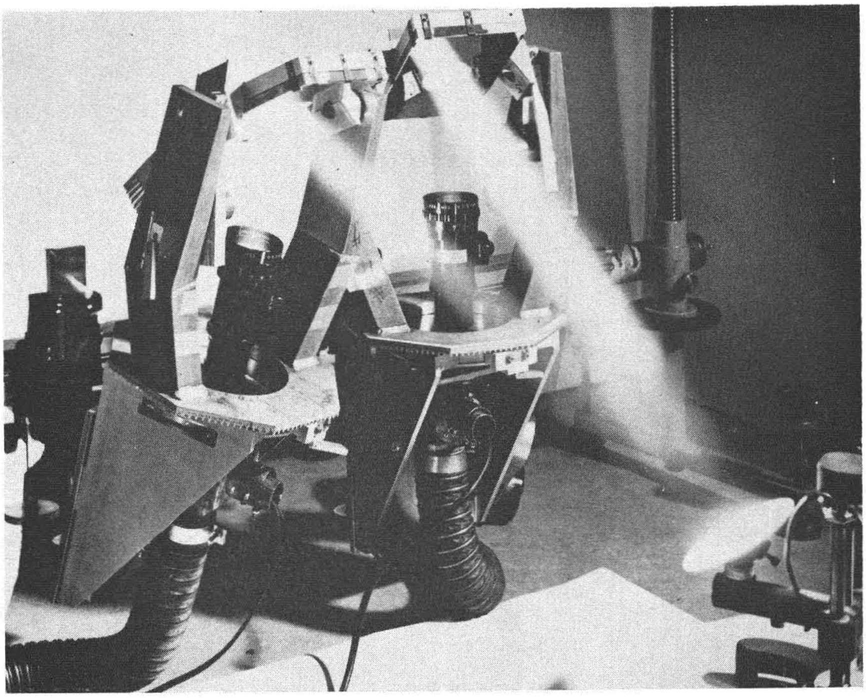

FRONTISPIECE. Prototype Surveyor stereoplotter. Each projector is a geometric analog of the Surveyor television camera. Glass diapositives approximately 11×11 mm. are used in the projectors, and the stereoscopic model can be viewed on the platen of a conventional tracing table.

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Surveyor Spacecraft Television Photogrammetry

Rough profiles can be drawn from lens-focus data and from shadow measurements

(Abstract on next page)

INTRODUCTION

LARGE-SCALE MAPS of the moon, required for investigation of lunar geology, can be made with television pictures from the Surveyor spacecraft. The U. S. Geological Survey, in cooperation with the Jet Propulsion Laboratory, has developed and tested methods of making these maps. The Surveyor television camera is inadequate for conventional photogrammetry, but maps made from its pictures are sufficiently accurate that small structural details can be delineated for preliminary geologic evaluation.

Pictures from Surveyor I were essentially

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monoscopic. The use of a mirror in the camera assembly produced a slight stereoscopic effect with a maximum possible base line of about 2 inches, but this effect is nearly useless for photogrammetric mapping. Sketch maps are made from Surveyor I pictures solely from lens focus information, shadow measurements, and knowledge of horizontal and vertical mirror-pointing angles. Future Surveyors may return stereoscopic pictures taken with base line of a foot or more, and maps made from these pictures will be much more accurate. Mapping of this kind will require the combined efforts of the geologist and photogrammetrist. Conventional aerial photographs show details which, for the most part, are familiar to the trained photogrammetrist. They very large scale Surveyor pictures, on the other hand, contain details familiar only to a student of lunar surface morphology and cratering phenomena. One untrained in these disciplines might recognize a few craters and fragments, but most of the details would be unfamiliar and easily misinterpreted.

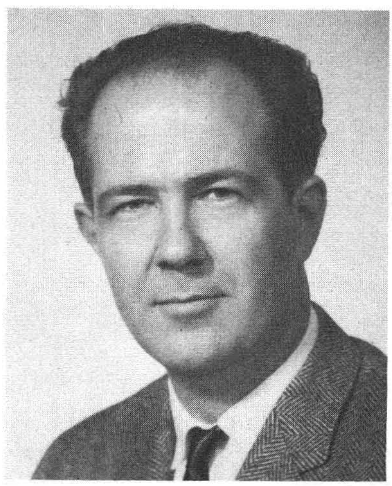
ABSTRACT: *Sketch maps made from pictures taken by the Surveyor television cameras are used to evaluate the relationship between small features on the lunar surface. An anaglyphic plotter specially designed for use with pictures from a two-camera Surveyor spacecraft has been developed for stereoscopic mapping. A prototype model of this plotter was used with test pictures to make a map at a scale of 1:1.5 and a contour interval of 7.5 mm. Planimetric sketches useful for geologic analysis can be made with monoscopic Surveyor I pictures by graphical and optical rectification methods. Rough prcfiles can be drawn from lens-focus data and from shadow measurements.*

SURVEYOR CAMERA GEOMETRY

The Surveyor camera is, in essence, a remotely operated transit. It transmits pictures with a known field of view taken at known horizontal and vertical angles. Operation of the camera is completely controlled from earth. The camera is mounted in a fixed position at an angle of 16° to the vertical axis of the spacecraft. Images are reflected into the camera by a mirror which is rotated by stepping motors in discrete steps of azimuth and elevation. The focal length of the lens is adjustable from 25 to 100 mm., but all television surveys are made using either the 25 or the 100 mm. focal length. Intermediate positions are used only in an emergency. The lens can be focused at any one of 50 focus settings. The approximate image format is 11 mm. square and is composed of 600 scan lines.

The precision of photogrammetric image reconstruction of Surveyor pictures on earth is degraded by correlated and uncorrelated errors of angular location of image elements. Correlated errors can be reduced by calibration of the system and by correlation of conjugate images from one picture to an overlapping one. The most serious errors, however, are the uncorrelated errors of image element location, which are random in their effect and can not be corrected by calibration, relative orientation of the pictures, or any other known method. For example, resolution is degraded by transmission noise and focus. The noise is composed of both coherent and incoherent components of the Surveyor pictures. Focus, because of the wide range of object distances in the high oblique pictures, is imperfect in most frames.

The ultimate limit of precision with which the location of images on a picture can be



RAYMOND M. BATSON

measured is determined by the resolution of the system. Perpendicular to the scan lines, this would be twice the distance between scan-line centers, or 36 microns in the image plane. Calibration of the Surveyor I camera shows that the resolution (at 15 percent relative response) along the scan lines is equal to the resolution normal to the scan lines.

Table 1 lists the most significant sources of angular error and their probable magnitude when the focal length of the lens is set at 100 mm. The figures for the resolution limit, random electronic distortion, optical distortion, and nonlinearity of the vidicon raster were derived by calibration of the Surveyor I camera. The other figures were derived by calibration of Surveyor test cameras. It should be noted that the figures are given for pictures taken with the narrow-angle focal length. When focal length is set at 25 mm., all distortions except those introduced by mirror-pointing inaccuracies are about four times as large.

Figure 1 shows the geometric relations in

TABLE 1. SOURCES OF ANGULAR ERROR IN PHOTOGRAMMETRIC MEASUREMENT OF SURVEYOR TELEVISION PICTURES

	Approximate Magnitude of Error (milliradians)
Uncorrelated errors:	
Resolution limit	±0.2
Noise introduced in transmission of picture to earth	Highly variable.
Imperfect focus	±0.2
Random electronic distortion in video scan	±0.2
Correlated errors:	
Mirror-pointed errors	±2
Optical distortion	Variable, but worst case between 0.3 and 1.
Nonlinearity of vidicon raster	Do.
Inaccurate location of principal point	10
Inaccurate measurement of principal distance	Ranges from 0 to 0.4.

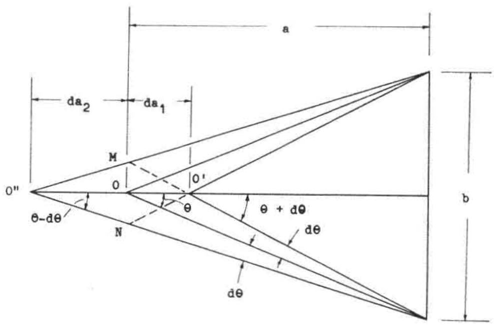


FIG. 1. Angular relationships in stereophotogrammetric measurement with Surveyor pictures. Distance b is the base line between camera nodes, a is the distance to an object O whose location is to be determined, and θ is half the angle of convergence between rays from the nodes to the object. The errors in distance measurement, da_1 and da_2 result from error in angular measurement, $d\theta$ at the nodes.

the plane containing the nodes or perspective centers for two stereoscopic pictures and an image element whose distance from the base line is to be measured.

The location of an object at O in Figure 1 could be determined stereoscopically within the boundaries of the quadrilateral $O''M\,O'N$. As base-distance ratios are small, the distance between M and N is very small, and the errors da_1 and da_2 in measurement of distance from the base line are the most significant errors.

Even if all correlated errors in a stereoscopic model of Surveyor pictures could be corrected by clearing vertical parallax, the relative orientation of the model still could not be determined to a precision better than the total precision of angular measurements of the image elements in each picture. The probable total error $d\theta$ in absolute angular measurement must, therefore, include the effects of errors in relative orientation. The root-mean-square of all the uncorrelated errors except electronic noise in Table 1 is about ± 0.35 milliradians. If this is also the error with which relative orientation is achieved, probable total error $d\theta$ would be $(\pm\sqrt{2})$ (0.35), or about 0.5 milliradians. This figure represents the minimum theoretical value of $d\theta$. Larger errors, as might be expected, were found when actual mapping was attempted with test pictures.

STEREOSCOPIC MAPPING WITH SURVEYOR PICTURES

A prototype of a special anaglyphic stereoplotter designed to make maps from stereoscopic pictures taken by a two-camera Sur-

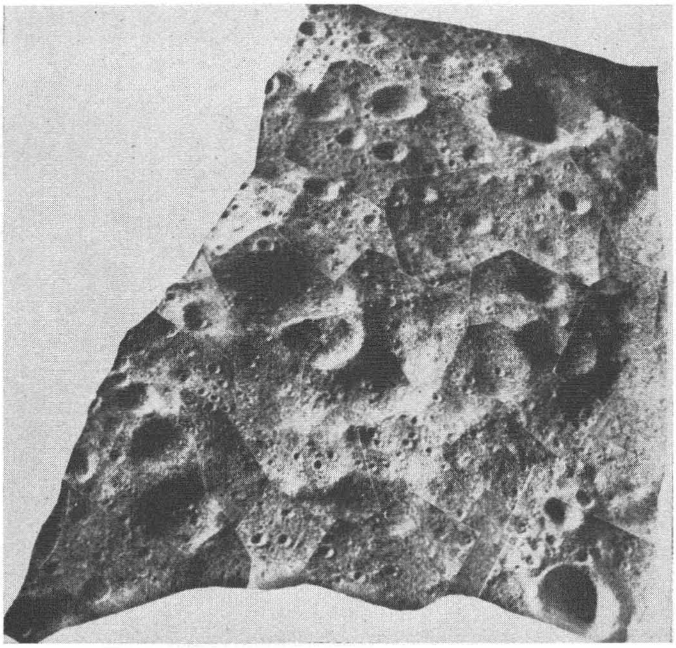


FIG. 2. Mosaic of television pictures from a simulated Surveyor camera. The surface model was made nearly a year before Surveyor I landed. Crater size-frequency distribution was extrapolated from Ranger spacecraft television pictures.

veyor (Frontispiece) has been constructed by the U. S. Geological Survey. First-order plotters could be used to make maps with some of the Surveyor pictures, but these plotters will not accommodate the full range of orientations present over most of the Surveyor panorama. Like conventional anaglyphic plotters, the Surveyor plotter consists of two projectors that are geometric analogs of the television cameras, and a tracing table. Conjugate glass diapositives 11 mm. square are placed in the projectors, the mirrors are set to the azimuth and elevation angles at which the camera mirrors were oriented when the pictures were taken, and the resulting model is projected onto the platen of the tracing table. Relative and absolute orientation are achieved by an initial setting of the mirrors and projectors to values derived from the telemetered information received at the time each picture was taken. These settings are modified slightly to clear parallax where the telemetered information does not supply sufficiently accurate data.

The prototype plotter was tested with pictures of a fresh lava flow near Flagstaff, Arizona, and with pictures of a model of the lunar surface made of sand. All pictures were taken with a slow-scan television camera similar to the Surveyor flight models. The images were recorded on 35 mm. film and printed on glass plates for compilation.

The lava flow pictures were used to test the potential of the system for measuring large structures at large distances when base-distance ratios are between 0.1 and 0.2. When base-distance ratios were greater than 0.2, conjugate images of the extremely rough surface of the lava flow were so dissimilar that stereoscopic fusion was impossible. Although the work was done with a prototype instrument which did not have the geometric fidelity and the fine adjustment capability desirable for production mapping, the experiments demonstrated the validity of the concept and the magnitude of errors which could be expected. The value of $d\theta$ (Figure 1), derived empirically by field checking range measurements (da_1 and da_2) was about 2 milliradians, resulting in a ranging error of ± 0.15 m. at 10 m. and ± 0.6 m. at 20 m.

The cimpilation of contour lines on distant features at small base-distance ratios was complicated by the efforts of the operator to find the surface he was attempting to measure and by the very rough and intricate nature of the topography. Although the stereoscopic effect appeared to be fairly strong, the operator could move the floating mark large distances horizontally along a line to the camera

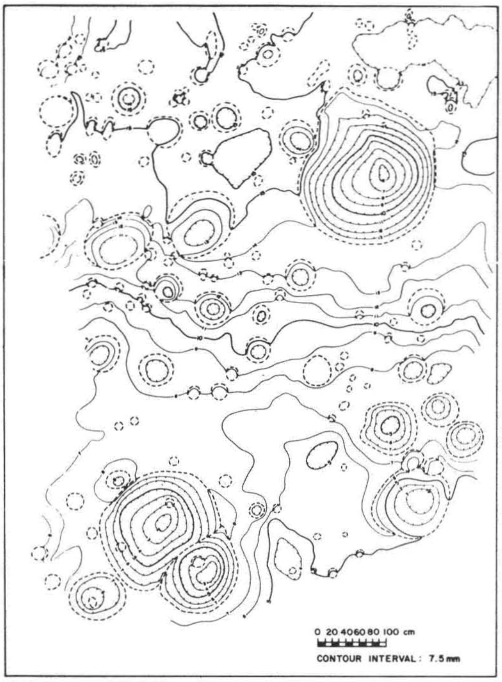


FIG. 3. Contour map of the surface model compiled with the Surveyor stereoplotter and pictures in Fig. 2. Physical measurement of the model showed that the map datum was tilted a total of 40 minutes along its greatest dimension, and after adjusting for this tilt, most elevations interpolated from contour lines were found to be accurate within ±4 mm.

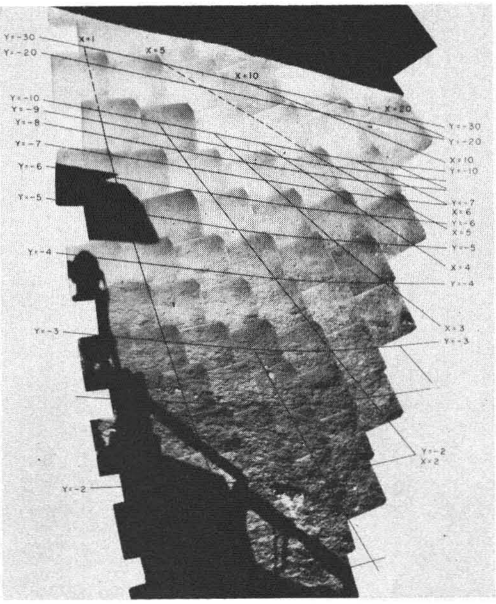


FIG. 4. Mosaic of Surveyor I pictures. A perspective grid of rectangular coordinate intersections has been superimposed over the mosaic for preliminary measurement of the surface. Numbers are in meters.

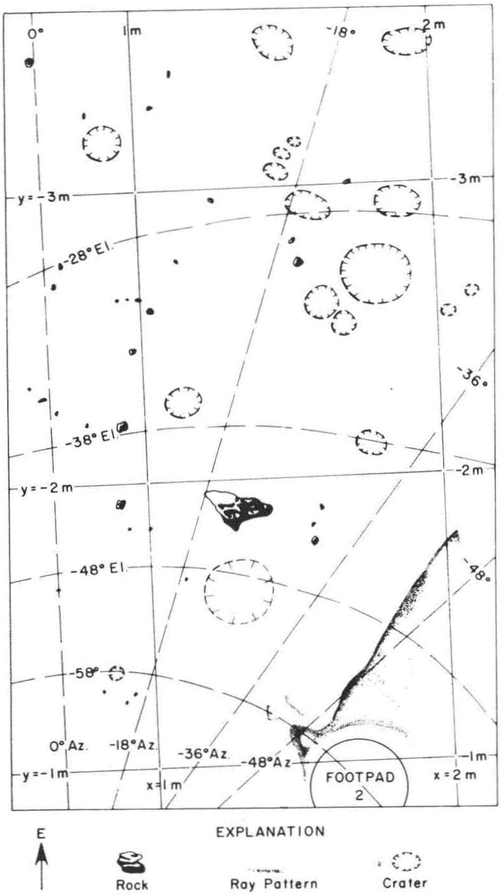


FIG. 5. Graphical plot of prominent features in part of a Surveyor I panorama. Dashed lines are the traces of frame centers on an assumed datum as the mirror is moved in azimuth or elevation. Most of the area covered in this section appears in Figure 4, but many of the features are not visible in that figure because they were plotted from pictures of the area under different illumination.

without materially affecting its appearance relative to the stereoscopic model. Contour lines were distorted along the line to the camera by an amount much greater than the depth of the surface details he was attempting to portray. The resulting contour map bore slight resemblance to a control map compiled by conventional methods, and the attempt to compile contour lines of the lava flow was abandoned.

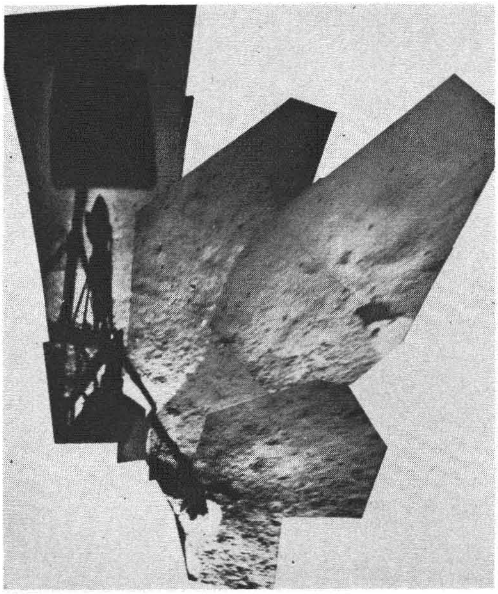


FIG. 6. Rectified mosaic of wide-angle pictures taken by Surveyor I. The prints were made with a projector from the Surveyor stereoplotter.

The effort to map a theoretical model of the lunar surface was more successful (Figures 2, 3). Figure 3 is a contour map of the top two-thirds of the model (Figure 2). Illumination angles were similar on conjugate frames, and the surface was topographically similar to that at the landing site of Surveyor I. Base-distance ratios were between 0.4 and 0.7. The map was compiled at a scale of 1:1.5 with a contour interval of 7.5 mm. The accuracy of the map was checked by physical measurement of the model. The datum of the map was found to be rotated only about 40 minutes of arc from that of the model, and after adjustment for this tilt more than 90 percent of the contours were found to be correct within one-half their interval. The empirically determined value of $d\theta$ in this case was on the order of 1 milliradian.

MONOSCOPIC MAPPING WITH SURVEYOR PICTURES

For preliminary work, a grid of plane rectangular coordinate intersections in meters similar to a Canadian perspective grid can be placed over an unrectified flat mosaic (Figure 4). From this grid, the approximate size distribution and location of objects of interest can be plotted on rectangular coordinate paper. The grid is based on the assumption that the surface of the landing site is coincident with the plane of the footpads of the spacecraft.

Detailed mapping is done by means of a combination of optical and graphical rectification methods. Where possible, surface orientation assumptions are based on the limited controls provided by focus ranging surveys and by shadow measurement. Well-defined features can be plotted on a grid of the intercepts on an assumed surface of vectors from the camera mirror rotation axis (Figure 5). A Surveyor stereoplotter projector is used to make rectified photographic prints from which a mosaic can be made (Figure 6). Combining the two methods, a rectified mosaic is made on which significant details visible on unrectified pictures but obscure or distorted after rectification are enhanced by hand retouching.

The small depth of field at the 100-mm. focal-length setting of the Surveyor camera enables measurement of the general configuration of the surface within about 10 m. of the

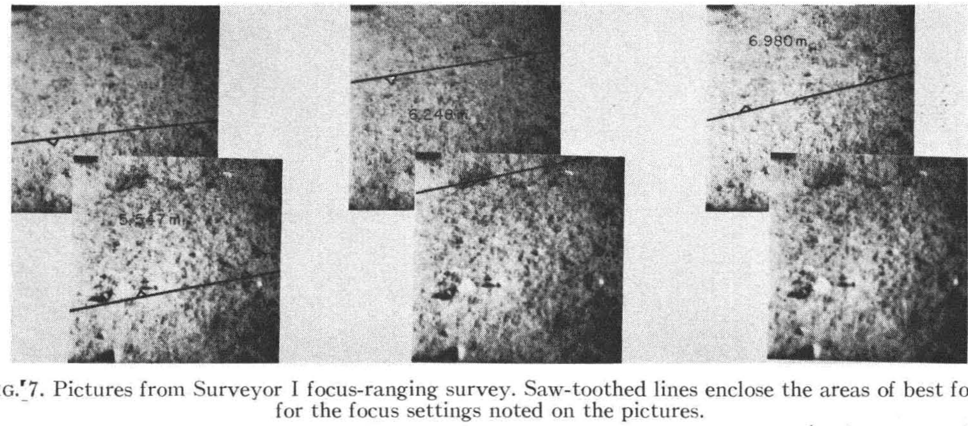


FIG. 7. Pictures from Surveyor I focus-ranging survey. Saw-toothed lines enclose the areas of best focus for the focus settings noted on the pictures.

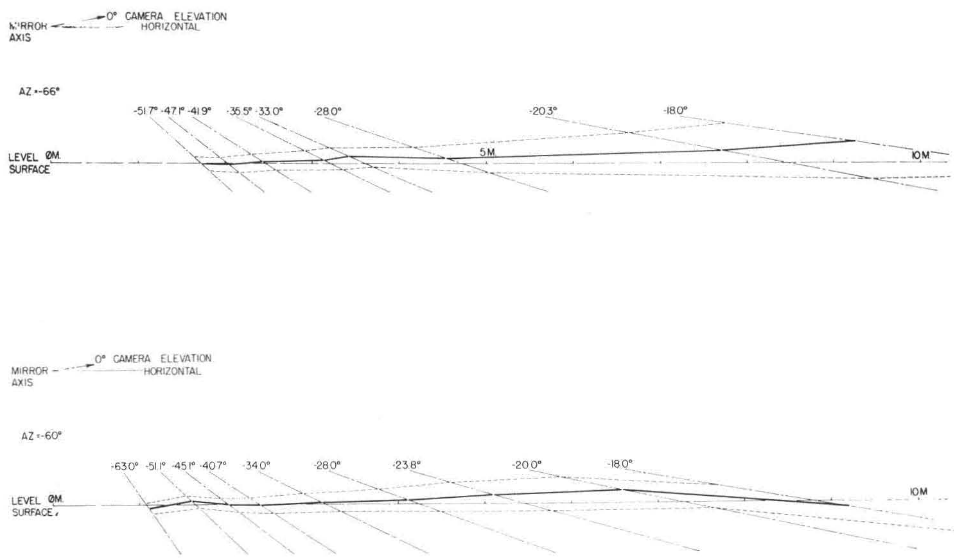


FIG. 8. Profiles of the Surveyor I landing site. Dashed lines show error that would be caused by a misinterpretation by 1 focus step. The plane on which the profiles are plotted is that generated by the centerline of a picture format as the camera mirror is rotated in elevation, and is only approximately normal to the plane of the spacecraft footpads.

spacecraft. Pictures taken by Surveyor I at the same mirror azimuth and at adjacent elevation settings are shown in Figure 7. The focus settings of each of the pictures are noted in the Figure, and the area of best focus is outlined on the pictures. The change in focus is clearly discernible on enlarged 8×10-inch prints of each picture. The pictures at the same azimuth and elevation were taken at consecutive lens "focus steps," and the resolution difference from one focus step to the next is discernible on the photographs. The precision with which distance is measured by focus, therefore, depends on the distance between focus settings, which increases with distance from the camera. Figure 8 is a series of profiles derived by systematic focus ranging; they show that the Surveyor I landing site is relatively flat. The dashed lines are the profiles that would have been derived if the analysis were incorrect by one focus step. Figure 9 shows the location of the profiles with respect to the spacecraft.

The measurement of shadows provides another method for determining object distances. Figure 10 is a picture taken by Surveyor I of the shadow of its own solar panel, the size and orientation of which are known. The shadow makes a fairly good stadia rod. The distance of the shadow from

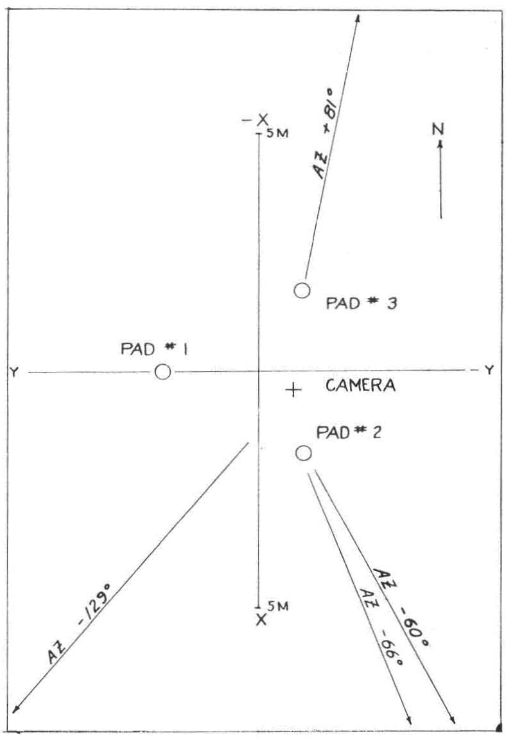


FIG. 9. Trace of the profiles in Fig. 8 on the Surveyor I landing site.

the camera can be easily computed from its angular width, linear width, and horizontal and vertical direction from the camera. Other parts of the spacecraft can be used in a similar manner to compute distances, although not as conveniently.

Conclusions

High-resolution pictures of the lunar surface taken by Surveyor spacecraft television cameras can be used to make useful base maps for geologic analysis. The measurement error with respect to the distance between the surface and the camera is very high compared with that of conventional photogrammetric methods, but relative location of surface features is sufficiently accurate for many kinds of geologic analysis.

Maps with contour intervals as small as 7.5 mm. can be made of surfaces within about 4 m. of the spacecraft from stereoscopic pictures with a base line of about 1.4 m. The precision with which any map can be made diminishes rapidly with distance, and contour mapping with stereoscopic Surveyor pictures at distances greater than about 20 m. from the spacecraft does not appear to be practical. If the surface being mapped is as smooth as that of the Surveyor I landing site, pictures with base-to-distance ratios as large as 0.7 can be fused stereoscopically, but as the surface roughness increases, stereoscopic fusion with large base-distance ratios becomes increasingly difficult.

Planimetric sketch maps can be made monoscopically with Surveyor pictures by graphical or optical rectification. The geometry of the rectification can be determined within broad limits by systematic focus ranging with the camera lens and be measurement of spacecraft shadows on the surface. The precision of maps made with monoscopic Surveyor pictures is probably lower by an order of magnitude than that of maps compiled with stereoscopic Surveyor pictures. They are comparable with sketch maps made by pace and compass methods on earth, both in use and in precision.

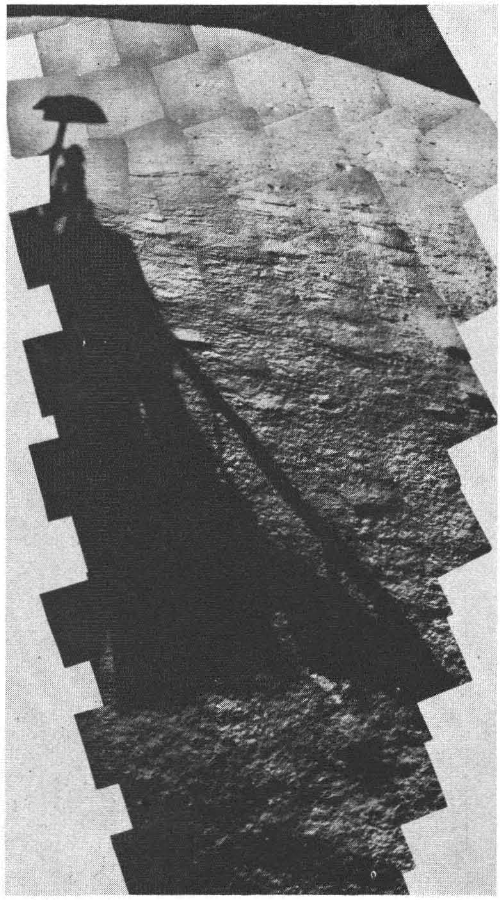


FIG. 10. Shadow of the solar panel of the Surveyor I spacecraft on the lunar surface. Distance measurements can be made from the picture of the shadow, given the size and orientation of the panel.