DONALD K. MCCASH
Optical Systems Division
ITEK Corporation
Lexington, Mass. 02173

Apollo 15 Panoramic Photographs

An Optical-bar panoramic camera was used.

(Abstract on next page)

INTRODUCTION

AS PART OF NASA'S Apollo 15 experiment for the scientific exploration of the Moon, the Itek Optical Systems Division supplied a 24-inch focal-length optical-bar panoramic camera (Figure 1) which was installed in the Scientific Instrument Module, bay 1 of the Apollo Service Module. The optical-bar camera's role in the mission was to provide high-quality stereo photographs of a large area of the lunar surface to aid in the selection of potential landing sites and future exploration areas, and to provide selected detailed information to support the selenodetic and cartographic goals of the experiments. Additionally, the photographs will establish the vehicle landing constraints related to the selected landing sites and aid in defining the design parameters of future mobility units and ground support facilities.

THE CAMERA

The camera comprises three major assemblies (Figure 2): (1) the roll-frame assembly, which basically provides the platform for the rotating lens system, (2) the gimbal-structure assembly, which rocks the roll-frame assembly back and forth to provide stereo photographs and to compensate for the forward motion of the vehicle, and (3) the main frame assembly, which attaches to the vehicle and provides a platform for the film transport system as well as the roll-frame and gimbal-structure assemblies.

The roll-frame assembly includes the lens system, a circular cage of rollers which supports the film, a variable-slit assembly, and a capping shutter. The lens is an eight-element, field-flattened Petzval type, polished to a surface accuracy of within one-millionth of an inch. Two mirrors fold the

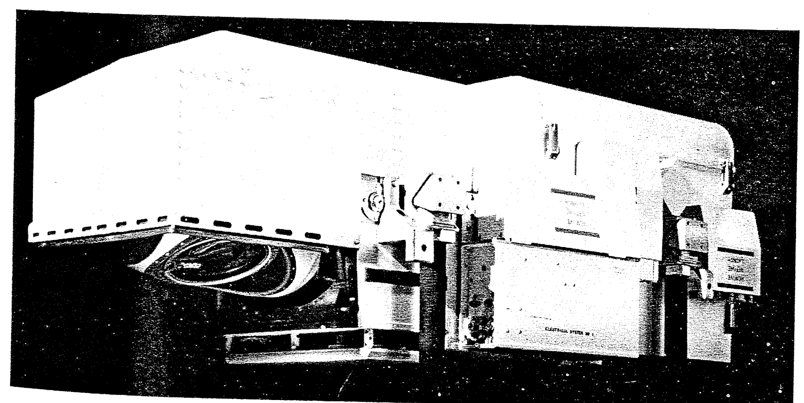

FIG. 1. The Itek 24-inch optical-bar panoramic camera for NASA's Apollo 15, 16, and 17 lunar experiments.

ABSTRACT: *The Itek optical-bar panoramic camera was used during the Apollo lunar exploration. Convergent panoramic stereo photographs have a distinctive geometry and stereograms of several features of the lunar surface are included.*

24-inch focal length into a more compact configuration by introducing two angles in the optical path (Figure 3). The camera has a relative aperture of $f/3.5$ and a field of view of 10 degrees 46 minutes. The individual picture size is 45.24 inches long and 4.5 inches wide. Resolution of approximately 135 lines per millimeter is achieved on 80 percent of the imagery, with no imagery being below 108 lines per millimeter at low contrast.

During the operation of the camera, the lens is rotated about an axis which is parallel to the Apollo Command Service Module at a rate related to the apparent ground speed. A capping shutter opens during the time the lens passes through a 108-degree arc below the vehicle.

Light entering the lens during this scan period is focused onto the film through a variable-width slit located at the rear of the lens system next to the film. The slit is continuously variable (governed by signals from a light sensor and V/h sensor) from a minimum opening of 0.015 inch to a maximum opening of 0.300 inch. The width of the scanning slit at any particular time combined with the scanning rate (the rate of rotation of the lens) establishes the photographic exposure time.

The gimbal-structure assembly, to which the roll frame assembly is attached, provides for both forward-motion compensation and stereo coverage by rocking forward and aft (up and down) along the axis of vehicle travel. For forward-motion compensation, the gimbal structure moves in the direction of apparent ground motion at the exact rate necessary to *freeze* the image during exposure. This avoids blurring which otherwise would occur if photographs are taken from a fastmoving vehicle.

If the camera operates in the stereo mode (Figure 4), the gimbal structure automatically pitches alternately from a position 12.5 degrees forward to 12.5 degrees aft of the vertical between successive exposures. That is, one exposure will begin with the gimbal structure in a position 12.5 degrees forward of vertical, the next exposure will begin with the structure at a position 12.5 degrees aft of vertical, and for the next it will shift to the 12.5 degrees forward position once again. The cycle rate of the camera is set so that a 100-percent overlap between stereo pairs is maintained. Upon proper viewing, the two photographs of the same gound area thus taken from different angles provide a 25-degree convergent stereo image.

A velocity to height ratio (V/h) sensor and an incremental shaft-angle encoder control the camera-operating cycle. The V/h sensor continuously determines the rate of apparent motion of the ground scene, and controls both the motion of the gimbal structure for forward-motion compensation and the speed of rotation of the lens system (the optical bar). The speed of the film across the roller cage is, in turn, controlled by the rotation of the optical bar. A light sensor determines the degree of ground scene brightness. This information is combined with the information from the V/h sensor in the exposure-control assembly, which adjusts the slit mechanism to provide the proper exposure of the film. The incremental shaft-angle encoder, in combination with a cycle-control assembly, provides the timing and synchronization for the operating sybsystems of the camera.

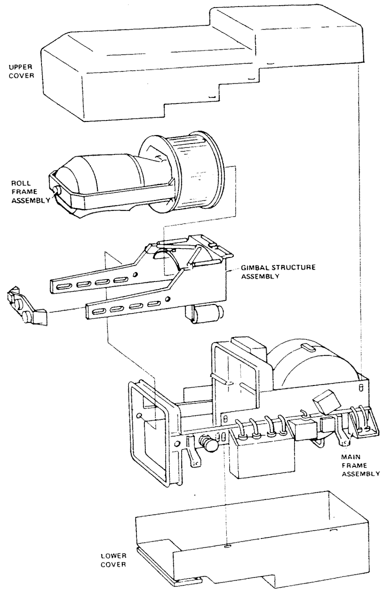

FIG. 2. Major assemblies of the panoramic camera.

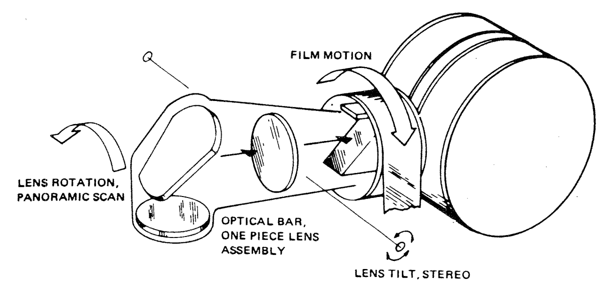

FIG. 3. Schematic diagram of the folded optical system.

The main-frame assembly is mounted to the vehicle and supports the gimbal structure and all other components, including the film supply and takeup mechanisms. The film-metering roller (Figure 5) continuously moves film from the supply cassette to a supply shuttle (a system of fixed and suspended rollers which stores a surplus of film ready for use). At a rate synchronized with the cycle rate, a framing roller intermittently draws film across the revolving roller cage in the direction opposite to that of lens rotation, through the focal plane, and then into a takeup shuttle. The supply shuttle is refilled during that portion of the cycle when the film remains stationary over the roller cage. Film in the takeup shuttle is continuously drawn into the takeup cassette. The surplus of film which is intermittently entering and leaving the supply and takeup shuttles pro-

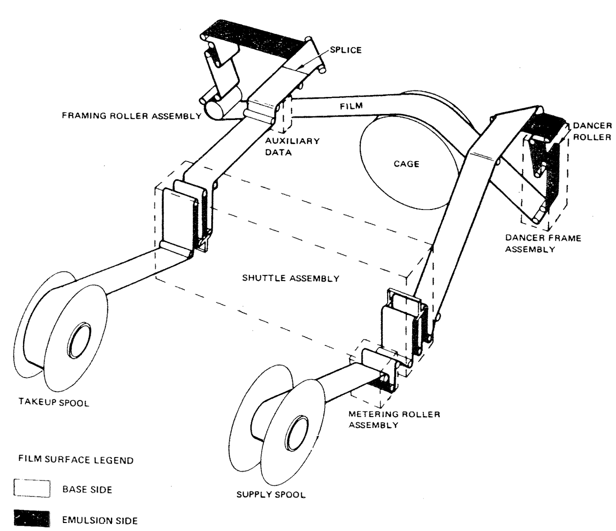

FIG. 4. Schematic diagram of the film transport system.

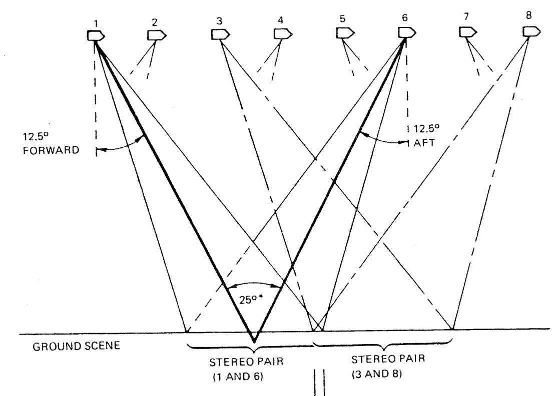

FIG. 5. Camera operation for 25° convergent stereo photos.

vides the flexibility required to maintain constant film tension throughout the system while the gimbal assembly tilts through its stereo and forward motion compensation cycle.

Because the camera lens rotates at a distance from the image surface (the radius of the roller cage) which is not equal to the focal length of the lens, lateral image motions could be introduced. During the exposure cycle, the film is moved across the roller cage in a direction opposite to the lens rotation to compensate for these image motions. The rate of film transport is proportional to the rotation rate of the lens.

The film takeup cassette is removed from the camera by an astronaut during an extravehicular activity (EVA) and stored aboard the Command Module for return to Earth.

Nominal photographic parameters for the Apollo XV mission were as follows:

Lens focal length	24 inches
Altitude	60 nautical miles
Scale at nadir	1:182,000 (1 inch = 2.5 n.mi.)
Frame dimensions	4.5 × 45.25 inches
Field of view	10° 46′ × 108°
Ground coverage	11.7 n.mi. × 183 n.mi.
Resolution	108 to 135 lines/mm
Ground resolved distance at nadir	5.6 to 4.5 feet

STEREOSCOPIC PHOTOGRAPHS

Stereoscopic viewing of unrectified convergent stereo photographs is somewhat more complex than viewing near-vertical stereo photographs. In vertical photography, the horizon line in the direction of flight appears at infinity and, therefore, the lines on the ground that are parallel to the line of flight are parallel to each other in the photograph. Stereo viewing conditions are then obtained simply by orienting the stereo pair with the images of the line of flight parallel to each other, in a common vertical plane and parallel to the viewer's eye base. The stereo conjugate imagery throughout the remainder of the photography will also meet the viewing criteria without translation or rotations. Additionally, in near vertical stereo photography, the conjugate images in the pair are nearly equal scale. The near vertical stereo condition for a panoramic stereo pair is illustrated in Figure 6.

In convergent stereo photography, lines parallel to the line of flight on the ground appear to converge to a finite horizon point in the image and, therefore, none of them are parallel to the imaged line of flight or to each other. This is illustrated for a single image in Figure 7.

FIG. 6. Geometry of near-vertical panoramic stereo photos.

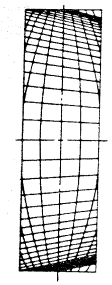

FIG. 7. Panoramic image geometry for a tipped (pitched) scan plane.

The angle (in the image) between the line of flight and any other ground parallel can be determined from

$$\tan \gamma = \sin \alpha \tan \zeta$$

where γ is the angle with zero scan line (or line-of-flight image), α is the scan angle and ζ is the pitch angle.

Convergent image geometry can more accurately be discussed in terms of perspective centers, epipoles, epipolar rays and epipolar planes. Correct stereoscopic viewing is performed in epipolar planes. For the present purpose, these relationships can be defined as follows:

Epipolar axis. The line joining the two perspective centers which generated the stereo pair.
Epipoles. Points of intersection of the epipolar axis and the film cylinder. This is where the horizon or convergence point would be imaged if the film could be extended to this point. Of course, this is modified by the depression angle of the actual horizon.
Epipolar Planes. Planes through the epipolar axis and an object point.
Epipolar Rays. Lines of intersection of epipolar planes and the negative surface.

In the above formula, the epipolar planes formed by lines parallel to the line of flight

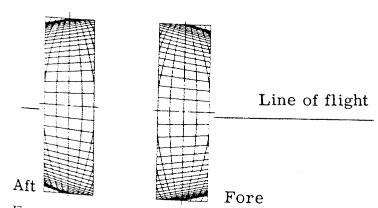

FIG. 8. Geometry of a convergent stereopair.

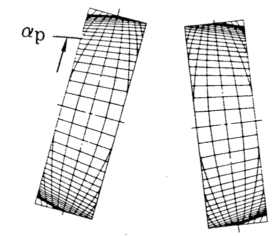

FIG. 9. Convergent stereopair rotated for epipolar ray orientation.

but at scan angles α appear in the image as epipolar rays with the angles γ with respect to the image of the line of flight.

Observing a stereo pair taken with a pitched (ζ) condition, one finds the geometry illustrated in Figure 8. Note in this figure, that the only epipolar rays that are parallel (and of the same object area) are the rays representing the line of flight. Therefore, for correct stereo viewing of other than the region near the line of flight, the photographs must be rotated through angles γ for any region of the photographs represented by a common scan angle α. If epipolar rays are not made parallel by this rotation, unacceptable large y-parallaxes will occur in the stereo view. Figure 9 shows a properly rotated pair for region α_p.

The term *region* has been used to indicate that each ray need not be rotated and related to the eye base, because the human visual system is tolerant of considerable amounts of y-parallax before discomfort is sensed. (Figure 10).

Convergent stereo imagery also results in considerable scale changes of conjugate object areas except for the central scan trace (normal to line of flight) for truly 100 percent overlap pairs. This condition results from imaging conjugate areas on the leading and trailing edges of the format where slant distances to the objects vary. This will not normally be disturbing because the human visual system will accommodate up to 20 percent scale variation before encountering serious discomfort. (Figure 11).

Under most stereo viewing conditions, the relief (height) of three dimensional objects on the lunar surface will seem to be exaggerated.* This vertical exaggeration aids in interpretation and will not create vertical measurement errors if the exposure factors

* See also several articles on vertical exaggeration in August and December issues of this Journal.—*Editor.*

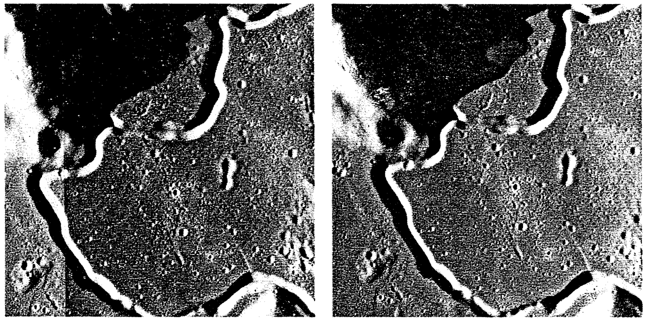

FIG. 10. Landing site at Hadley Rill. This photo was made on revolution 16 about four hours after the LEM landed. The landing site is about $\frac{3}{16}$ inch to the right of the rill and $\frac{3}{4}$ inch from the top of the photo. The area covered in this stereogram is about 25 × 25 km.

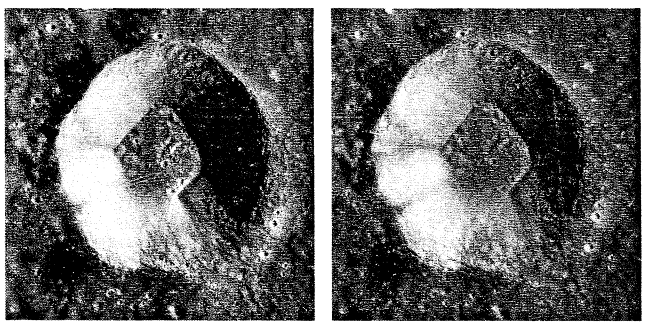

FIG. 11. An unnamed crater, about 20 km in diameter, photographed on revolution 15.

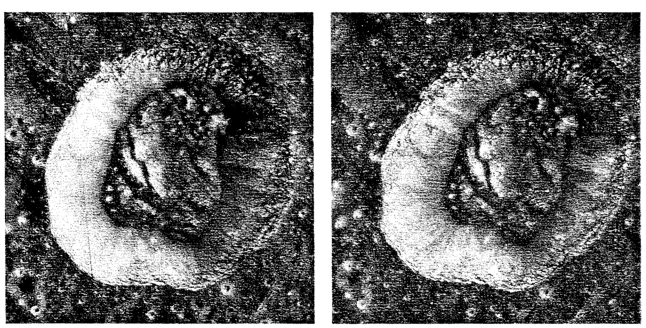

FIG. 12. An unnamed crater, about 20 km in diameter, photographed on revolution 15.

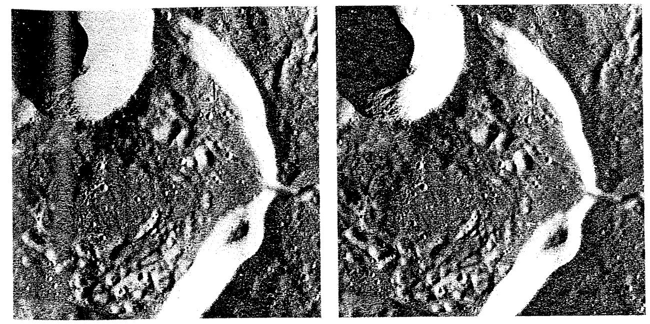

FIG. 13. KRIEGER. The light-toned crescent is the west wall of Krieger, a crater about 12 miles in diameter located about 5° (100 miles) north of Aristarchus. The smaller crater is estimated to be six miles in diameter and one mile deep. Photos made during revolution 72.

of scale and base-to-height ratio are taken into consideration. To determine the exaggeration of relief for a specific viewing situation one may apply the formula:

$$\text{Exaggeration of relief} = \frac{\text{Air-base}}{\text{Orbit altitude}} \times \frac{\text{Actual viewing distance}}{\text{Eye base separation}}$$

Contact prints of stereopairs are best examined with mirror stereoscopes because of the size of most of the major features. A lens stereoscope may be used, but with some difficulty because of overlap between the prints. The stereograms included herein are approximately 2× reductions of the contact prints, and were made for examination with the commonly available 2× or 4× lens stereoscopes. Because they were made from unrectified negatives exposed at different aspect angles, some geometric distortion is apparent. Captions accompanying the stereograms give approximate dimensions of major features and other information. Most of the pictured features have not been named because of their small size (Figure 12). Only a portion of a large named crater or mare can be included in a single photograph. For example, Mare Crisium, near the landing site, has a diameter of about 300 miles; at least 50 photographs would be required to completely cover this feature. (Figure 13).

At the time this article was prepared very

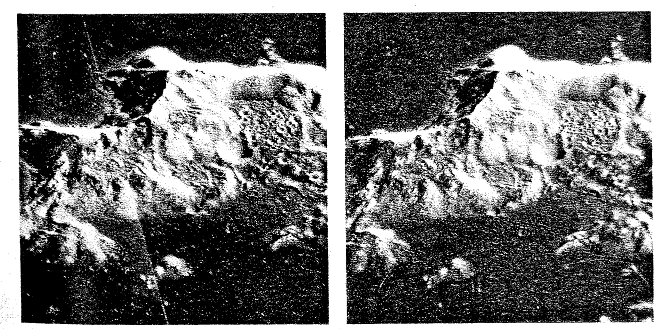

FIG. 14. TSIOLKOVSKY. A large mountain in the center of Tsiolkovsky crater on the far side of the moon. Width of area covered is about six miles, depth about 17.5 miles. Photo made on revolution 15.

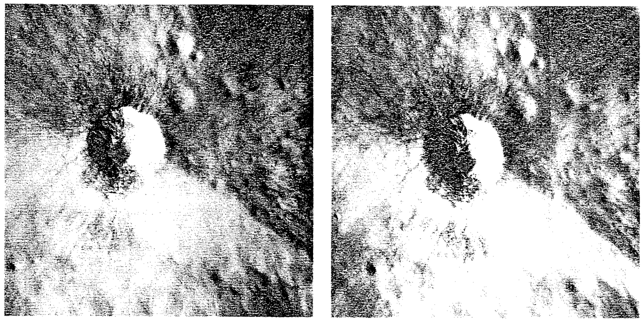

FIG. 15. Unnamed crater about 5 km in diameter on the crest of a ridge.

little information was available as to altitudes of different exposures or location and identity of features. The dimensions cited in the captions are based on the nominal altitude of 60 n.mi. They were determined from transparent overlays which depict the images of 5-km square grid areas distorted to account for the panoramic format, camera tilt, vehicle orbital rate, and forward-motion-compensation pitch rate (Figure 14). The high resolution of the original negatives enabled NASA scientists to measure the height of the Lunar Excursion Module to within 2 feet of its actual height. This resolution is considerably reduced in the halftone illustrations (Figures 10 through 15) that were made from sixth-generation positive prints. (Itek was supplied with third generation negatives. Contact prints from these negatives were copied at about a 2× reduction. Contact prints from the copy negatives were used for the halftone cuts.)

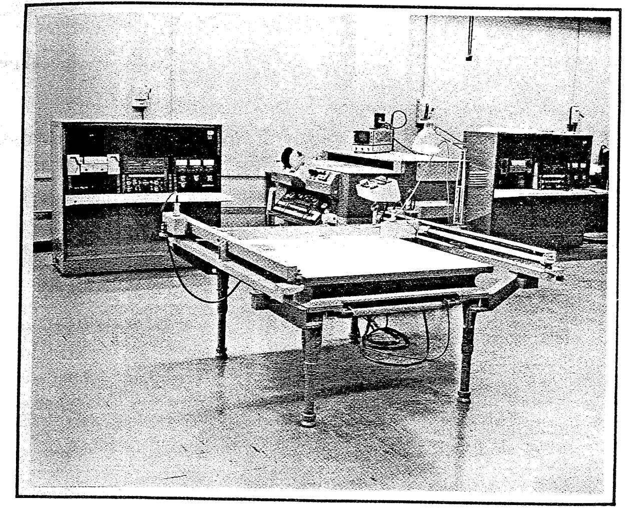

FIG. 1. Analytical plotter system used in the stereophotogrammetric reduction.

CHARLES G. PETERSON
Aeronautical Chart and Information Center
St. Louis, Missouri 63118

Compilation of Lunar Pan Photos

A large-scale topographic chart is produced using convergent panoramic photos and the analytical stereoplotter.

(Abstract on page 76)

INTRODUCTION

APOLLO 15 generated a vast amount of high-resolution panoramic photography which cannot be readily utilized on conventional stereoplotters to extract topographic information. In order to demonstrate the feasibility, versatility, and accuracy achievable from this panoramic material on the AS-11B1 analytical stereoplotter[1], a stereophotogrammetric compilation of a large-scale (1:25,000) topographic chart was performed.

The AS-11B1 system shown by Figure 1 has many unique properties that enable it to handle many non-standard photogrammetric applications. These properties are:

- Ability to compensate for panoramic geometry,
- Real-time digital computer,
- Wide range of focal lengths,
- Automated stereoplotting,
- Offset model capability and
- Model deformation coefficient correction.

Thus the plotter system is capable of handling a wide range of photography from vertical frame photographs to convergent panoramic photographs. The convergent panoramic photographs do not need to be transformed or rectified prior to use in the AS-11B1 plotter. The plotter can also correct for: lunar curvature, film shrinkage, lens distortion, image motion, vehicle motion, and stereo model deformation.