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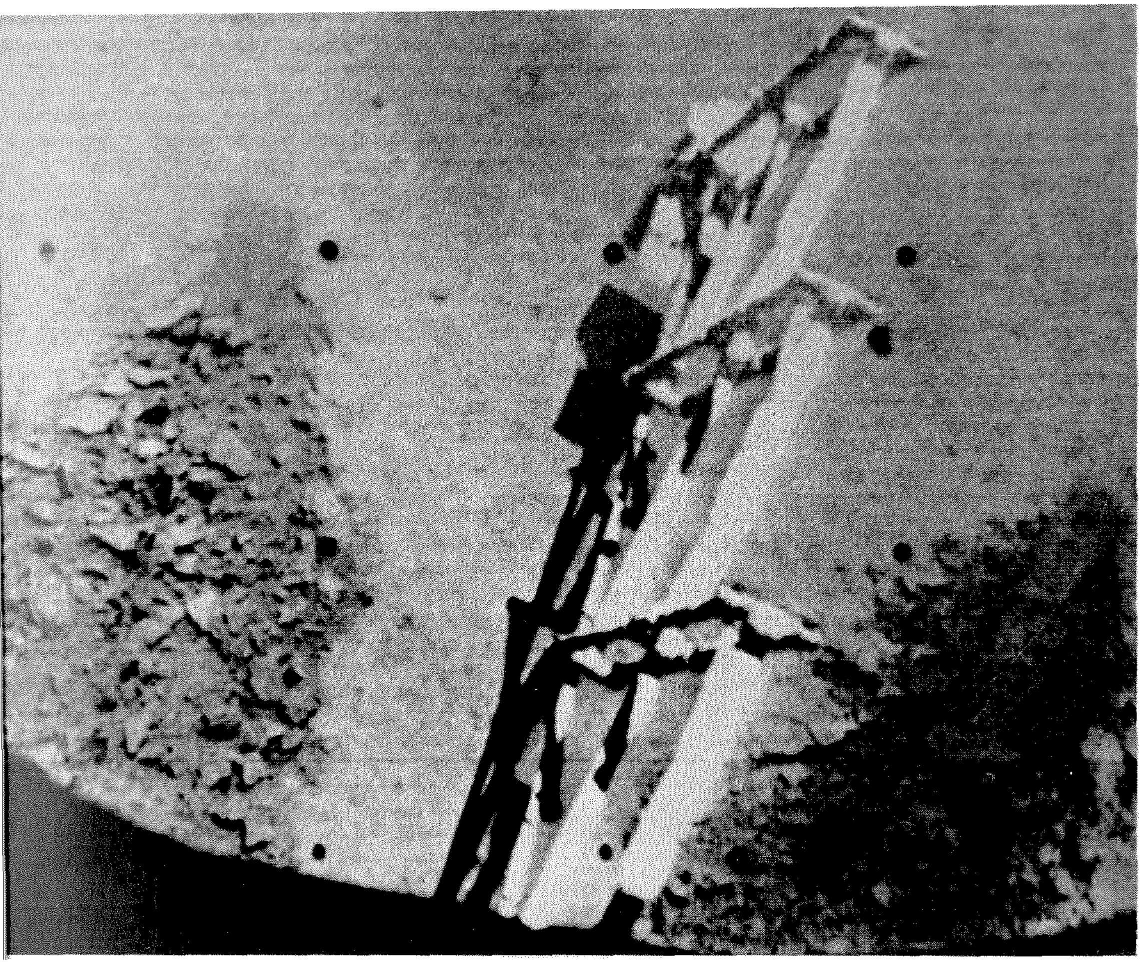


The depth of these trenches excavated in the lunar soil by the surface sampler is not apparent, as the picture was taken with the sun almost over the spacecraft.

DIGGING ON THE MOON

by Ronald F. Scott

Prior to the flight of Surveyor I in June 1966, plans had been made to launch seven "engineering" Surveyor spacecraft before flying any Surveyors with scientific apparatus aboard. These seven were to evaluate the feasibility of the soft landing technique. After the success of Surveyor I, however, the plans were changed to include the carrying of scientific experiments as early as possible.

Among the experiments which had been proposed and brought to an advanced stage of development was the surface sampler device. This instrument had originally been constructed to obtain a sample of the lunar surface for analysis by other equipment on board. The analysis apparatus, however, proved to be too heavy to be accommodated and was left out of the scientific payload plans in the early 1960's.

Subsequently, I proposed that the surface sampler be employed as a tool for measuring the *mechanical* properties of the lunar surface material. For this purpose it was suggested that the sampler be instrumented with strain gauges and an accelerometer to record the forces applied by the sampler to the lunar surface. At the time the experiment was conceived, the nature of the lunar surface, as it would be viewed by a landed spacecraft, was completely unknown. Materials ranging from extremely soft powders through vesicular rocks and lavas to solid rocks had been postulated. It was important, therefore, to have a device capable of yielding information on any of these materials. The surface sampler had this versatility.

Ronald F. Scott, Caltech associate professor of civil engineering, specializes in the fields of soil mechanics and foundation engineering. Through his association with Caltech's Jet Propulsion Laboratory he became interested in the mechanics of soil behavior on extraterrestrial bodies and, in 1963, proposed to NASA a soil mechanics experiment to be carried to the moon on a Surveyor spacecraft. When this experiment flew with Surveyor III in April, Dr. Scott, as principal investigator for the experiment, was largely responsible for directing its operations. "Digging on the Moon," has been adapted from a civil engineering seminar lecture given at Caltech by Dr. Scott on May 25.

In the summer of 1966 a study was made which indicated that a modified version of the surface sampler could be carried on Surveyor III. The sampler was to be substituted for an approach television camera which had been planned for the spacecraft but which, after the success of the Orbiter lunar pictures series, was concluded to be unnecessary. However, in order for the surface sampler to take the place of the camera, in the time remaining before launch it had to be modified to fit all the existing electrical and mechanical arrangements made for the camera. Consequently, the strain gauges and the accelerometer had to be abandoned.

In looking for a substitute measurement of the force applied by the surface sampler to the soil in a bearing or trenching test, engineers investigated the behavior of the d.c. electric motors used for operating the sampler. They found that the force could be estimated by measuring the amount of current taken by each motor during its operation. This, then, would be the only information of a quantitative nature that could be obtained from the device after it was modified.

Surveyor III was launched in April 1967. Its total scientific payload included a television camera and the nine-pound uninstrumented surface sampler. In spite of some difficulties following an abnormal landing, in which the vernier engines did not turn off at the planned height of 13 feet above the surface, the surface sampler and the television camera were successfully operated throughout the ensuing lunar day. However, the condition of the spacecraft telemetry prevented making measurements of the motor currents as had been intended.

The surface sampler consists essentially of a bucket which has a small door and is mounted at the end of an extensible trellis. Four electric motors control the operation of the sampler, moving it in specific ways: left and right, up and down, extension and retraction, and opening and closing the bucket door. Each motor can be operated on command to run for either 2.0 seconds or 0.1 seconds.

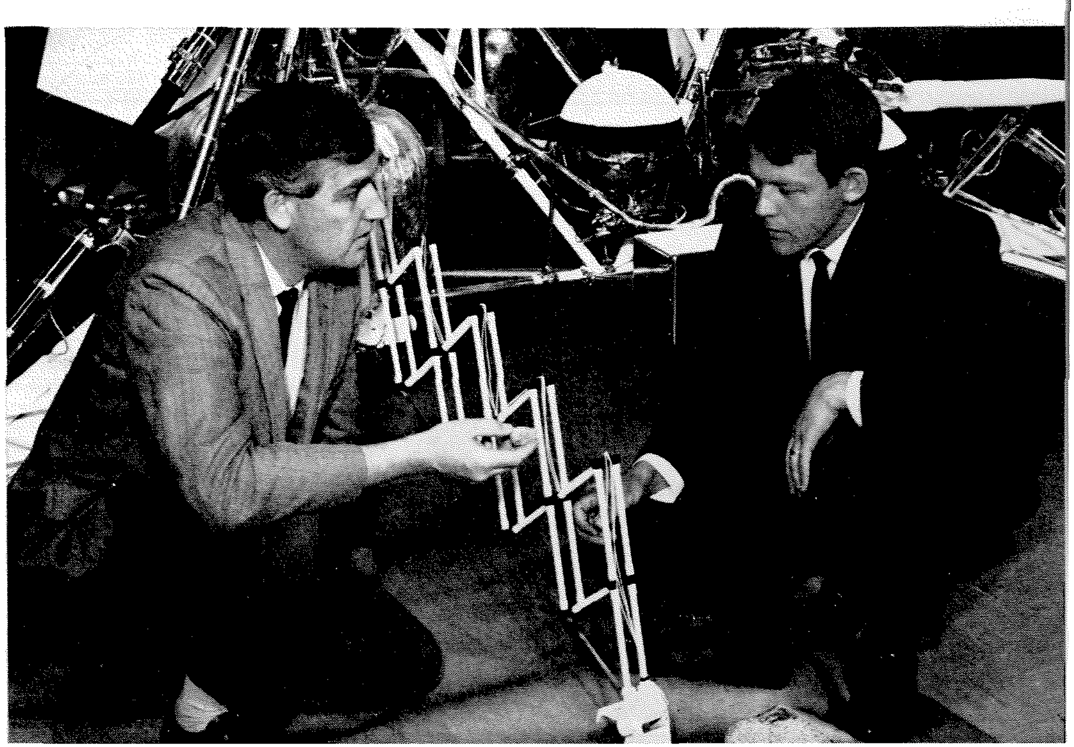
The distance moved by the scoop itself depends on which motor is being used, on the extension distance of the scoop, the load on the motor, and the temperature at the time the command is received. Since, on the lunar surface, the temperature of each motor can be approximately estimated, and since it is possible, from looking at the television pictures, to estimate the distance that the surface sampler has moved, an approximate calculation can be made of the force acting on the surface sampler scoop during that motion increment.

In addition, information can be obtained on the maximum forces applied to the lunar surface by a knowledge of the conditions under which each motor stalls. In some of the tests carried out, motor commands were sent until no further motion of the surface sampler was observed, indicating that a stall condition had been reached.

The area of the lunar surface which is accessible to the surface sampler is a space of about 24 square feet between spacecraft legs two and three. The sampler can touch the surface at a minimum distance of about 30 inches from its axis and can be extended to a maximum of about 60 inches.

The base of the sampler door is a small rectangular area measuring 1 by 2 inches. The sampler can be pushed into the lunar surface with the scoop door either open or closed and can be lifted and dropped to the surface from any height up to 30 inches.

On the first lunar day of operation, the surface sampler was directed in this way: First, narrow



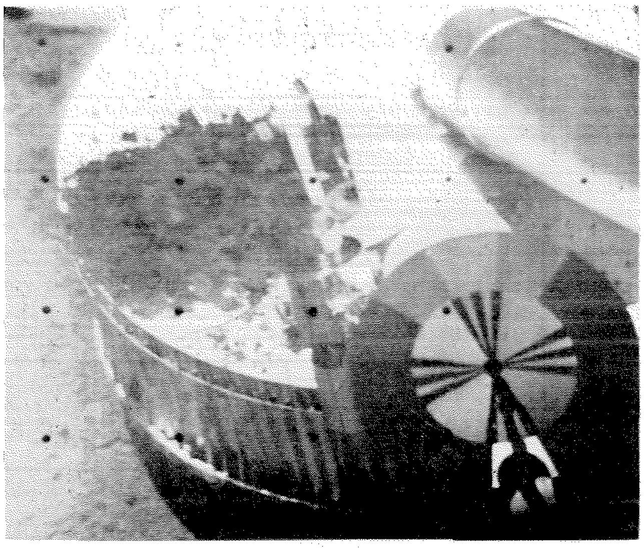
Floyd Roberson (right), JPL engineer and cognizant scientist to the surface sampler experiment, and Ronald Scott examine the sampler mounted on the full-scale model of Surveyor at JPL. The two engineers have worked together on the experiment since 1963. Roberson translates the requirements of the experiment, as described by Scott, into forms for the apparatus design engineers to work with.

angle surveys of the lunar surface in the area of the sampler operations were taken with the television camera. These were used to select suitable locations for the surface sampler testing.

Under normal conditions, a standard sequence of preprogrammed sampler operations would have begun at this time, starting with motion calibration tests. However, by the time the sampler temperature was high enough to begin operations, some difficulty had been experienced in rotating the mirror of the television camera. Consequently, after the calibration sequence had verified that the sampler was, in fact, operating in a reasonably normal manner, it was decided to make the first test on the lunar surface at a point within the field of view of the stuck television camera. (The difficulty with the camera was subsequently overcome.)

At a desk in the Surveyor Space Science Analysis and Command (SSAC) section of the JPL Space Flight Operations Facility (SFOF), Floyd Roberson, cognizant scientist for the surface sampler, and I were watching a television monitor which showed pictures of the sampler within a few seconds after they were taken. In addition, a polaroid picture was immediately taken of each television image and was handed to me to be referenced and cataloged. Next to us sat JPL's Jack Linsley, SSAC director, through whom all commands to the spacecraft passed.

Using the polaroid photograph and each picture as it appeared on the television screen and comparing them with our planned operations for that period, Floyd (and, at critical times, both of us) decided how many 2.0-second or 0.1-second commands were required to move the surface sampler to the point we had selected for a test. Floyd wrote down the commands necessary to move the sampler the required distance and handed them to Jack Linsley for verification. He passed them on to the controller for transmission to the spacecraft via the Goldstone Tracking Facility—all within seconds.



The pile of lunar soil dumped on footpad two by the surface sampler came from a clod which the sampler tried to pick up, but crushed. The circular object in the right foreground is the color calibration chart. Behind it is one of the attitude control jets.

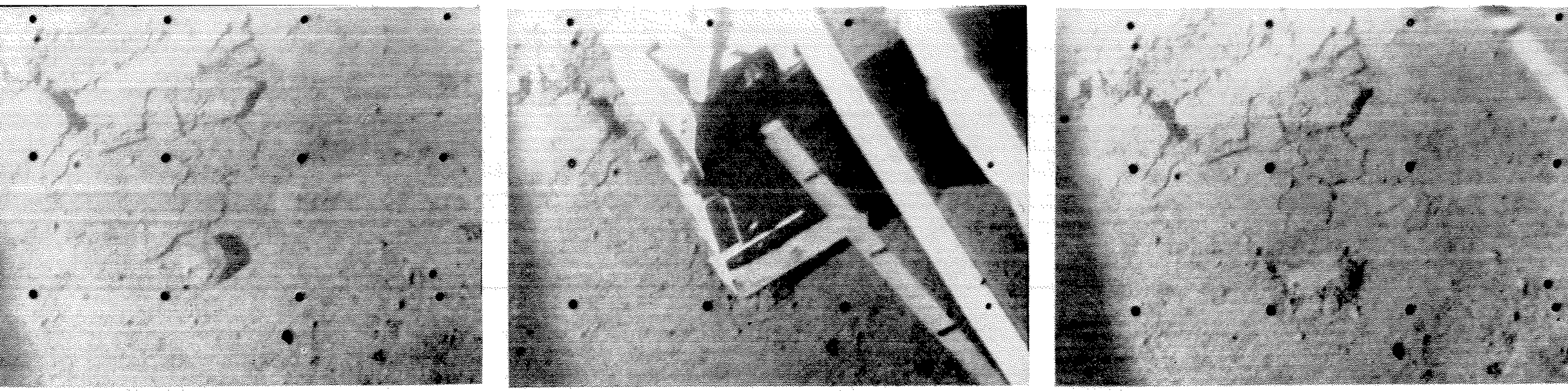
The commands to the sampler were followed by a command to the television camera to move, if necessary, in order to bring the sampler into its field of view and to take a picture. The picture which then appeared on our television monitor assisted us in deciding what move to make next. Thus the operation proceeded by a sequence of real-time pictures and decisions.

Several types of tests were carried out, since I was interested in a variety of material properties: (a) The mechanical strength of the lunar soil: this information is particularly important for use in the design of spacecraft for future manned and unmanned landings. (b) The density of the first few inches of lunar soil: it is of interest to compare this information with predictions about the density which have been made from earth-based radar and thermal measurements of the lunar surface. (c) The homogeneity of the lunar surface material. (d) The variation of the properties with depth. (e) An investigation of the nature of any accessible rocks. (Although many rocks are visible in photographs taken by Surveyor III, in its immediate vicinity only one or two small objects appeared as though they might be rock fragments.)

In the bearing tests, the sampler was driven downward until it was in contact with the lunar surface, and this position was identified. It was then driven further down by several successive 2.0-second commands until no further motion was observed. The motor was stalled. Narrow angle pictures were taken of the sampler scoop, both in the lunar soil and after the scoop was removed from the test point. From these pictures, the depth of penetration and the mechanism of deformation of the soil could be interpreted.

In the trenching operation, the scoop door was first opened and the surface sampler was commanded down into the lunar surface and then retracted back toward the spacecraft. The trench could be deepened, widened, or extended by successive passes through it.

During the formation of a trench, the lunar surface broke up into lumps and clods of material. These were believed to be either aggregates of finer-grained material or rock fragments. In order to determine just what their composition was, an attempt



The round object in the center foreground of the first picture is thought to be either a rock fragment or a soil clod. When the surface sampler is moved to bear down gently on the object, it disintegrates, indicating that it was a clod. A bearing test impression can be seen in the upper left corner of all three pictures.

was made to pick up one of the fragments which had been displaced during the trenching operations. However, when the scoop door was closed on it, the object was crushed. Apparently it was an aggregate of finer particles. A portion of the fragment which was still in the surface sampler bucket was taken to footpad two and dumped. An evaluation of its color characteristics was made by viewing the soil through the camera's color filters.

Other objects also appeared on the lunar surface which were brighter than the surface. One of these was picked up in the side of the surface sampler bucket and was brought closer to the television camera for viewing. When the bucket door was closed on the object (exerting a pressure of several hundred pounds per square inch) and it did not crush, it was assumed to be a rock fragment.

Later, when the surface sampler was moved in order to place this object on footpad two, the fragment was lost from the sampler. Apparently it was squirted from the spring-loaded door. When the loss was discovered, the sampler was lowered to the lunar surface, and the door was opened to see if the fragment had broken. No pieces were found inside the sampler bucket. It appeared that the fragment had been ejected intact.

The resistance of the soil to penetration by the sampler in an impact test arises from both the soil's static strength and its density. As the velocity of the impact increases, the part played by density becomes more important in comparison with the static strength of the material. Consequently, impact tests from different drop heights in which only the maximum penetration is measured can be used to evaluate this density approximately. The static strength is given by the bearing tests.

It appears from the surface sampler tests that the lunar soil is fine-grained material possessing a small amount of cohesion (in the order of a few hundredths of a pound per square inch) and an angle of internal friction of about 35 degrees, similar to that of a dry terrestrial sand. The impact and other test results appear to show that the material possesses an essentially normal terrestrial soil density of about 1.5 grams per cubic centimeter. When the sampler was pushed into the soil in the bearing test, the soil was displaced out of the way of the surface sampler, and it appeared that the material was very nearly incompressible.

The physical parameters describing the lunar soil which appear from these simple surface sampler tests have a broader significance than only their engineering value for the design of future spacecraft. They make possible scientific interpretations of the physical state of the material.

These results indicate that the very high porosities and low densities which had sometimes been postulated as being lunar soil conditions do not, in fact, exist throughout the first few inches of lunar soil at the Surveyor III landing site. Ideas about lunar surface processes have had to be revised. It had been thought that in the very high vacuum at the lunar surface, meteorite bombardment would produce particles with extremely clean surfaces. The fragments would, therefore, adhere strongly to one another and possibly also to spacecraft components. The measured small amount of cohesion seems to indicate that the particles are not extremely "clean," that primary bonding forces are not acting between lunar soil particles, and that van der Waals forces are more probably present.

The lunar soil has shown a tendency to adhere inside the surface sampler bucket with a cohesion of the same order of magnitude as in the undisturbed soil. The area in which the surface sampler operated appears to be fairly homogeneous in its properties, but there are distinct indications in the trenches that the material is firmer or denser with depth within a few inches from the surface. The deepest trench was approximately seven inches, and the material at that depth was relatively firm compared to the surface.

At this time only the most preliminary evaluation of the tests and their results has been made. But the surface has been scratched, and our knowledge has been extended in a most direct way.