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Photographic Systems for Apollo

New camera systems are designed to take advantage of physical film recovery

(*Abstract on next page*)

THE PRIMARY OBJECTIVE of the Apollo program, announced by President Kennedy in May 1961, was to land a man on the Moon and return him safely to Earth in the decade 1961–70. Without NASA's unswerving attention to that objective, the astonishing success of Apollo XI in July 1969 could not have been achieved.

PLANNING FOR LUNAR EXPLORATION

With that original goal attained, a program for systematic exploration of the Moon was outlined by the GLEP (Group for Lunar Exploration Planning), which was established after the Second Conference on Lunar Science and Exploration held in Santa Cruz in July 1967. The GLEP concluded that the best use of the Apollo capability would be a sequence of manned landings at sites of diverse geologic conditions. The detailed knowledge obtained at these sites could then be extrapolated to large areas of the lunar surface by means of photography and other orbital sensors.

In theory at least, the Ranger and Lunar Orbiter programs were to have provided information adequate for selection of Apollo landing sites; and indeed, the locations for Apollo Missions XI, XII, and XIII were selected mainly on the basis of Orbiter high-resolution pictures. But examination of the extensive low-resolution Orbiter coverage convinced the GLEP that more knowledge would be gained if sites outside the original Apollo landing zones were explored.

HASSELBLAD PHOTOGRAPHY

Throughout the Apollo program the Hasselblad camera has been the workhorse for both orbital and surface photography. On the Earth-orbiting Apollo IX, a battery of four of these cameras, equipped with 80-mm lenses, was mounted in the hatch window of the Command Module. Three of the cameras exposed black-and-white film with green, red, and infrared filters bandwidths comparable to those planned for the Earth Resources Satellite. The fourth camera exposed infrared color film which simulated the combination of the three separate bands. A strip of photographs covering terrain from California to Georgia was obtained.

In the lunar program the Hasselblad camera has generally been used with an 80-mm. lens to obtain overlapping photographs in continuous strips. A 250-mm. lens was used on Apollo XI to take oblique photographs, through the Command Module window, of scientific sites of particular interest. On Apollo XII an attempt was made to photograph potential landing sites recommended by the GLEP by using a 500-mm. lens and mounting the camera on a bracket in the

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hatch window. The entire spacecraft was pitched in synchronism with its forward motion while the astronaut kept the same scene in the field of view. This technique provided both image motion compensation and an adequate stereo base from a sequence of photographs. However, the complicated operation restricts the number of targets that can be photographed because of the necessity of completely reorienting the spacecraft between scenes, and it was only marginally successful in providing the hoped-for high resolution.

ABSTRACT: *The primary objective of the Apollo Lunar Program is to provide data for landing sites. The primary objective of Skylab is to demonstrate the ability of men to operate in space for extended periods of time. As a consequence, neither the missions nor the cameras in either program are optimum for photogrammetric operations. Nevertheless they provide an opportunity to evaluate the contribution that photogrammetry and space can make to the exploration of our own and other planetary bodies in the solar system. New equipment includes: an 18-inch fl camera exposing 430 frames on a roll of 5-inch wide film; a panoramic system of 24-inch fl, 108° sweep, 4.5 by 45-inch film for 1650 exposures; a terrain camera of 3-inch fl, 4.5×4.5 film frame; a stellar camera of 3-inch fl on 35-mm film; and a laser altimeter. Six multispectral cameras, 6-inch fl on 70-mm film are planned for Earth photos from Skylab.*

In October 1969, the Apollo Orbital Science Photographic Team was formed to recommend the photographic equipment and operations to get the maximum scientific return from the remaining missions. The Team was not, however, completely free in selecting the camera systems to be used. It was necessary to choose cameras either available or far enough along in development so that they could meet the rigid timetable of qualifying for the missions, which were then scheduled at approximately four-month intervals. Furthermore, severe space and operating conditions had to be met. Consequently, the cameras selected were compromise solutions adopted from existing units.

The Lunar Topographic Camera

The first new photographic system is a modified Hycon KA-74 reconnaissance camera of 18-inch focal length, exposing 430 frames in each magazine of 5-inch roll film. This camera is mounted by a special fixture in the Command Module hatch window. When it is in place, it extends back into the vicinity of the center seat so that one astronaut must leave his couch while the camera is in operation. Forward-motion compensation is provided by rocking the entire camera in its mount during the exposure. Adequate stereo base is obtained by taking pictures with the camera axis vertical on one orbital pass and directed 20° forward or aft on the succeeding pass, depending on the lighting conditions.

The astronaut-photographer has a control box which, in addition to counting frames, permits him to establish the V/H rate* by setting the altitude obtained from the spacecraft guidance system. The number of frames per minute and the exposure time per frame are also set manually according to preflight computed data.

This camera was carried aboard Apollo XIII and was actually mounted in position ready for lunar approach photography when the oxygen tanks exploded, with consequences all too well known. It will be carried again on Mission XIV, scheduled to return to Frau Mauro in December of this year; and on Mission XV, presently planned for March next year.†

The Scientific Instrumentation Module

With Apollo XVI, in August 1971†, lunar photography will take on new dimensions. This will be the first operation of the SIM, the Scientific Instrumentation Module, a section of the Service Module containing a variety of orbital science experiments. After the surface operations have been completed and the Landing Module has rejoined the Command and Service Module, the door of the SIM will be jettisoned and three days of orbital science will follow. Depending on fuel con-

* Velocity of the vehicle; height of vehicle above lunar surface.

† These dates have been changed since the presentation of the paper.

straints, a small plane change may be made to increase the orbit inclination and hence the total surface area available for photography.

The Lunar Panoramic Camera

A major component of the SIM will be a panoramic camera for providing high-resolution photographs of large areas of the lunar surface. This camera will have a 24-inch focal length and an aperture of f/3.5. The 108° sweep angle will expose a frame $4\frac{1}{2}$ by 45 inches on 5-inch roll film; 6250 feet of thin-base film will provide for 1650 exposures. Stereo coverage can be obtained by rocking the camera $12\frac{1}{2}$° forward or aft between succeeding exposures. Forward-motion compensation will also be provided by this rocking action.

The camera, now under construction by Itek, is a modification of a currently available rotating-optical-bar camera. Its principal elements are the main frame that mounts rigidly to the spacecraft and carries the supply and takeup film spools; the stereo gimbal assembly that can rotate about a transverse axis to provide stereo convergence and forward-motion compensation; and the roll-frame assembly that carries the rotating lens and moving-film rollers.

The folded optical system rotates about its longitudinal axis to scan the lunar surface. Simultaneously the film is moved in the opposite direction around the roller cage and past the exposure slit. This arrangement makes it possible to have a film drum of only 5-inch radius rather than the effective 24-inch radius required by conventional panoramic camera design. Thus a camera of extremely high capability can be compressed into the limited space available.

A V/H sensor will provide the signal for controlling the forward-motion compensation. A light sensor mounted on the stereo gimbal will adjust the exposure time by modifying the width of the slit. From the nominal altitude of 111 km. the camera can provide about 1.5 meters surface resolution at the spacecraft nadir. In the monoscopic mode each frame will cover 290 km. across track and 20 km. along track; each vertical photograph will overlap the preceding one by 10 percent at the nadir.

In the stereo mode, the camera will rock through the 25° convergence angle between each two exposures. The forward exposure from station 1 and the aft exposure from station 6 will overlap by 100 percent to form a stereo model, and each succeeding stereo model will overlap the preceding one by 10 percent.

The Metric Camera System

Mounted on the front shelf of the SIM on Apollo Missions XVI through XIX will be the Metric Camera System comprising a terrain camera, a stellar camera, a laser altimeter, and a precise timing mechanism. The stellar camera will look to the side of the orbital plane; to provide a clear field, the entire system will have to be deployed outside the SIM for photography.

The terrain camera will have a 3-inch focal length, f/4.5 lens, and will expose a format of $4\frac{1}{2}$ by $4\frac{1}{2}$ inches on 5-inch roll film. The stellar camera will use a 3-inch focal length, f/2.8 lens, and will record on 35-mm. film; its optical axis will be at 96° to the axis of the terrain camera so that no part of the lunar horizon will be included in the field of view. The laser altimeter will be mounted with its transmission and receiving optical axes parallel to those of the terrain camera; its accuracy will be about ± 2 m. The mid-point of recording of the terrain camera, stellar camera, and laser altimeter will be synchronized and recorded on the terrain camera film with an accuracy of ± 1 millisecond.

The terrain camera will have a 10-mm. reseau engraved on the glass focal-plane plate. Two sets of artificially illuminated fiducials and one set of naturally illuminated fiducials will be provided. A V/H sensor will control forward-motion compensation, with an accuracy of 3 percent, by moving the focal plane plate during the camera exposure. The fiducials will be flash-exposed within 1 millisecond of the exposure. Automatic exposure control will set the between-the-lens shutter in five steps in the range 1/15 to 1/240 second.

The surface resolution will depend on solar altitude and the accuracy of forward-motion compensation. For the nominal altitude of 111 km (60 nautical miles) with Kodak 3400 film, the expected resolution will be about 90 feet per line pair at high contrast, decreasing to about 200 feet at low contrast (characteristic of high solar altitude).

The forward overlap of successive frames can be adjusted preflight. For the missions now planned, the available 3,600 exposures will permit the total area overflown to be covered with 78 percent forward overlap. This means that every point on the ground will be seen on 4 consecutive photographs with a maximum base-height ratio of 1.0. In addition to providing geometric strength for triangulation, the four views will permit a study of the Moon's peculiar photometric characteristics.

The data block on each frame of the terrain camera will be recorded by 4 columns of 32 photodiodes. These will record the day, hour, minute, second, and millisecond of the mid-point of each exposure, the altitude measured by the laser altimeter, and the shutter-open time to 1/10 millisecond.

The stellar camera format will be 1 by $1\frac{1}{4}$ inches on 35-mm. film. Four fiducials and a 5-mm. reseau on the glass focal-plane plate will be edge illuminated to record on the film. The resultant prefogging will have the additional advantage of hypersensitizing the film for stellar exposure.

A fixed exposure time of 1.5 seconds should provide 25 to 75 star images per frame, depending on the location of the field of view in the celestial sphere. This sensitivity takes into account the nominal space-craft attitude rates and the orbital rate.

The terrain and stellar cameras are being built by Fairchild Space and Defense Systems. The laser altimeter is being built by RCA, but Fairchild is responsible for incorporating it into the metric camera package. Installation of all systems in the SIM is the responsibility of North American Rockwell.

Film Recovery

The films exposed by both the panoramic and the metric camera systems will be collected in special quick-release magazines and recovered from the SIM by the astronaut. A single release handle will cut the film, close the light-tight compartment, and release the film-return magazine. The magazines will then be stowed in the Command Module for return to Earth.

Lunar Surface Coverage

The photogrammetric value of the missions largely depends on the extent of the lunar surface which can be photographed. The Apollo program is still primarily oriented towards surface science, and the photogrammetrist's principal impact is to push the landing sites to the maximum latitude, thus permitting a larger area to be photographed under adequate lighting conditions.

Before the failure of Apollo XIII, Tycho at latitude 40° S was a prime landing site, but this has now been dropped from consideration. Marius Hills at 16° N and 56° W is the probable site for Mission XVI. Mission XVII will probably go to Descartes at 10° S and 16° E. Mission XVIII is currently planned for Hadley Rille at 24°N and 4°N. The total coverage obtainable from these missions, although covering an extensive area of the Moon's surface, is still far less than photogrammetrists would like.

Panoramic Rectification

The characteristics of the camera systems impose major considerations on the ground-data handling problems. Primary among these is the rectification of the panoramic photographs. Rectification is essential to bring the photographs to a common scale for realistic visualization of topographic relief and to permit direct utilization of the images in mosaics and photomaps.

The proposed rectifier is an analog of the taking camera. The film is carried on a circular platen whose radius is equal to the 24-inch equivalent focal length of the camera. Longitudinal displacement of the film with respect to the center of the arc will compensate for roll of the spacecraft. A moving light source traverses the length of the film to make the exposure. The projection lens rotates at a rate controlled by a mechanical inversor so that the Scheimpflug condition is always satisfied. The projected image is then reflected to the easel. The tilt of the easel can be adjusted to compensate for the $12\frac{1}{2}°$ stereo convergence as well as for spacecraft pitch. The longitudinal curvature of the easel can be adjusted to simulate the curvature of the lunar surface for various orbital altitudes.

The rectifier is limited to a scan range of $\pm 35°$ from the nadir and can accommodate a camera tilt of $-1°$ to $+20°$. Curvature of the easel restricts the altitude to 150 km., which is well beyond the nominal 111 km at which Apollo missions are planned.

The resolution, measured at the input scale, will vary from 90 line pairs/millimeter on axis to 50 line pairs/mm. at 35° maximum scan. The displacement of images from all causes is specified as 1,000 micrometers circular probable error. Thus the rectified pictures are not designed for photogrammetric use, but will have adequate geometry for photointerpretation.

The major limitation of the rectifier is the $\pm 35°$ scan angle compared to the $\pm 54°$ scan angle of the camera. This limitation is imposed by the optical characteristics of the projection lens. Nevertheless, the output film will be 9 inches wide and nearly 70 inches long per frame. Furthermore the total 70° scan angle will equal the angular field of the metric camera.

Metric Camera Data Analysis

Wrapped up in the combination of surface photography, stellar photography, laser altimetry, timing data and spacecraft tracking data is the possibility of deriving, or significantly improving, knowledge of selenodetic parameters. These include:

- The lunar ephemeris describing the position of the Moon's center of mass with respect to the Earth;
- The physical librations describing the periods and amplitudes of the Moon's short-term angular motions about its center of mass;
- The mathematical reference surface and coordinate system with origin at the center of mass, and axes alined with the principal axes of inertia;
- A network of photoidentifiable points on the lunar surface located in the defined coordinate system with an accuracy of 10 to 15 meters sufficient for future cartographic products, and surface and orbital navigation;
- The coefficients in the spherical harmonic expression of the Moon's gravitational field.

The validity of the results obtained for these fundamental quantities completely depends on the extent of surface coverage obtained. An optimum mission would be near-polar inclination, 93 km altitude, near-zero eccentricity, and a 29-day lifetime to provide total Moon coverage in a single lunation. Such a mission exceeds the performance capability of the Apollo spacecraft, but there is some hope that missions XVIII and XIX may be changed to orbit only, thus permitting all these good things to be accomplished.

A major effort is of course required to provide the analysis, computer programming, mensuration, and calculation. But its cost would be only an insignificant part of the expense of the whole Apollo Program, and the scientific return would make the program worthwhile.

The Skylab

The Apollo Lunar Exploration Program was originally planned and funded for a total of 20 missions. Last fall it was decided to take the booster from Apollo 20 and use it to launch Skylab I, which will operate in Earth orbit. The empty stage of the S-IVB rocket will be converted into a laboratory capable of supporting 3 men for periods up to 30 days. It will also mount a number of Earth-sensing and astronomical experiments. The Apollo Command and Service Module will be used as a ferry to change crews in the Skylab on a 3-month rotation plan.

It is planned to launch Skylab I in the Fall of 1972. Depending on how schedules are maintained in the next two years, this will place it after lunar mission XVII or XVIII, and it will introduce a year's hiatus in lunar landing operations. It is for this reason that consideration is being given to changing the later lunar missions to orbit only.

Multispectral Camera System

Photogrammetrists are principally interested in a multispectral photographic experiment for operation in Skylab I. A contract has recently been issued to Itek to develop an array of six cameras. These will be of 6-inch focal length, f/2.8 aperture, and record on 70 mm. film. The optical axes of all cameras will be alined with an accuracy of 1 arc minute, and the focal length and distortions will be matched so that all pictures can be accurately registered. Forward-motion compensation will be provided by rocking the frame which carries the six cameras. The cameras will be capable of 120 line pairs/mm. at high contrast on Kodak 3400 film. Four black-and-white spectral bands of 1/10 micrometer bandwidth between 0.5 and 0.9 micrometers are planned. The other 2 cameras will carry color and color infrared film. It is hoped that this experiment will provide a major increase in knowledge of the use of multispectral photography for Earth resources.

Other Skylab Proposals

Skylab, being a manned mission at 50° inclination and 235 nautical miles (435 km.) altitude is not an optimum mission for obtaining mapping photography. It will, however, provide an opportunity to investigate the usefulness of space photography for establishing map control by photogrammetric triangulation, and map compilation or revision using a photographic image base. Several alternate camera systems are under consideration.

The 18-inch-focal-length camera from the lunar program is one possibility. Adequate stereo base could be obtained by using 2 cameras, or by rocking the camera forward and aft between successive exposures.

For later Skylab missions the Hycon lunar cameras may be replaced by a metric camera of 12-inch focal length exposing a format of 9 by 18 or 9 by $14\frac{1}{2}$ inches on $9\frac{1}{2}$-inch roll film with forward overlap of 70 percent in the long dimension. This would provide a strong geometric configuration for control extension.

The 24-inch focal length panoramic camera is another possible choice for later Skylab missions.

Conclusion

The primary objective of the Apollo Lunar Program is to provide data for landing sites. The primary objective of Skylab is to demonstrate the ability of men to operate in space for extended periods of time. As a consequence, neither the missions nor the cameras in either program are optimum for photogrammetric operations. Nevertheless they provide an opportunity to evaluate the contribution that photogrammetry and space can make to the exploration of our own and other planetary bodies in the solar system.

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