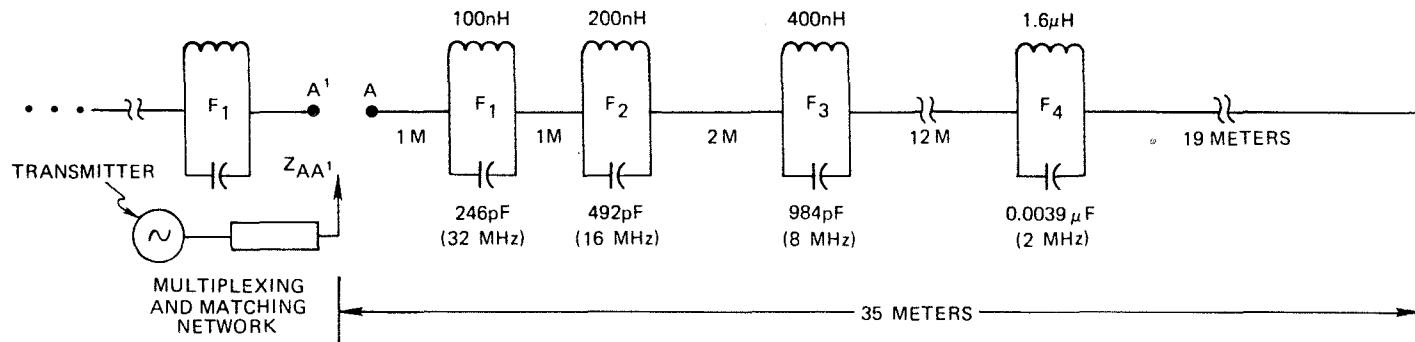


Fig. 10 This is an electrical schematic of the SEP transmitting antenna. Only one-half is shown because the antenna is symmetric about the mid-point. Total length (tip-to-tip) of the physical length of the antenna for each frequency used in SEP is 2, 4, 8, 32, and 70 meters.

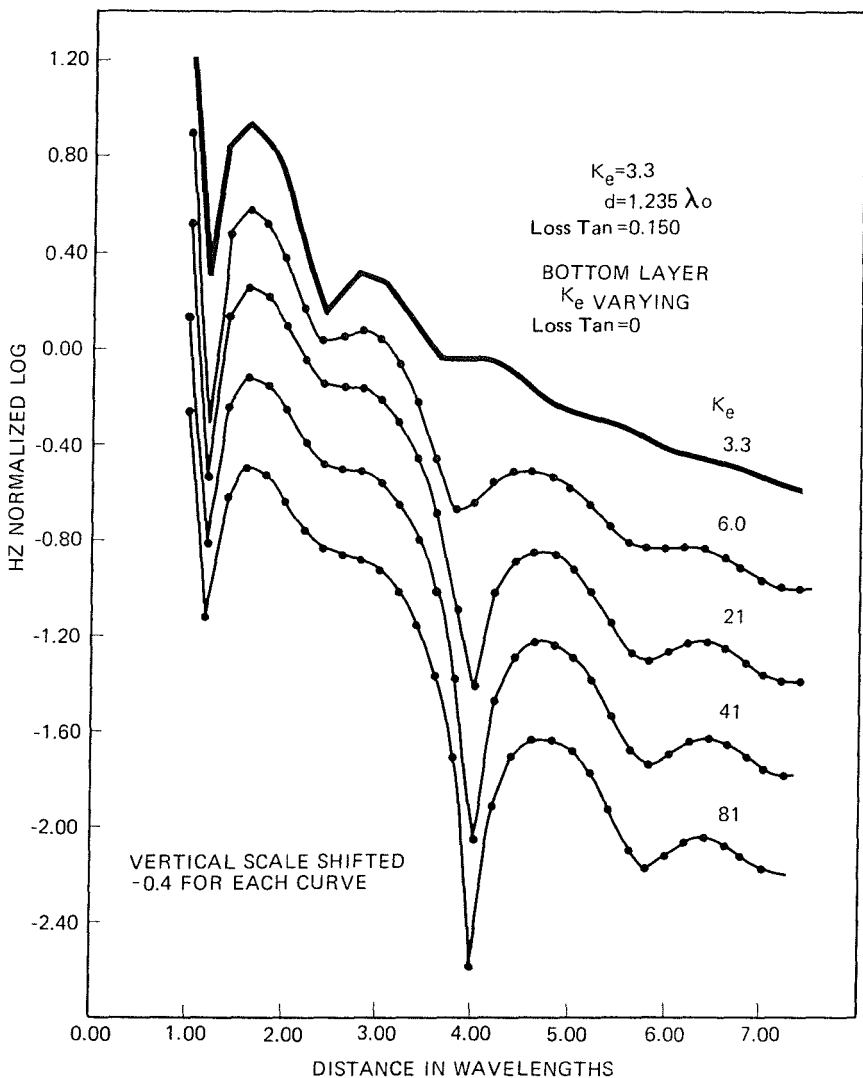


Fig. 11 These are the curves showing the theoretical vertical component of the magnetic field strength of the electromagnetic wave, normalized and plotted on a logarithmic scale versus distance in free space wavelengths between the transmitter and receiver. The top curve of this set represents what is expected for an infinite half space because there is no change in dielectric constant at the bottom layer. The interference pattern is that produced between parts of the wave traveling immediately above and below the interface. As the dielectric constant of the bottom layer is increased, reflections from the bottom layer have a more pronounced effect on the interference, becoming greatest for the dielectric constant of water (81). (After Kong and Tsang, private communication)



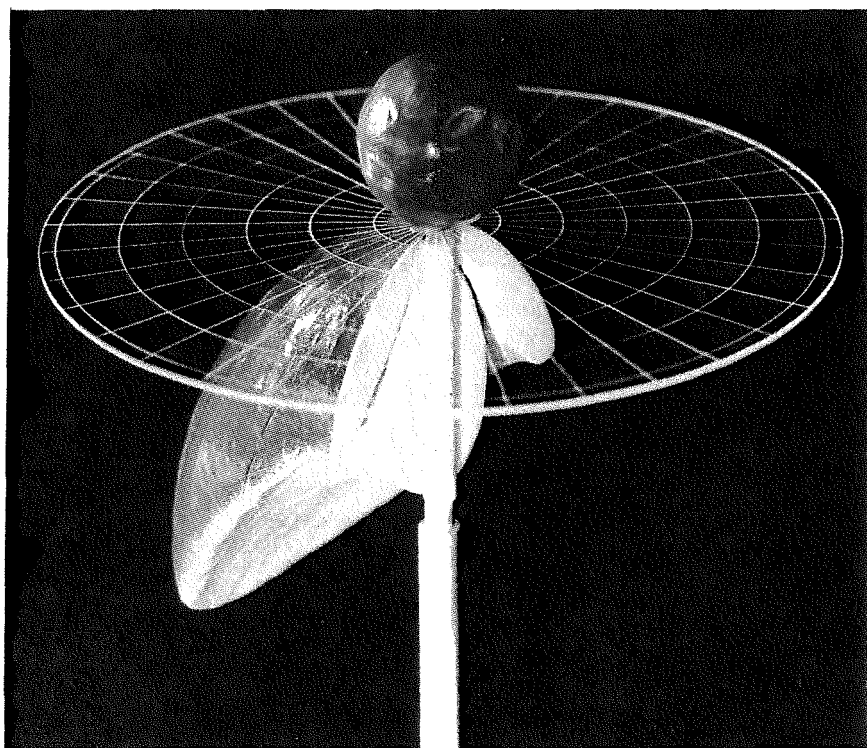
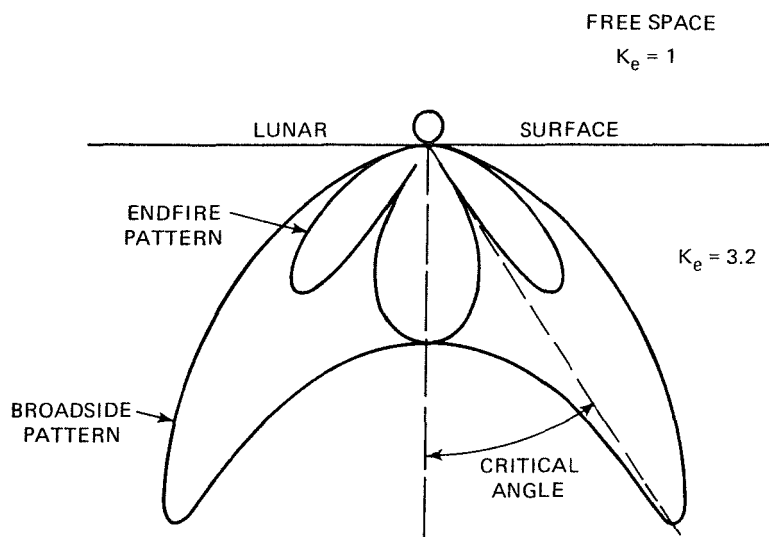


Fig. 12 This is a model of the idealized radiation pattern for the SEP transmitting antenna on the Moon.

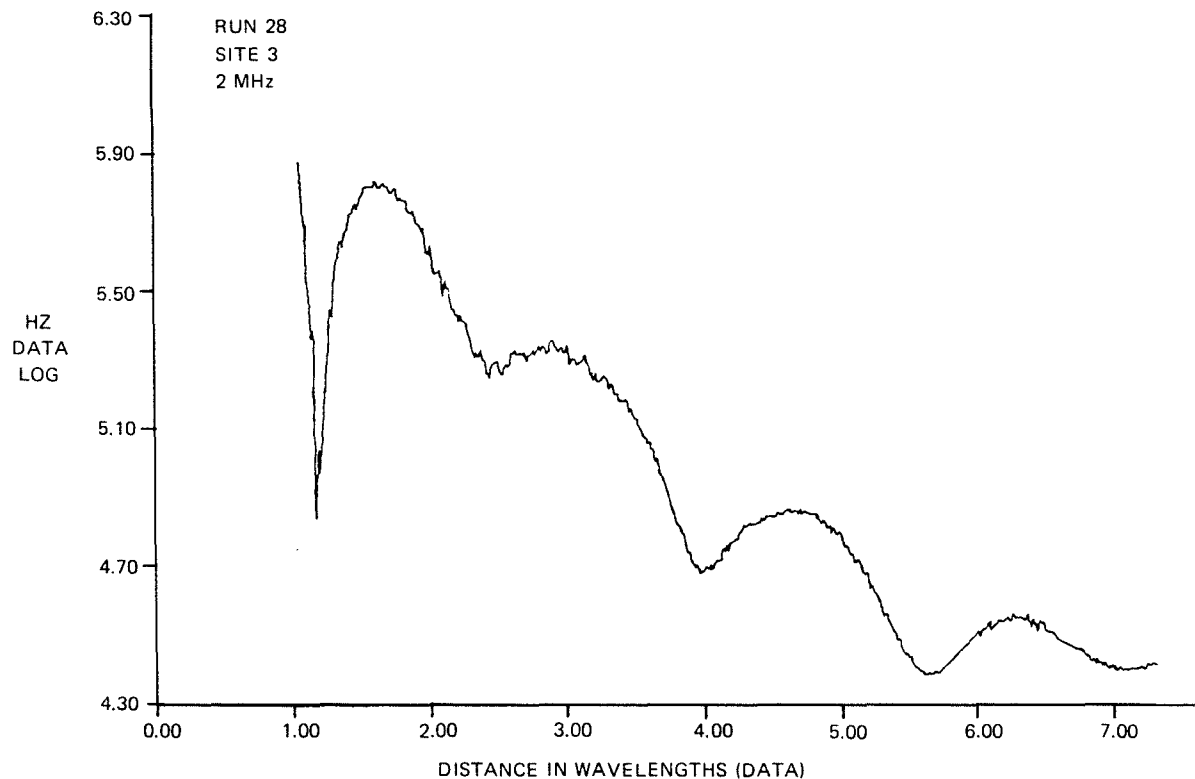


Fig. 13 This field data, taken on the Athabasca Glacier, shows the vertical component of the magnetic field strength of the electromagnetic wave at a wavelength of 150 meters. Note the similarity between this curve and the set of theoretical curves shown in Fig. 11.

extra recorder connected to the Field Evaluation Model (FEM), in addition to a magnetic tape recorder, that will not be used with the actual flight model. Why? To see the results immediately and thus save time in the event of difficulties with equipment. Remember, at that time, we were actually testing the equipment concepts as well as gathering data that would be used to gain experience in the interpretation process.

The FEM was used in 1972 in the tests on the Juneau ice fields. The objective there was to obtain data on several well-studied glaciers with which to increase our experience in the interpretation of SEP data. We obtained traverses over many features that may occur also on the Moon: semi-infinite half-space, buried ridge of rock beneath the ice, crevasses, and the condition of snow and ice with low density (about 0.2) at the surface and increasing steadily with depth (to about 60 meters where the density increases abruptly because the snow turns to ice). We even created a crater on one glacier in order to study its effect on our experiment.

In Fig. 13, we show a sample of data from the Athabasca glacier. The dielectric constant (or speed of travel of the radio waves) and the losses estimated from this pattern correspond well with the same quantities measured by previous investigators using different methods. The thickness of the glacier estimated from the interference pattern matches very closely the thickness as determined seismically and actually measured by others in boreholes. Such excellent correspondence between the results obtained with our SEP equipment and those obtained by other investigators with entirely different methods has given us great confidence in our equipment and techniques.

## OUR HOPES

The scientific exploration of the Moon in the Apollo program has led to surprise after surprise. The magnetic fields were much higher than expected. The lunar rocks brought back to Earth were extremely old (from 3 to greater than 4 billion years), showed strange compositions (compared with Earth rocks), and, perhaps most surprisingly, contained absolutely no water. The temperatures deep inside the Moon seem to be unexpectedly low but the heat flowing from the interior to the surface of the Moon is high—a paradox that is not yet resolved. If we receive SEP data back from the Moon, then we are sure that we can estimate the values of the electrical properties of rocks *in situ* on the Moon. Just that alone will be valuable. But we are also sure that we will “see” any layering that may be present. We will “see” any

lateral changes in electrical properties. We will easily "see" scattering objects, a very significant contribution towards understanding the local landing site.

We have designed our equipment to work in the hostile environment of the Moon. We are sure that it will work. We are less certain about exactly what we will find in the analysis of our data. Remember that the Moon has been full of surprises. We shall be disappointed if the SEP experiment does not uncover several more surprises. Their correct interpretation is likely to be far more valuable than the routine verification of the expected. Such surprises are the excitement of Science.

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