FRONTISPIECE. Semi-improved mosaic of a lunar surface model in the near-field. The lower edge of the model is about 5 feet from the camera, the far edge about 11.5 feet. See text page 170.

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Compilation of Surveyor Television Mosaics

Joined views of the lunar surface are needed in time to make camera adjustments before the mission ends.

(*Abstract on next page*)

INTRODUCTION

METHODS OF MOSAIC CONSTRUCTION and image analysis for Surveyor television were developed and tested by the U. S. Geological Survey, in cooperation with Jet Propulsion Laboratory, following tests of the Surveyor television experiment. The test results were used to develop data reduction methods for successful Surveyor missions. These tests were conducted on the Bonito Lava Flow near Flagstaff, Arizona and in the laboratories of the U. S. Geological Survey in Flagstaff.

The Surveyor spacecraft is designed to land on the moon, and, with various instruments, to telemeter information about the lunar surface to receiving stations on the earth. The first Surveyors carry a single slow-scan, high-resolution vidicon television camera as part of their instrument packages. Later missions may incorporate two such cameras on each spacecraft for stereoscopic examination of the landing site.†

* Publication authorized by the Director, U. S. Geological Survey. This paper presents the results of one phase of research sponsored by the National Aeronautics and Space Administration through the Jet Propulsion Laboratory, California Institute of Technology.

† Bird, T. H., "Large-Scale Lunar Photogrammetry," PHOTOGRAMMETRIC ENGINEERING, Vol. XXXII, No. 2, March 1966.

The initial camera operation is a 360° panoramic survey in the wide-angle mode, which provides a "quick look" for preliminary evaluation of factors affecting the recorded images, such as luminance and topography. Subsequent surveys are taken in the narrow-angle mode to produce optimum focus and exposure through a number of iterations. The number of iterations for focus may be reduced during two-camera missions by stereoscopic range finding, but trial-and-error methods must be used during single-camera missions. If all transmission and recording parameters are calibrated, optimum exposure settings for the camera can be determined by examining the recorded television images. Anomalies in camera operation may become readily more apparent by meticulous image analysis than by any other means, and corrective measures may be taken to ensure complete photographic coverage of the landing site.

ABSTRACT: *Field and laboratory tests of the Surveyor television system by the U. S. Geological Survey, in cooperation with the Jet Propulsion Laboratory, have resulted in techniques for assembling mosaics of Surveyor television pictures. Some mosaics, primarily the "analytical" type, are used to analyze data content of the television pictures to provide the basis for improvement of further survey sequences during mission operations. The value of these mosaics was demonstrated during the successful mission of Surveyor I. Other types, the "semi-improved" and the "spherical" mosaics, are used primarily for post-mission data analysis. With these techniques, the mosaic team of the U. S. Geological Survey has learned to assemble analytical mosaics at the speed at which the camera takes pictures: a full panorama of about 1,000 frames in less than 2 hours.*

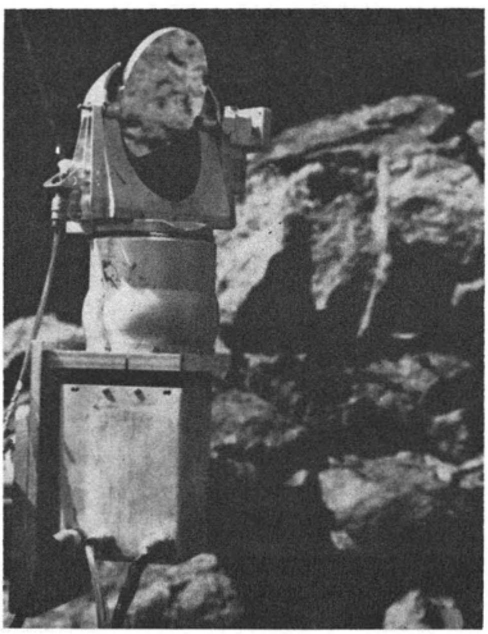

FIG. 1. Prototype Surveyor television camera built by Hughes Aircraft Company. The mirror rotates in step detents in azimuth and elevation and reflects images into the camera.

Single pictures taken by the Surveyor television camera are very difficult to interpret because of the low resolution in the wide-angle mode, the very small field of the narrow-angle mode, and peculiar orientations in both modes produced by a rotating mirror.

A photographic mission of this type is so complex that the above analyses can be made only by reference to mosaics of the television frames compiled as they are received and completed in time to revise sequences during the life of the spacecraft. As time becomes available, during and after the mission, the mosaics are refined and used as photographic base material for extensive scientific examination and analysis of the lunar surface.

CAMERA GEOMETRY

A prototype of the Surveyor television camera, built by Hughes Aircraft Company, is shown in Figure 1. The camera is mounted rigidly on the spacecraft, with its optic axis pointing upward. A mirror, which rotates in 3°-horizontal steps and in $2\frac{1}{2}$°-vertical steps, reflects images into the zoom lens, which focuses them on the faceplate of the vidicon tube in the camera. Because the camera is fixed, images rotate on the vidicon faceplate as the mirror is rotated in azimuth. The mirror can be rotated a full 360° in azimuth, and in elevation from 65° below spacecraft horizontal to 45° above it before serious vignetting by the camera structure takes place.

Each camera has a zoom lens, which is operated only in the end-focal-length positions of 25 and 100 mm. and can be focused from 4 feet to infinity in 50 discrete focus steps. A narrow-angle frame taken with the lens at its 100-mm. focal length has a field of view of approximately 6°. The 25-mm. focal length presents a field of view of about 25° in each frame, but the resolution of surface elements is much lower than that of the narrow-angle pictures.

The field of view of the camera is determined by the image size (11 mm. square) on the vidicon faceplate and by the principal distance of the lens, which varies with focus and focal length.

Mosaic Projections

A mosaic of Surveyor television images can be compiled almost entirely analytically, with reference to image content only as a check, if the appropriate parameters of camera geometry are known and if no anomalies occur in the survey sequence. In practice, although the field of view in each frame varies with focus changes and the mirror-pointing angles are not perfect, mosaics sufficiently clear for mission analysis can be

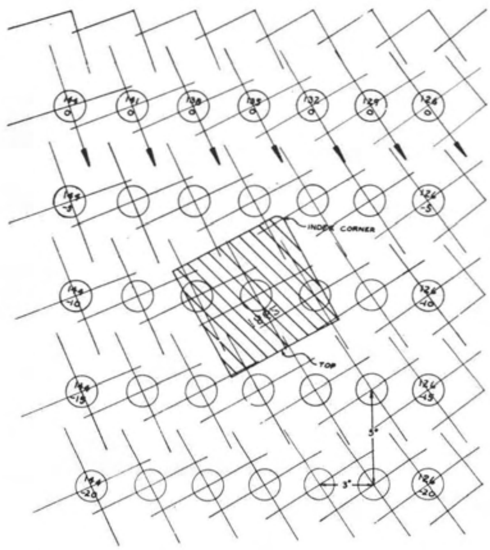

FIG. 3. Part of the control grid for a narrow-angle mosaic. Crosses show theoretical position of frame center lines for the azimuth and elevation shown in the circles at the centers of the crosses. Hatched square is the location of the frame taken at 135° azimuth, −10° elevation.

assembled on predrafted control grids. These are compiled by conventional cartographic methods through knowledge of camera geometry.

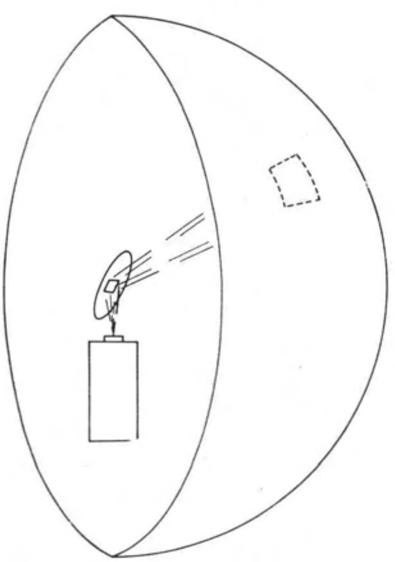

FIG. 2. Diagram of the Surveyor spherical mosaic analogue. The field of view of the camera forms a square of constant size on a surface at a constant distance from the camera for a given focal length lens.

If the television camera and mirror assembly is at the center of a sphere, the field of view can be traced on the surface of the sphere for each mirror setting (Figure 2). The diameter of the sphere is proportional to the size of the frame. If the frame size is fixed at 48 mm.×48 mm.,* the sphere diameter in the wide-angle mode would be about 8 inches and in the narrow-angle mode about 34 inches. Therefore, a mosaic to display a full 360° panorama of unrectified narrow-angle pictures 48 mm. square can be assembled only on the inside of a 34-inch sphere. The basic controls for positioning the individual photographs in the spheres are 5° parallels for camera mirror elevations from −65° to +65°, and 3° meridians over 360° in camera mirror azimuth. A scribed cross which delineates frame rotation at each azimuth-elevation position has proved to be the most useful method of controlling frame rotation. The "top" of the frame is indicated by an arrow on the rotation cross (Figure 3).

* This is the size of the photorecorded image provided by the Ground Data Handling System at Jet Propulsion Laboratory during mission operations.

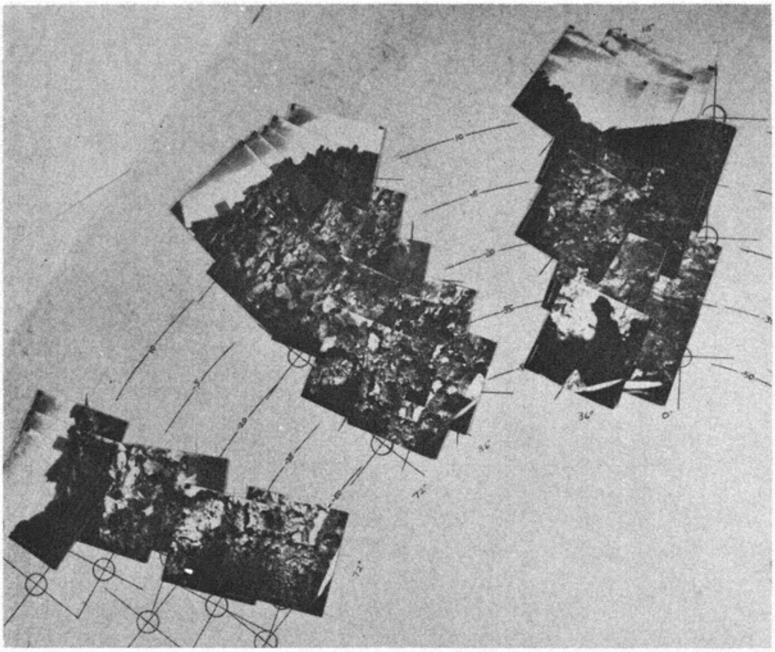

FIG. 4. Part of a mosaic of wide-angle photographs from a field test on "flower" projection. The angular dimensions of each segment correspond approximately to those of a flat mosaic of a standard narrow-angle sector.

Supplemental control points, such as frame members of the spacecraft or mirror pointing correlations derived by calibration of the cameras, may be added to the basic control grid by standard cartographic methods.

Because the time for making mosaics during a lunar mission is short, a mosaic of a full panorama can best be assembled by a team of technicians, each working on a different part of the mosaic. This is obviously impractical using spheres. A flat mosaic, however, can be constructed with unrectified prints if

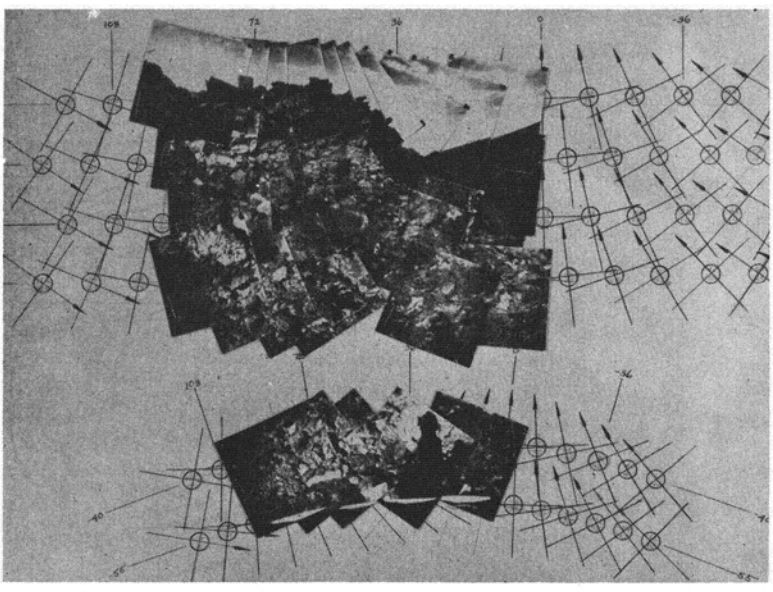

FIG. 5. Combination cylindrical and conic projection of a part of a wide-angle panorama mosaic.

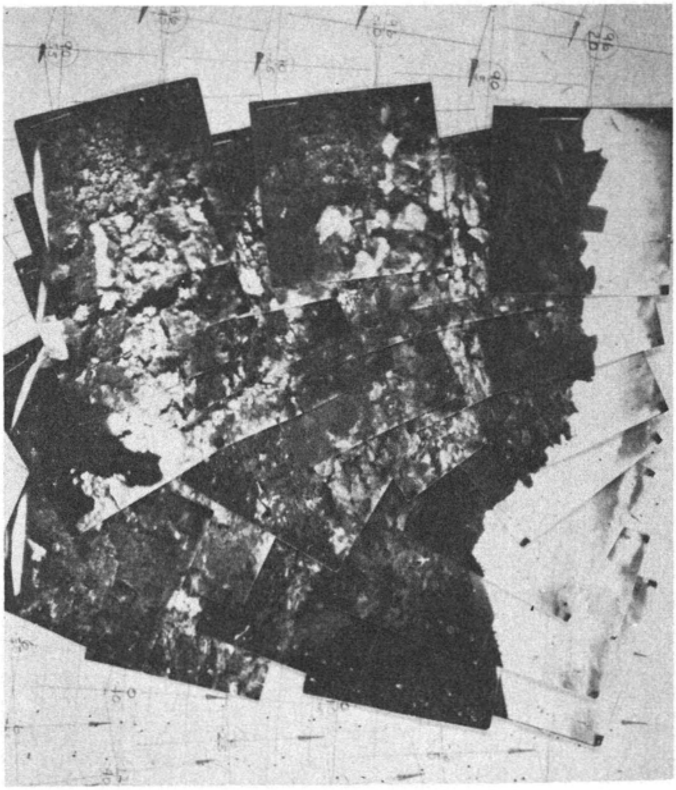

FIG. 6. Cylindrical projection of part of a wide-angle panorama mosaic. Images match fairly well vertically, but are widely separated horizontally in the lower elevations.

some distortion is acceptable and if each mosaic sector is only a small part of the full panorama. The grid pattern on the sphere just described can be projected onto a cylinder tangent to the sphere along a given meridian. Figuratively speaking, the cylinder is then cut longitudinally and spread on a flat working surface. Sectors extending 18° in azimuth either side of the line of tangency and from the −65° elevation to the horizon are of a practical size for the narrow-angle flat mosaics. Orientation crosses, arrows, and other annotations used on the spherical grids as shown in Figure 3, are retained on the flat projections.

Wide-angle mosaics present a different problem. Although the field of view of a wide-angle frame is approximately 25°, the pictures produced during the mission are only 48 mm. square. Where the mosaic of a sector of narrow-angle pictures is more than 1 foot by 2 feet in area, the same angular coverage in wide-angle format is about the size of a standard postcard. Several wide-angle mosaic projections were tested, including an appropriately reduced narrow-angle sector projection arranged in a circular array like the petals of a flower (Figure 4). This method isolates, in wide-angle format, the approximate areas that appear on the narrow-angle mosaics, and facilitates image correlation between the two types.

Wide-angle mosaics arranged this way are disconnected, however, and it is difficult for the analyst to get a quick, overall view of the terrain. A composite cylindrical and conic projection was developed to overcome this difficulty. The cylinder is tangent to the 0° elevation of the sphere, the cone to the −55° elevation. This produces a panoramic mosaic of the scene down to about the −35° elevation and a separate panorama of the scene below this elevation (Figure 5). Distortion in experimental mosaics was within acceptable limits. For mission analysis, it has proved feasible to extend the cylindrical projection to −65° and eliminate the conic part altogether (Figure 6).

It is ironic that the wide-angle camera-operation mode, which produces the smallest

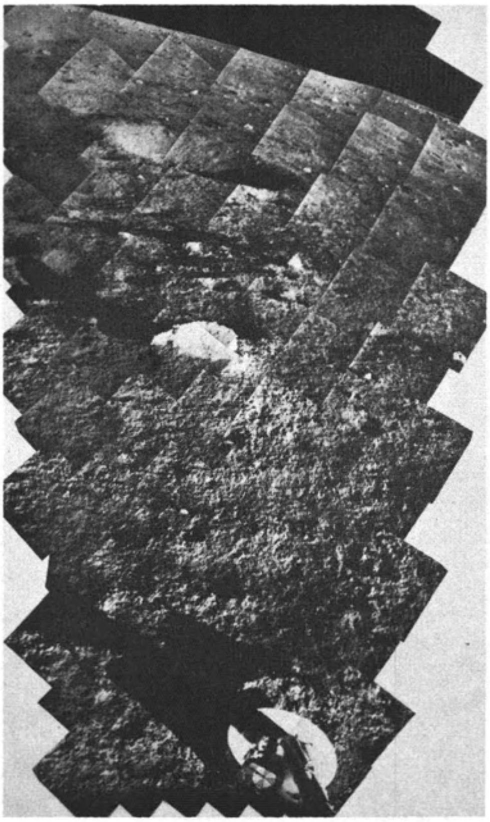

FIG. 7. Semi-improved mosaic of pictures from Surveyor I. The camera is looking to the southeast during late lunar afternoon. The sun is approximately 10° above the western horizon. The total field of view is about 60° vertically and about 30° horizontally. The horizon is approximately level, but appears sloped because the camera is mounted with a 16° tilt to the northeast. The footpad (lower right) is about 250 mm. in diameter and approximately 1.8 m. from the camera. Grains as small as 0.5 mm. in the vicinity of the footpad are resolved on the original negatives. The rock in the center of the field is about 0.5 m. long and about 5 m. from the camera. On close examination, its texture appears vesicular, or possibly coarse-grained with intergranular pore spaces. The crater between the rock and the horizon is about 3 m. in diameter about 11 m. from the camera. The horizon is about 2.5 km. distant. Shading at the bottom of the mosaic is camera structure vignetting.

amount of pictorial information, should cause the most difficulty in developing mosaicking techniques. Part of the difficulty is that plotting all possible frame centers and their attendant rotation markers and arrows would result in a hopelessly undecipherable tangle of lines. The wide-angle survey sequence must therefore be designed in advance of the mission so that appropriate projection grids may be drafted. Any deviation from the planned sequence then requires that the mosaicker interpolate the frames and, although this is fairly easy to do, it introduces a source of possible confusion and error if the mosaicker is working at high speed under the pressures of mission operations.

Mosaic Types, Uses, and Construction

The spherical mosaic type was discussed first here, not because it is the simplest to assemble, but because the concepts involved are basic to other mosaic types. The analytical flat mosaic is actually the first type that is constructed during a Surveyor lunar mission because it can be done quickly enough to provide input to further mission command sequences.

Equipment required for construction of analytical mosaics consists of a supply of $16\times32\times\frac{1}{2}$-inch tackboards of cellotex, cork or similar material; a supply of prepared mosaic projections for the appropriate sectors; staples, and a hand-stapling machine from which the base has been removed so that the staples may be driven directly into the tackboards.

A prepared grid (Figure 3) is placed on a tackboard panel, and the photographic prints are stapled to it. Ten grids are required to present a full panorama of narrow-angle frames whereas only one is required for a wide-angle panorama. The circled line intersections represent center points for each picture plotted at the correct mirror elevation and azimuth setting. The direction of the crossed lines at the circled intersections represent the correct orientation of the center lines of the photograph as delineated by the reseau pattern on each frame. The arrowhead on one of the intersecting lines represents the top of the frame as it would appear on a television monitor. It is helpful to staple the prints in such a way that the staples are covered by other prints, and to place a sheet of clear plastic over the completed mosaic sector.

Because the camera may not execute commands correctly, the mosaicker should examine the areas of overlap between each new frame and the ones that have already been stapled to the board, to make sure that he is placing the frame correctly. If conjugate images are not present, and image quality in the overlap area is degraded, the mosaicker may hold the frame and make a similar check with the next frame, until he has verified that the frames are being received in their correct order. If conjugate images ob-

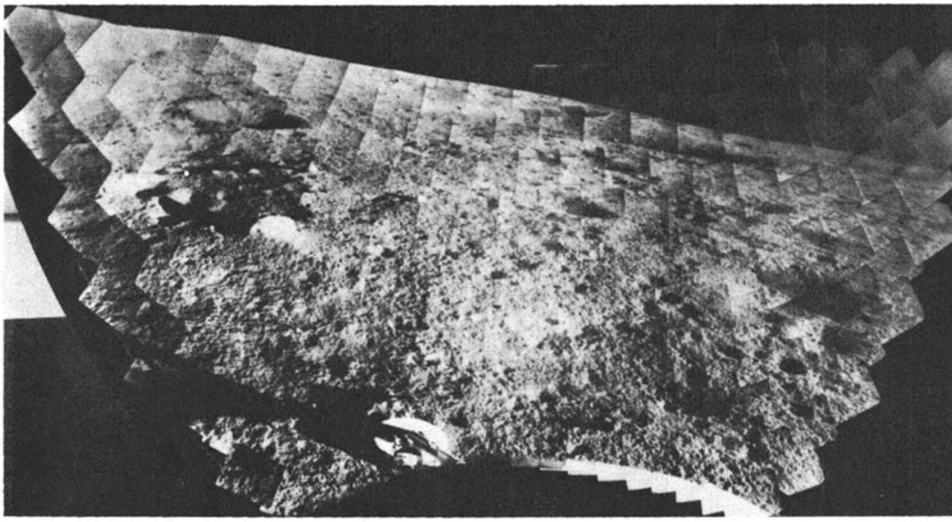

FIG. 8. Partial spherical mosaic of Surveyor I television pictures. The angular width of the panorama is about 120° and the height between 50° on the right and 60° on the left. The sector shown in Figure 7 is on the left. The pictures were taken at the same time as those in Figure 7, with a sun elevation of about 10°.

viously are not present, he may assume that the camera has made an unprogrammed step away from the area being mosaicked, and he will then continue the mosaic from a location that, in his judgment, is likely to be correct.

"Semi-improved" mosaics can be compiled of those small segments of the lunar scene that have special scientific interest. Some semi-improved mosaics are compiled as time is available during a Surveyor mission, but the most extensive use of this type of mosaic is in postmission analysis. Compilation is done almost entirely by reference to conju-

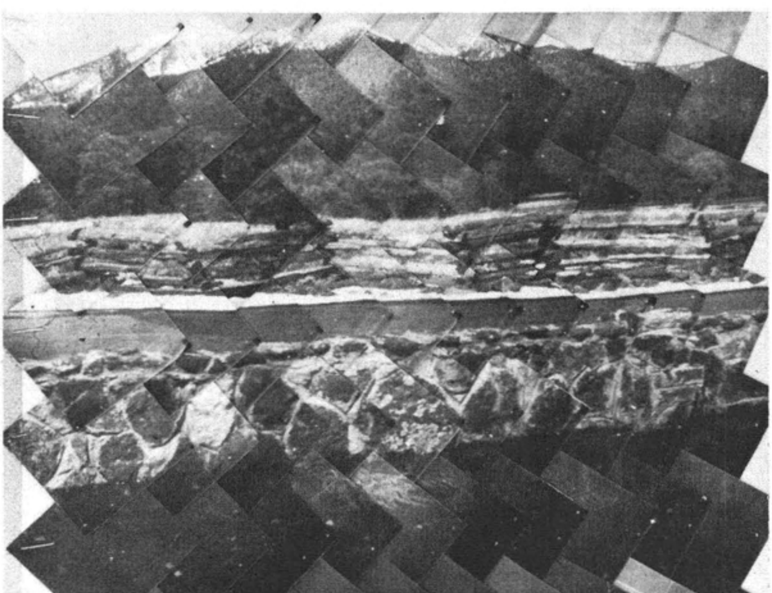

FIG. 9. Segment of an analytical mosaic taken on the earth. No anomalies are present. The stone wall in the foreground and the rail fence beyond it provide reference lines for illustrating the anomalies in the following figures.

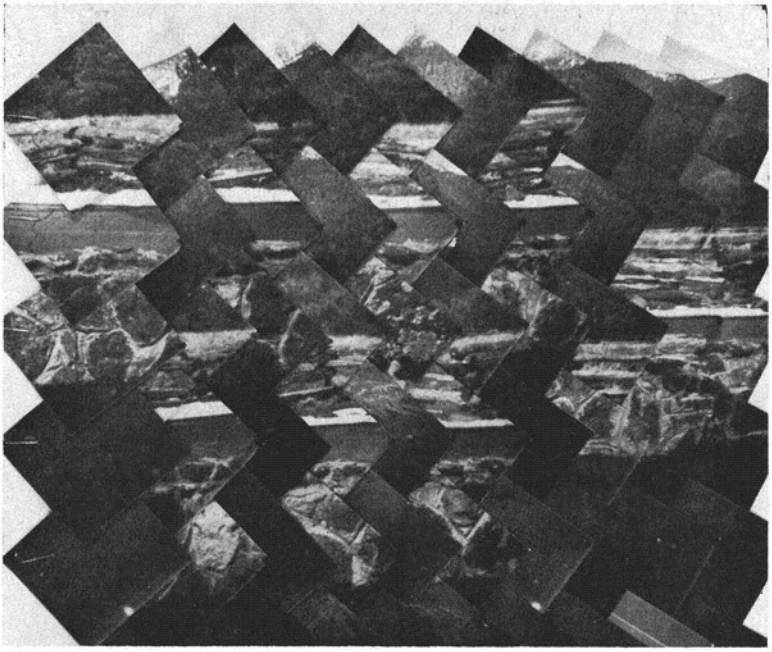

FIG. 10a. Mosaic with a camera skip anomaly.

gate images between frames. The center lines of the areas are compiled first, the only assumption being that the centers of adjacent frames lie on a straight line. After this cross of control frames is laid down, the frames in each quadrant are fitted to the cross by matching images, until the segment is complete. The frame edges are trimmed and the prints are fastened to the base with rubber cement. The Frontispiece and Figure 7 are semi-improved mosaics of Surveyor television pictures.

Spherical mosaics are assembled in much the same way as the semi-improved mosaics. A 180° section of a spherical mosaic is compiled by first mosaicking all the pictures along an elevation below the horizon, and then working up to the horizon and down to the bottom of the mosaic. Figure 8 is a partially complete spherical mosaic.

The compilation process could be carried further, by assembling mosaics from analytically adjusted and rectified prints, although this technique has not yet been developed.

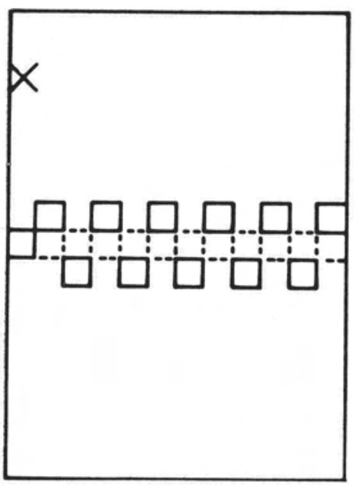

FIG. 10b. Diagram of a mosaic with a camera skip anomaly, showing how a horizontal line of frames is displaced when the mirror moved to the point designated by an X, but the camera failed to take a picture there.

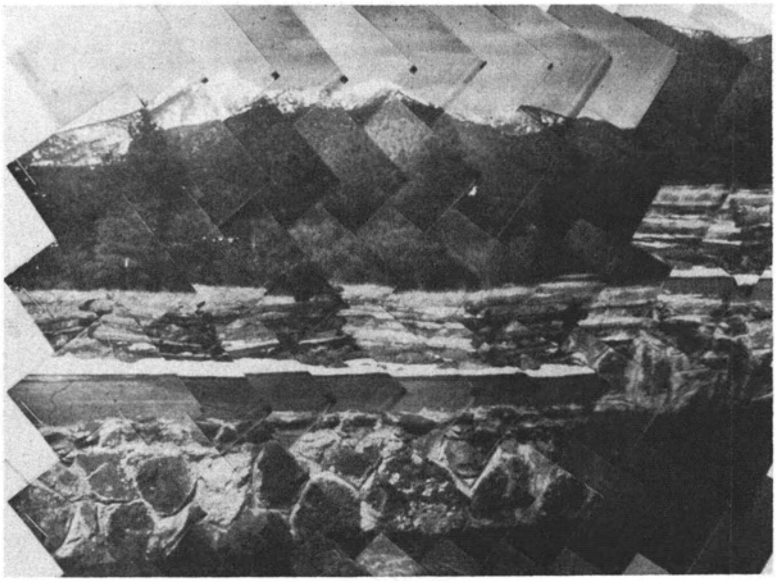

FIG. 11a. Mosaic with a mirror skip anomaly.

The methods discussed in this paper are sufficient for subjective analysis interpretation. Further development of mosaic techniques would be useful in photogrammetric reduction of Surveyor television mosaics.

TELEVISION SEQUENCE ANOMALIES

Any nonstandard camera operation that displaces frames from their predicted location during a television survey sequence will disrupt the orderly compilation of an analytical mosaic. If frames are placed on the analytical grid without regard to survey anomalies that might be present, the context of the mosaic may be completely destroyed.

Figures 9 through 13 illustrate the effect of some common anomalies when pictures are taken in successive vertical sweeps. If the sequence is programmed so that the camera is to take 10 pictures in a vertical line, and the mirror steps 10 times, but the camera takes more or fewer than 10 pictures, the anomaly type is defined as either "camera duplicate" or "camera skip" frames. In tests, this type of anomaly occurred far more frequently than any other type. On the other hand, if the camera takes a picture at each mirror position, but the mirror moves either too many times or not enough times, the resulting anomalies are called "mirror skip" frames or "mirror duplicate" frames.

As shown by Figure 10 through 13, the

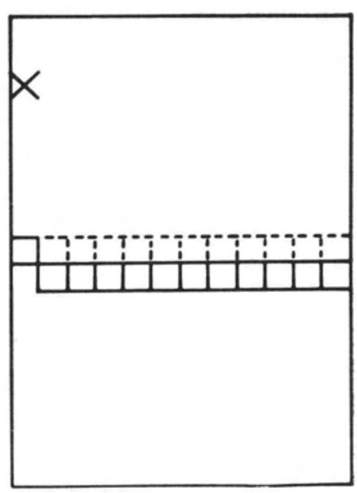

FIG. 11b. Diagram of a mosaic with a mirror skip anomaly, showing how a horizontal line of frames is displaced when the mirror skipped past the point designated by an X, but still took the anticipated number of frames along the vertical sweep.

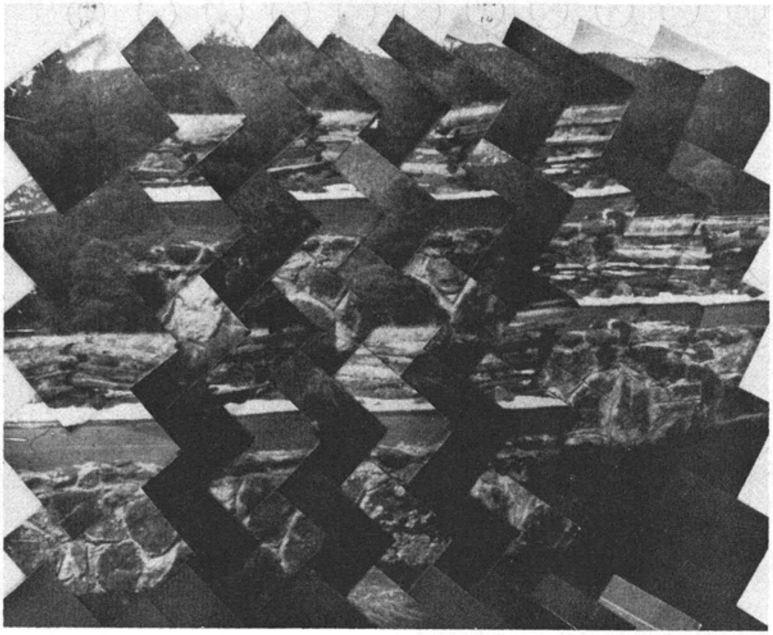

FIG. 12a. Mosaic with a camera duplicate frame anomaly.

difference is important. Tests have shown that it is much more difficult to correct an anomalous mosaic after it has been assembled than it is to watch for sequence anomalies and correct the mosaic during assembly. The four-member team of technicians who performed the Surveyor I mission mosaicking operations demonstrated its ability to spot sequence anomalies, correct them on the mosaic, and still place the frames in their correct position in the mosaic. Unless the anomalies are very complicated, the team is able to match the speed at which the television camera takes the pictures, a full narrow-angle panorama of about 1,000 pictures in less than two hours. To achieve this speed requires constant practice, an ability to recognize conjugate images on different frames, even when one or both frames are degraded and the conjugate images appear quite dissimilar at first glance, a thorough understanding of geometry of the camera, the types of camera survey sequences and the anomalies peculiar to each type.

SUMMARY

Field and laboratory tests of television systems like those of the Surveyor have pro-

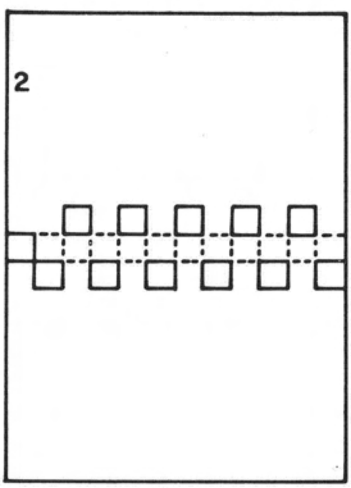

FIG. 12b. Diagram of a mosaic with a camera duplicate frame anomaly. The mirror stepped the requisite number of times, but an extra frame was taken at the point marked "2."

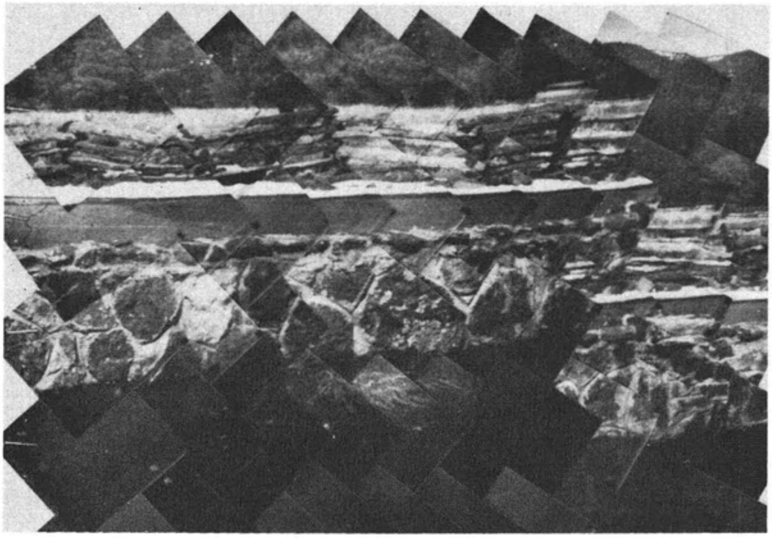

FIG. 13a. Mosaic with a mirror duplicate frame anomaly.

duced data which was used to develop techniques for compilation of three types of mosaic thought necessary for the efficient scientific analysis of the lunar scene viewed by the Surveyor spacecraft. These three types are used both during and after each successful Surveyor landing.

1. The mosaic that can be assembled most rapidly for use in sequence quality analysis is the analytical flat mosaic, in which frames are stapled to prepare projections on tack-board panels. Experienced technicians can construct this type of mosaic as rapidly as the television camera takes pictures, and thus can provide scientists with an early, reasonably coherent view of the lunar scene in the vicinity of a landed Surveyor spacecraft. Because the camera surveying operations are prone to certain malfunctions, the mosaicking team must be trained to recognize and correct these malfunctions rapidly enough to present a coherent mosaic to analysts in time for them to make inputs to further camera command sequences before the spacecraft mission ends.

2. To make semi-improved mosaics, the pictures are placed by careful adjustments between matching images and plotted control. These mosaics cannot be assembled as rapidly as the analytical mosaic, but present a much "cleaner" picture. Its primary use is for postmission analyses of parts of the lunar scene, but some semi-improved mosaics will be assembled as time is available during the Surveyor missions.

3. The spherical mosaic presents a coherent picture of the full panorama view by the spacecraft television cameras. They will not be assembled until after each single-camera mission, but when two-camera flights begin, a spherical mosaic will be compiled from pictures taken by each camera. These will be used on a special stereoscope now under development by the U. S. Geological Survey. Mosaic construction techniques on spheres are similar to those for semi-improved mosaics, except that the latter are compiled in small segments on a flat surface.

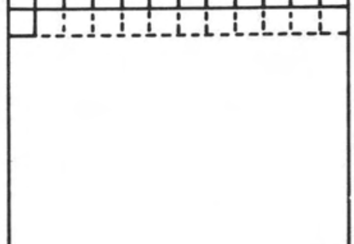

FIG. 13b. Diagram of a mosaic with a mirror duplicate frame anomaly. The mirror stepped one less than the requisite number of times, and took an extra frame at the point marked "2."