OFFICE OF THE SECRETARY OF DEFENSE

5-25-68

MEMO FOR Col Worthman

Pls retain. I am sure there is more to follow will send copy of letter to Gruner.

I have sent Don Steering a copy of the letter and a buck slip saying I told Johnny that Hoenig didn't agree without action.

John

OFFICE OF THE SECRETARY OF DEFENSE

① Dr Wilson [illegible] 4-25-68

MEMO FOR ② Dr Foster

Dr Flax has seen

Dr Hornig is interested in this one. He feels the original paper was all right.

Mr [redacted] believes our action and resolution is satisfactory.

The Natl Academy of Sciences may discuss our classification policy when [redacted] speaks but no definite word that he will [redacted]

(DOD

COVERING BRIEF

To: DDR&E

18 April 1968

From: AD/ST

Problem:

To acquaint you with the background and current status of Mr. [redacted]aper, "Mapping from Satellite Photography."

Background:

Last November, [redacted] Chief Scientist, Autometric Operation, Raytheon Company was invited to present a paper to the American Society of Photogrammetry and the George Washington University, as part of the latter's Distinguished Lecture Program. [redacted]elected "Mapping from Satellite Photography" as his topic, a subject which flows naturally from his Autometric activity, where he works on portions of the National Reconnaissance Program (his clearances are SI, TK).

He processed his paper, at the last minute, through DIAMC (mapping and charting), which believed that, with a few changes, the paper was presentable.

During discussions on the subject, [redacted] appeared quite hostile to security review (or control). It was as a result of this experience, as well as experiences with certain ACIC mappers and charters, tha[redacted] NRO, and [redacted]IA, instituted a procedure calling for all cleared DOD persons to send any papers they prepared on earth-sensing to DIAXX, prior to presentation, publication, or regular (white) submission to ASD/PA (see Tab A).

On January 24, 1968, the Raytheon Company sent a paper, "Mapping from Satellite Photography," to ASD/PA, requesting clearance for presentation at the Canadian Institute of Surveying at Edmonton, Canada on January 31.

Reviewing a copy of the paper, I was struck with the many security problems it raised (see Tab B). [redacted]ad employed a very positive tone throughout; his references to resonant altitudes, 80 n.m. as a practical perigee, the feasibility of stellar photography, Mark 5 recovery vehicles, the deboosting procedure, and the use of thin base film could only have come from someone thoroughly acquainted with the NRP.

This January version of [redacted] paper was very similar to the November version, but did extend a little farther into forbidden areas. I advised DIA that this paper could not be given. I asked if the DIA and the NRO Staff would be embarrassed over denying clearance in January to a paper that had cleared in November. Colonel Worthman reviewed my copy of the paper and said he shared my concern. Our decision was passed to Autometrics.

On January 30, we received a call from the local Autometrics office and were advised by [redacted] a security administrator, that Raytheon had instructe[redacted] to become ill and return home from Canada. [redacted] also informed me that (1) the National Academy of Sciences had the offending speech in galleys for inclusion in a forthcoming manual of the American Society of Photogrammetry but that Autometrics was withdrawing it promptly from publication, and (2) the National Academy of Sciences had booked [redacted] for a series of speaking engagements as a Visiting Lecturer on this same subject. Could Autometrics representatives meet with someone to discuss this problem?

On February 13, DIA sponsored a meeting to examine the extent of [redacted] problem. Colonel Worthman and I joined this meeting and explained, in detail, the national policy background for the security actions we had taken. We analyzed [redacted] paper, pointing out to him that it is virtually impossible for a cleared person to write on satellite reconnaissance without giving something away. He, and persons like him, were very close to a situation where one can be a member of the team and keep silent or not make the team and be vocal.

[redacted] and the Autometrics representatives who accompanied him were respectful and cooperative. [redacted] raised two follow-on problems:

1. An American Society of Photogrammetry request that he present a paper on lunar mapping during its March convention.

2. An International Society of Photogrammetry request that he organize a presentation on NASA Photogrammetric Space Program to be given at Lucerne, Switzerland next summer.

I promised [redacted]hat we would give him prompt replies on both questions. I also told him that I would ask the NRO's [redacted] (a mapping expert) to meet with him to search for a good technical area in which [redacted] could prepare speeches and papers in the future. It seemed important to us to give [redacted] a safety valve of some kind so that he could continue to be active in journals and symposia.

The answer to a safety valve for [redacted] turned out to be the photogrammetric geodesy of the moon. [redacted]orked out terms of reference in this regard:

1. Size and density of control nets to be based explicitly on lunar requirements.

2. Cameras for lunar mapping to be frame cameras of 6-, 12- and 24-inch focal lengths. There would be no mention of panoramic or strip cameras.

3. References to orientation of terrain cameras and/or the vehicle by the use of stellar cameras would be based on data collected from ESSA BC-4 cameras.

4. Discussions of moon-mapping at scales such as 1 to 50,000 or better would reference aircraft program capabilities already known to the scientific public.

Based on these guidelines, [redacted] agreed that he could prepare a good paper for the March meeting of the American Society of Photogrammetry and did so (see Tab C).

Regarding his Lucerne meeting, [redacted] arranged to have Dr. Loman or Dr. McNair (both unwitting) prepare a paper on the uses of GEMINI photography, emphasizing geology and map revision.

In summary, our arrangements were such that [redacted] no longer walked the borderline of NRP disclosure. He would, however, be able to continue to give excellent papers in his field of interest, following our guidelines.

Present Status:

Several weeks ago, Mr. Heinz Gruner, President of the American Society of Photogrammetry, sent a letter to Dr. William Pecora, Director, U.S. Geological Survey, protesting the restrictions placed on [redacted] paper (see Tab D). Dr. Pecora sent the letter to Dr. Don Hornig, asking for advice in answering it. Dr. Hornig, in turn, sent it to Dr. Flax, asking for "the wording of a letter that Dr. Pecora might send as a reply to Mr. Gruner"(see Tab E). 1003

Since the entire action was taken by OSD, specifically in the DDR&E and DIA arenas, I have advised Don Steininger that we would reply directly to Mr. Gruner. He has cleared this proposed action with Dr. Pecora.

Implementation:

Tab F is a proposed reply to Mr. Gruner. Essentially, we tell him that OSD took the action, that such actions are routine with our contractors, that they are taken in the national interest, and that [redacted] now has an excellent new paper which Mr. Gruner can use to replace the previous version.

Recommendation:

That you sign Tab F.

[redacted]

PRECEDENCE

DTG

COMMUNICATIONS

FROM: SSO DIA WASH DC

TO: [redacted]

SPECIAL INSTRUCTIONS:

DIST.
SAFSS

~~SECRET~~ TTTTT ~~TALENT KEYHOLE~~ CHANNELS

DIAXX [illegible] DEC 67 TCS 31304-07

1. RECENTLY PROPOSED SPEECHES AND ARTICLES FOR PUBLICATION HAVE INDICATED THAT DOD HAS AN ACTIVE INTEREST IN SATELLITE PHOTOGRAPHY OF THE EARTH. THESE ITEMS PROPOSED FOR PUBLICATION ALSO INDICATE A CURRENT DEFENSE CAPABILITY TO ENGAGE IN SATELLITE PHOTOGRAPHY JUST FROM THE VOLUME OF ARTICLES AND THEIR RELATED SUBJECTS.

2. IN ORDER TO PRECLUDE ANY FURTHER LAPSES IN WHAT SHOULD OR SHOULD NOT BE PRESENTED AT OPEN MEETINGS, THE FOLLOWING PROCEDURE WILL BE ADHERED TO BY ALL DOD AND DOD CONTRACTOR PERSONNEL HOLDING TKH CLEARANCES:

A. ALL SPEECHES OR PAPERS bearing in any sense on satellite operations or products WILL BE SUBMITTED TO DIA (ATTN: DIAXX-3) FOR APPROVAL. THIS WILL BE DONE PRIOR TO THE COMMITMENT ON THE PART OF THE AUTHOR TO PRESENT

COORD:
NRO [illegible]
DIAXX [illegible]

DATE	TIME
1	
MONTH	YEAR
DEC.	67
PAGE NO.	NO. OF PAGES
1	2

DRAFTER — TYPED NAME AND TITLE
H. D. MYLES
CDR, USN
PHONE 55371

RELEASER — SIGNATURE
TYPED (or stamped) NAME AND TITLE
R. A. GLASS
Major General, USA

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Excluded from automatic downgrading and declassification

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OR PUBLISH AN ARTICLE.

B. AFTER DIAXX SECURITY REVIEW, THE PAPER WILL BE RETURNED FOR SUBMISSION THROUGH NORMAL CHANNELS FOR REVIEW AND APPROVAL.

C. IN NO CASE WILL A CLEARED AUTHOR SUBMIT A TITLE, ABSTRACT, OR ARTICLE TO A SCIENTIFIC OR TECHNICAL SYMPOSIUM OR PUBLISHER PRIOR TO THE COMPLETION OF THESE PROCEDURES.

3. IT IS REQUESTED THAT ALL DEPARTMENTS AND COMMANDS BRING THIS TO THE ATTENTION OF THEIR CLEARED CONTRACTOR PERSONNEL.

4. THIS POLICY IS APPLICABLE TO ALL DOD ELEMENTS GOVERNED BY THE TALENT CONTROL SYSTEM MANUAL S-5001.2 (M-1).

CONTROL NO.	TOR/TOD	PAGE NO. 2	NO. OF PAGES 2	MESSAGE IDENTIFICATION

REGRADING INSTRUCTIONS Excluded from automatic [illegible]

SECURITY CLASSIFICATION HANDLE VIA
SECRET TALENT-
CONTROL SYSTEM

[redacted]

MAPPING FROM SATELLITE PHOTOGRAPHY

(Revised for publication, December 1967)

[redacted]

AMERICAN SOCIETY OF PHOTOGRAMMETRY
National Science Foundation
Visiting Scientist Program

8041,8042

MAPPING FROM SATELLITE PHOTOGRAPHY

[redacted]

Within the memory of many men now alive, maps were made by the ground surveyor lugging his theodolite, plane table, and alidade across the plains and up the mountains. In the years following World War II, the ground surveyor was largely replaced by the cartographic aerial camera and the photogrammetric plotting instrument. This innovation produced quantum jumps in production, geometric accuracy, and content of topographic maps.

Where Do We Stand Today

At the present time fully ninety percent of all new map compilations are produced photogrammetrically. Yet in spite of more than half a century of effort, the mapping task is woefully incomplete. Around the world only about half of the land area is covered by principal arcs of triangulation, and much less than half by first and lower order triangulation. The status of compiled maps is indicated in this table.

WORLD WIDE AND U. S. MAP COVERAGE

World Map Coverage

Quality	Small Scale 1:600,000 and Smaller	Medium Scale 1:75,000 to 1:600,000	Large Scale 1:75,000 and Larger	Remarks
Adequate	—	15%	5%	Principally U. S. and Europe
Require Revision	30%	5%	5%	
Inadequate	70%	40%	10%	
Nonexistent	—	40%	80%	

U. S. Map Coverage

Quality	Small Scale	Medium Scale	Large Scale
Adequate	100%	96%	64%
Inadequate	—	4%	4%
Nonexistent	—	—	32%

Data compiled by Army Map Service, and exclude Antarctica

Of primary concern is the fact that the rate of obsolescense of existing maps nearly equals the production of new maps, so that with present techniques the job will never be completed. Furthermore, the map production cycle is about three years from photography to printing so that the new map is three years out of date on the day it is published.

Geographers would like to see the million scale map of the world (IMW) completed. They state that most 1:250,000 maps are deficient in content. They need large scale 1:25,000 maps of all populated areas. Geologists, engineers, and other map users need similar scales. However, of first priority to all is the rapid revision of existing maps. Some sort of Parkinson's Law operates to make maps most difficult to compile and most rapidly obsolete in precisely those areas where they are needed most urgently. Maps of large urban areas should be recompiled annually. The current cycle in the United States is five to ten years.

<u>The Gemini Photography</u>

The use of the artificial satellite as a camera carrying vehicle is expected to provide a jump in mapping capability comparable to that which the airplane made over the ground surveyor. The Gemini photography was made with an ordinary hand held Hasselblad camera. On missions 5 and 7 photographs were made of the Cape Kennedy launch area. These two pictures, never intended for cartographic purposes, were used to revise the planimetric detail on the existing Army Map Service 1:250,000 map of the area.

In another application of the Gemini photography, the U. S. Geological Survey compiled a mosaic of most of Peru, parts of Bolivia and Chile. Control points were selected from existing 1:1,000,000 maps and identified on the individual Gemini Frames. These were then rectified and photograph tilts of as much as 40° were removed. Despite 20,000 feet of topographic relief a reasonable match was obtained, and the resultant photomap gives a view of the country never seen before.

But these are baby steps. What could be done with a system actually designed with cartographic objectives in mind?

Map Requirements

Before exploring the potentialities of space cartographic systems, it would be well to recall the requirements for producing maps.

A topographic map contains three kinds of information. The first is content, i.e., the details which are represented on the map. Content is provided by photographic resolution and scale, or more directly by ground resolution. In this area the exact capability of space photography remains to be demonstrated. For a variety of reasons it seems probable that the ground resolution obtainable with a given lens-film resolution will be higher from space than a simple geometric extrapolation from the scale of airplane photography would indicate. A useful criterion to apply is that the photography can be enlarged until its resolution is equivalent to between 10 and 20 line pairs per millimeter. This will present all the information which the human eye can extract without enlarging the map scale by magnification. Not all map information is obtainable directly from photography, regardless of its scale or ground resolution. Data such as political boundaries, place names, and detail obscured by vegetation must be compiled on the ground or from other sources. It is estimated that if the suggested resolution criterion is applied, about 80 percent of the total map information can be extracted from the photographs.

The second kind of information is the position of the objects shown on the map. For some applications the relative positions of all objects will be sufficient, but it is usually necessary and always desirable to attempt to specify all positions with respect to some well defined coordinate system, either local or national. Map positions are indicated by the reference graticule: longitude and latitude, state coordinates, or military grid lines.

The third kind of information is elevation - generally shown by contour lines above a reference surface - usually mean sea level.

In the United States, criteria for position and elevation on maps exist in the National Map Accuracy Standards. Applied to photogrammetric mapping, these standards, and the higher resolution criterion defined above, result in the values given in the following table. A fixed contour interval does not necessarily go with a given map scale. An interval fine enough to depict the terrain will be chosen.

MAP ACCURACY REQUIREMENTS

Map Scale	Std. Error Position	Ground Resolution	Contour Interval	Std. Error Elevation
1,000,000	300 meters	50 meters	500 meters	150 meters
250,000	75	12.5	100	30
100,000	30	5.5	50	15
50,000	15	2.5	25	8
25,000	7.5	1.3	10	3

The numbers in this table represent the objectives against which a space cartographic system should be evaluated.

Orbital Constraints on Photographic Coverage

It is immediately clear that if full coverage of the Earth is required, a near polar orbit is necessary. Of course, if mapping is to be restricted to specific areas, orbits of lower inclination can be employed. But for elementary discussion only near polar orbits will be considered.

An orbit is approximately fixed in inertial space and Earth rotates beneath it. At practical altitudes the satellite period is approximately 1 1/2 hours and in that time the Earth will rotate some 22 1/2° of longitude, i.e., about 2500 km. Since no reasonable camera can cover 2500 km on a single photograph it is necessary to arrange the mission such that consecutive days will fill in the gaps. There exist so called "resonant" altitudes at 4, 145, and 303 nautical miles, at which each day's coverage would exactly duplicate the preceding day and the gaps would never be filled. In order to perform the gap filling function efficiently, it is necessary to make compromises in selecting orbital altitude, eccentricity, and inclination. Although orbits as low as 80 n.m. can be flown, for several reasons including spacecraft lifetime, an altitude of about 125 n.m. (232 km) is desirable.

As illustrated in Figure 1, the other critical parameter is the width of the ground track covered by the camera. This dimension, divided into the 2500 km between consecutive orbital passes will determine the minimum number of days in orbit which would be required to obtain complete coverage in the gaps. Quite obviously, if the spacecraft can remain in orbit for more than this minimum time, it will get more than one look at each spot. This is clearly desirable in view of the cloud cover which may be expected.

Resolution and Map Scale

The relationship between camera focal length, orbital altitude, lens-film resolution, and ground resolution is shown in Figure 2. For a wide angle cartographic camera, current technology limits average lens-film resolution to approximately 50 lines per millimeter. Thus, as indicated by line 1, a standard 6 inch camera, flying at 125 n.m. altitude, with this resolution, would produce a ground resolution of about 27 meters. Comparing this number against the resolution requirements stated earlier, it is evident that such a camera system would provide map content adequate for maps at about 1:500,000 scale. In order to obtain the 12 to 15 meter resolution required for maps at 1:250,000, a frame camera of 12 inch focal length, indicated by line 2, would be required.

To produce adequate resolution for the larger map scales with wide angle camera systems restricted to 50 lines per millimeter would

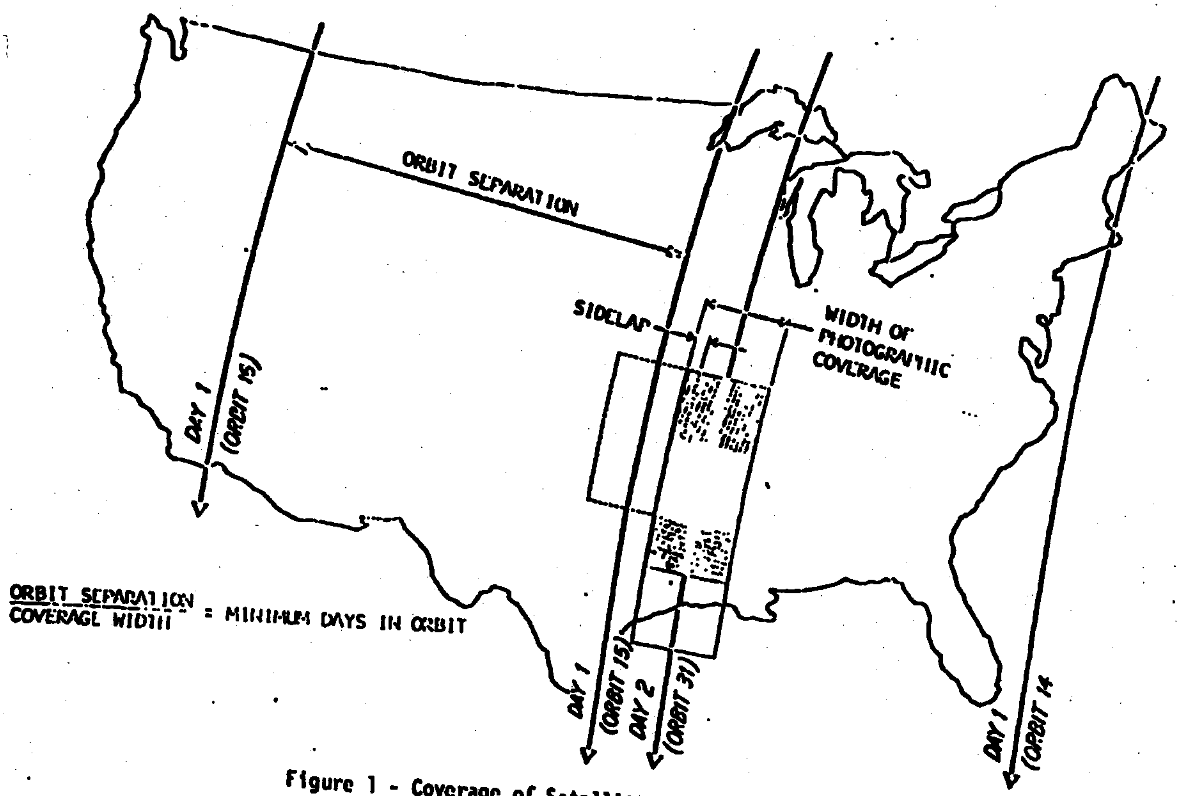


Figure 1 - Coverage of Satellite Photography

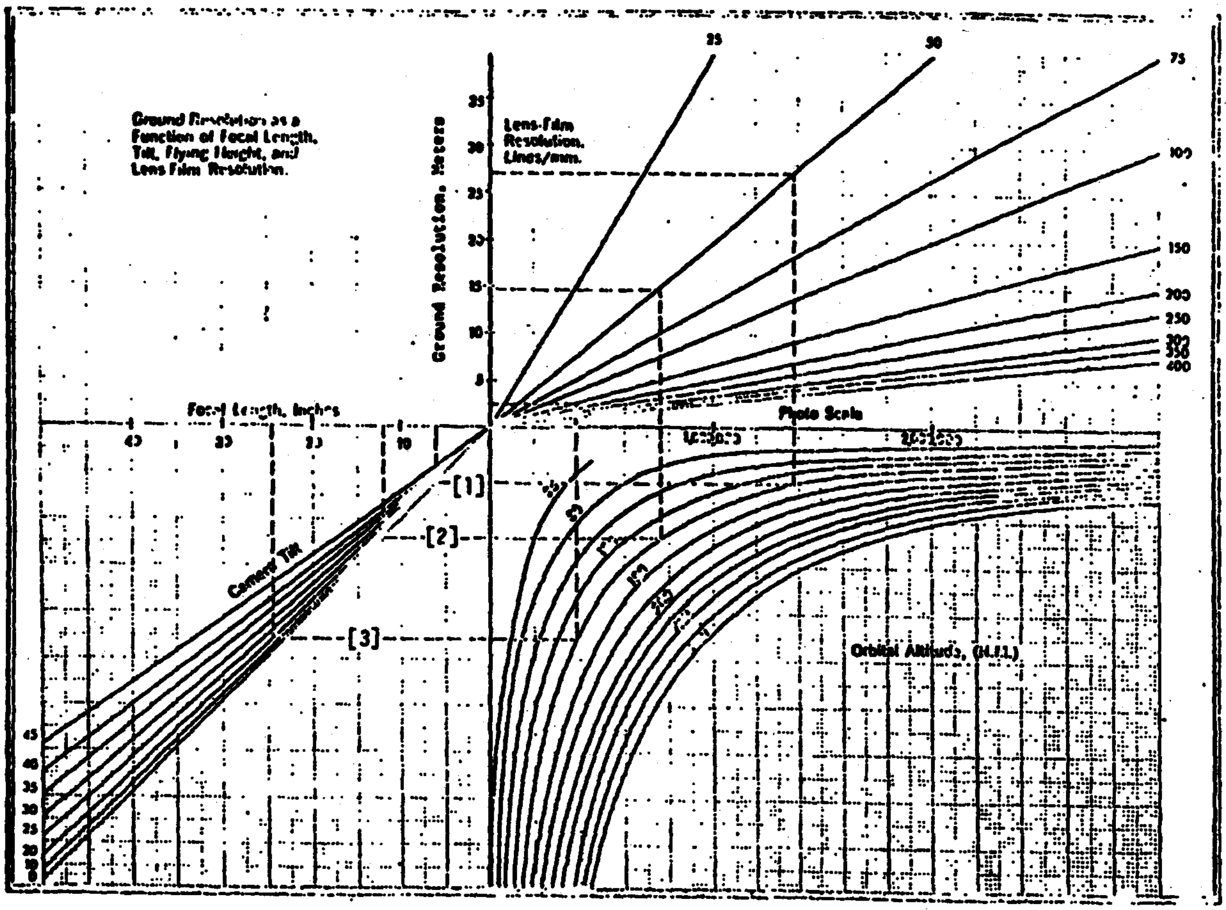


Figure 2 - Relation Between System Parameters

require cameras of extremely long focal lengths and unreasonable film formats. For this reason consideration is given to panoramic cameras which are capable of producing resolution between 100 and 200 lines per millimeter. Such cameras, however, have inherently poor geometric fidelity, and cannot satisfy the requirements for position and elevation accuracy. Line 3 on the chart shows that a 24 inch panoramic camera at 150 lines per millimeter could produce about 2 meters ground resolution - adequate for standard maps at scale 1:50,000, or, by relaxing the resolution criterion slightly, for maps at scale 1:25,000. Panoramic cameras require sophisticated and expensive photogrammetric instrumentation not generally available. For this reason an eventual operational system for producing or revising large scale maps may well go to longer focal length, narrow angle, frame cameras, which might attain 100 lines per millimeter and a corresponding ground resolution of 3.5 meters. The ground width covered by such a camera would necessarily be small. As a consequence the satellite would require a very long lifetime in order to be able to photograph any desired area with vertical pictures, or else the camera would have to take oblique pictures to the side of the ground track.

Geometric Map Accuracy

At an elementary level, the position and elevation accuracy obtainable by photogrammetric procedures is:

$$dP = \frac{H}{f}\,dx$$

and

$$dH = \frac{H}{f}\;\frac{H}{B}\,dx$$

where

dP = ground position accuracy
dH = ground elevation accuracy
H = flight altitude
B = distance between exposures making up a stereo pair
dx = accuracy of image measurement

Stereo base B is obtained by exposing the photographs at time intervals such that some part of the ground area covered by one photograph is also covered by a following photograph. With the 6 inch standard camera, consecutive photographs overlap by 60 percent and B = 0.6 H. In order to obtain adequate B with a 12 inch camera, a film format of 9 x 14.5 inches is proposed with a 9 inch dimension perpendicular to the flight direction. Consecutive photographs will overlap by 67 percent, and a stereo model will be composed of alternate photographs. This arrangement will provide an effective B = 0.8 H. Because 24 inch cameras have a narrow field of view, they cannot achieve adequate B by overlapping vertical photographs. Consequently two cameras will be required in a "twin convergent" configuration with one camera directed forward along the flight line and the other directed aft. If the angle off the vertical is 20° for each camera, the effective base in each stereo model will be B = 0.7 H.

The current level of accuracy in recovering the position of an image on a single photograph is approximately dx = 0.005 mm. This is representative of the relative accuracy which can be obtained in a single stereo model. However, as every photogrammetrist knows, a stereo model must be scaled, positioned, and levelled before geometric map data can be extracted from it. Conventionally this is done by reference to ground control, and errors accumulate alarmingly as one departs from the control.

In this regard, satellite photography will have an enormous advantage over aircraft photography. The satellite orbit is mathematically predictable, and if the time of each camera exposure is recorded precisely, the position of the camera can be accurately determined. Furthermore, as shown in Figure 3, a photograph of the star field can be made in synchronism with each terrain photograph, and measurement of the stellar photograph will provide the absolute angular orientation of the camera to a few seconds of arc. These data are equivalent to having ground control in every stereo

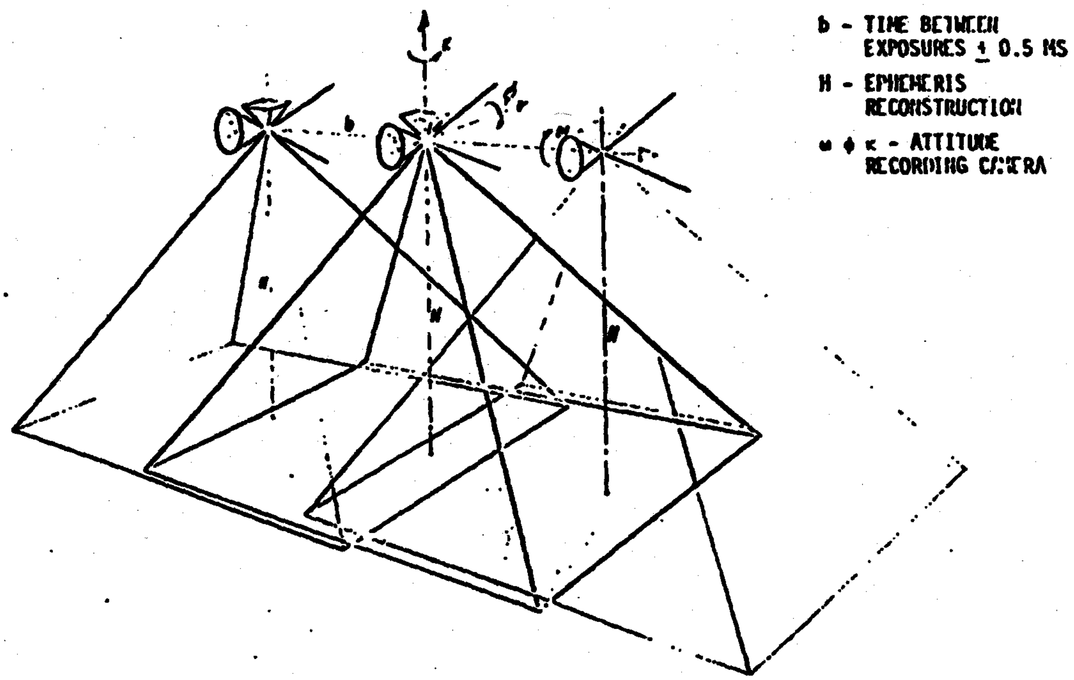


Figure 3 - Exterior Orientation of Satellite Photography

model. The consequence is that errors will not accumulate to the same extent when the photographs are triangulated in a strip or block, and a value of dx = 0.020 mm is expected to be a reasonable estimate of the absolute accuracy with which image positions can be recovered.

If the appropriate values of H, f, B and dx are applied for the three camera systems under consideration, the values listed in the following table are obtained.

GEOMETRIC MAP ACCURACY OBTAINABLE

	6 inch camera	12 inch camera	24 inch camera
Altitude H (125 n.m.)	232 km.	232 km.	232 km.
Focal length f	152 mm.	305 mm.	610 mm.
Relative accuracy position dP	7.7 m	3.8 m	1.9 m
elevation dH	12.8 m	4.8 m	2.7 m
Absolute accuracy position dP	30.7 m	15.2 m	7.6 m
elevation dH	51.3 m	19.0 m	10.9 m

If these geometric numbers and the resolution numbers previously discussed are compared with the requirements for mapping at different scales, the capabilities of the three camera systems can be summarized.

CAMERA SYSTEM CAPABILITY

Relative Mapping	6 inch camera	12 inch camera	24 inch camera
Content for map scale	500,000	250,000	25,000 to 50,000
Position accuracy for map scale	25,000	25,000	10,000
Elevation accuracy for contour interval	50 m	15 m	10 m
Absolute Mapping			
Content for map sclae	500,000	250,000	25,000 to 50,000
Position accuracy for map scale	100,000	50,000	- - -
Elevation accuracy for contour interval	200 m	50 m	- - -

The 6 inch system could satisfy the requirement for world wide small scale 1:1,000,000 and 1:500,000 mapping. The much more serious problem of medium scale 1:250,000 mapping could be satisfied by the 12 inch camera system which also has the important capability of providing adequate geometric control for the preparation of large scale 1:50,000 and 1:25,000 maps. The content for these large scale maps could be provided by the 24 inch camera systems. Thus an ideal system would be composed of both the 12 inch and 24 inch cameras. This would largely satisfy all current requirements for mapping at scales smaller than those needed for actual engineering construction.

What Are The Prospects

A year ago, the Department of the Interior announced its project EROS - for Earth Resources Observational Satellite. Although a number of proposals are under consideration, the most promising seems to be a camera system designed and built by RCA Astroelectronics Division. The camera is the ultra sophisticated child of the highly successful camera used in the now operational TIROS TV weather satellite system. The characteristics of the TIROS and the new vidicon are as follows:

COMPARISON OF TIROS AND EROS VIDICONS

	TIROS	EROS
Tube diameter	1/2 inch	2 inch
Picture area	1/4 inch square	1 inch square
Resolution	400 lines	8000 lines
Resolution elements	160,000	64,000,000
Sensitivity	0.4 ft. candle sec.	0.01 ft. candle sec.

In order to meet the requirements of a large number of scientists in the fields of agriculture, forestry, geology, geography, hydrology, and other natural resource disciplines, it is proposed to use three cameras to acquire photography in three different spectral bands.

These bands are selected to provide:

(a) The sharpest demarcation between land and water areas,
(b) The maximum discrimination of vegetation types,
(c) The greatest penetration of water.

Each frame of the proposed pictures will cover an area of 96 x 96 nautical miles and will provide a ground resolution of 100 to 200 feet from a circular orbit at 300 nautical miles. The orbit inclination will be 97° sun synchronous so that the illumination conditions will be identical for adjacent orbital passes. The satellite will weigh about 850 pounds, and can be launched by a Thor Delta from the Western Test Range. Solar cells and batteries will provide power for the cameras and for a 4 megacycle communication bandwidth required to transmit the pictures to ground stations. A video tape recorder will store the pictures until the satellite is within range of a ground receiving station. A lifetime of at least one year is planned so that repeated coverage can be obtained to determine the time variant characteristics of areas of special interest.

NASA's Lunar Orbiter program has clearly demonstrated the ability to acquire and transmit extremely high resolution photographs from space. However, photogrammetrists have learned to be suspicious of the geometric integrity of transmitted and reconstructed pictures. This fact and the lack of adequate stereo overlap makes the use of EROS photography for geometric mapping marginal.

In the Apollo program, it will be necessary to perform a number of Earth orbit missions to check out various parts of the system and procedures. NASA is studying the possibility of using one of these missions to carry a number of Earth sensing experiments. Among these would be a 6 inch focal length, 9 x 9 inch format, cartographic camera with a coupled stellar camera.

A study has been performed by Martin-Marietta Corporation to define the integration of this experiment with the other sensors and the spacecraft. They have proposed a new equipment carrier module which would replace the Lunar Module. It will consist of a welded aluminum truncated cone enclosure 84 inches in diameter at the experiment mounting end and 110 inches long overall. A truss, which will support the cone in the spacecraft adapter, will also serve to support all experiments not requiring in-flight access or pressurization. The cone itself will be pressurized and the camera system will be among the experiments in the pressurized section. The astronaut will have access to the experiment section through the air lock for such functions as changing the film magazines.

In operation the command and service module with the equipment carrier module will have its longitudinal axis normal to the Earth's surface and the cartographic camera will look down through the base of the cone. This configuration will provide the astronauts maximum terrain visibility through the Command Module windows.

The proposed parameters for the Apollo mission are:

APOLLO MISSION PARAMETERS

- Cartographic camera

  6 inch focal length, 9 x 9 inch format

- Orbit

  140 n.m. circular, 50° inclination
  (provides complete U. S. coverage)

- Lifetime
    - 14 days
      (provides 2 looks at every point)
- Film load
    900 frames each covering 210 x 210 n.m.
    (limited by stowage in CM for return to Earth)
- Total coverage
    13 million square miles
- Proposed launch date
    Spring 1969

Manned missions are extremely costly to fly, and they are restricted in the amount of photographic film and other data which can be physically returned to Earth. For these reasons, NASA is also considering unmanned photographic missions, and a study has been performed by Lockheed Missiles and Space Company to define the characteristics of such a system.

NASA envisions a spacecraft, illustrated by Figure 4, carrying three 6 inch focal length, 9 x 9 inch format, cartographic cameras. The use of three cameras will provide the multi-spectral capability for resource evaluation in addition to cartography.

The exposed film would be returned to Earth in a data recovery capsule. This part of the system has been developed and proved by General Electric Re-entry Systems Division for use in several Air Force experimental programs.

The general procedure is to mount the experiment instrumentation (cameras in this case) in the spacecraft and to feed the data (exposed film) to the attached re-entry vehicle. When the data acquisition mission is completed, the recovery vehicle is separated from the spacecraft and reenters the atmosphere. A parachute is deployed and the data package is snatched by aircraft. The spacecraft itself is then deboosted and splashes into the ocean. The recovery technology is clearly available. It remains

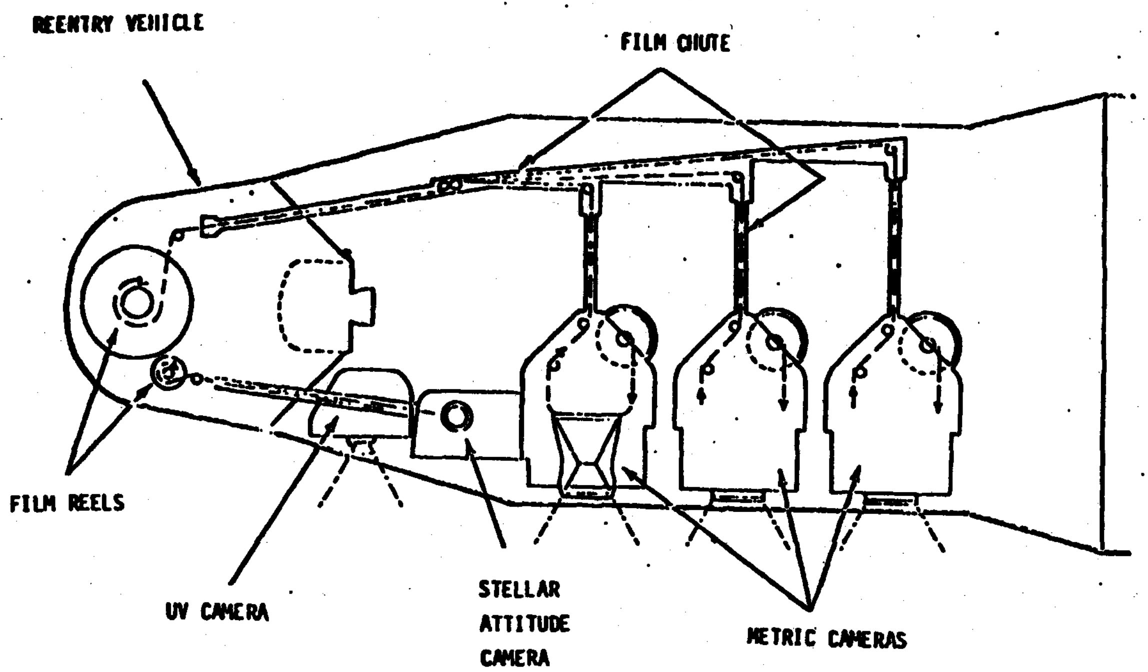


Figure 4 - Schematic for Film Recovery Satellite

to adapt the re-entry vehicle to the handling of photographic film. It is estimated that between 100 and 200 lbs. of exposed film could be returned from a single mission. With the vehicle in a sun synchronous polar orbit, with a lifetime of 3 weeks, a single camera could photograph nearly 30 million square miles. If the film load were divided among three cameras, the system could cover the entire United States in several spectral bands with a high probability of getting successful coverage.

What Are the Chances of Success

When a spacecraft is in orbit, its lifetime is necessarily limited. Since all costs have been accrued when the lifetime is terminated, the success depends entirely upon whether the mission objective has been accomplished during the lifetime. For a photographic mission, this is critically dependent upon the weather--or more specifically on the percentage of cloud free area during the daylight hours. Many studies of world wide cloud distribution have been performed, and the results of a number of them may be summarized as follows:

(1) With one look, a satellite will probably photograph 50 percent of the desired area. A second look will probably get 50 percent of the remainder; a third look 50 percent of what is left. This series would require an infinite number of looks to get 100 percent coverage. On the other hand, 4 looks would give 94 percent coverage and 5 would give 97 percent.

(2) To acquire photography at least 84 percent cloud free over the United States, a satellite launched in September would require 2 looks for the total southwest and a major portion of the midwestern and eastern sections; 3 looks would get most of the northwest but would still lose a section through Texas, Missouri, and the Dakotas.

(3) The probability of successfully photographing an area as a function of its percentage of possible sunshine is:

Percent of sunshine	Probability of success 2 looks	 4 looks
Over 90	0.99	0.99
80 - 90	0.95	0.99
70 - 80	0.90	0.99
60 - 70	0.82	0.96
50 - 60	0.75	0.93

(4) The percentage of coverage with an 0.9 probability of 1 or more cloud free passes is:

	2 looks	4 looks
U. S. - summer	84%	98.5%
U. S. - winter	20	77.5
World - all year	17	65

As a generalized conclusion, these studies seem to converge on the fact that a system providing 4 looks at the areas of interest is approaching the point of diminishing returns. With a 4 week lifetime for the spacecraft, the 12 inch camera would get 2 looks, and the 24 inch camera 1 to 4 looks depending upon the configuration selected. One or two satellites would probably achieve adequate coverage of all areas which are not perenially cloud covered. To hope to photograph such areas from a satellite is probably not realistic.

Is It Economically Feasible

Presume that an unmanned satellite is launched carrying both the 12 inch and 24 inch camera systems, and that a 200 lb. film load is distributed so that both cameras would be able to photograph the same total area. Using thin base black and white film and the orbital altitude of 125 n.m., each of the camera systems would be able to photograph 9 x 10^6 square miles. If the total mission cost is \$15 x 10^6, the photography costs \$1.67 per square mile for double coverage. Even if the photography is only 50 percent useful, the cost is \$3.34 per square mile.

Compared to these costs, conventional aircraft photography in the U. S. costs the U. S. Geological Survey between \$2.50 and \$4.00 per square mile on contract basis. Foreign photography, based on 650,000 square miles in South America, costs the U. S. Air Force about \$12 per square mile for single coverage. Thus purely on the basis of cost per square mile, space photography, particularly of remote areas, is clearly more economical.

The problem with these figures is that 1000 square miles from a satellite would cost the same \$15 x 10^6 as the 9 x 10^6 square miles. Looking at the problem in this way, and using \$4 per square mile as the cost of airplane photography, the breakeven point would occur at 3.75 x 10^6 square miles. That is, if more than 3.75 x 10^6 square miles of photography are required the satellite is the economic way to get it.

The fact of the matter is, however, that the total map producing capability of the United States could not turn out 3.75 x 10^6 square miles of conventional mapping in a year. However, the basic reason for this is found in the number of photographs involved.

Figure 5 shows the coverage produced by conventional aircraft photography compared to that which would be given by the 12 inch frame and 24 inch panoramic cameras. Also shown is the area of a standard 1:250,000 scale map sheet.

To photograph the 3 x 10^6 square miles in the United States, a standard 6 inch mapping camera flown at 30,000 feet would require a minimum of 100,000 stereo pairs. The proposed 12 inch camera system flown in a satellite would cover the same area in about 500 stereo models. To process 100,000 stereo models is unreasonable, whereas 500 is clearly within the capability of most agencies.

In addition to the simple processing of 100,000 stereo models, mapping by conventional photogrammetric procedures would require several hundred thousand ground control points at about \$300 per point, whereas the 500 stereo models of space photography could be compiled with a few thousand control points. Of even greater importance is the fact that

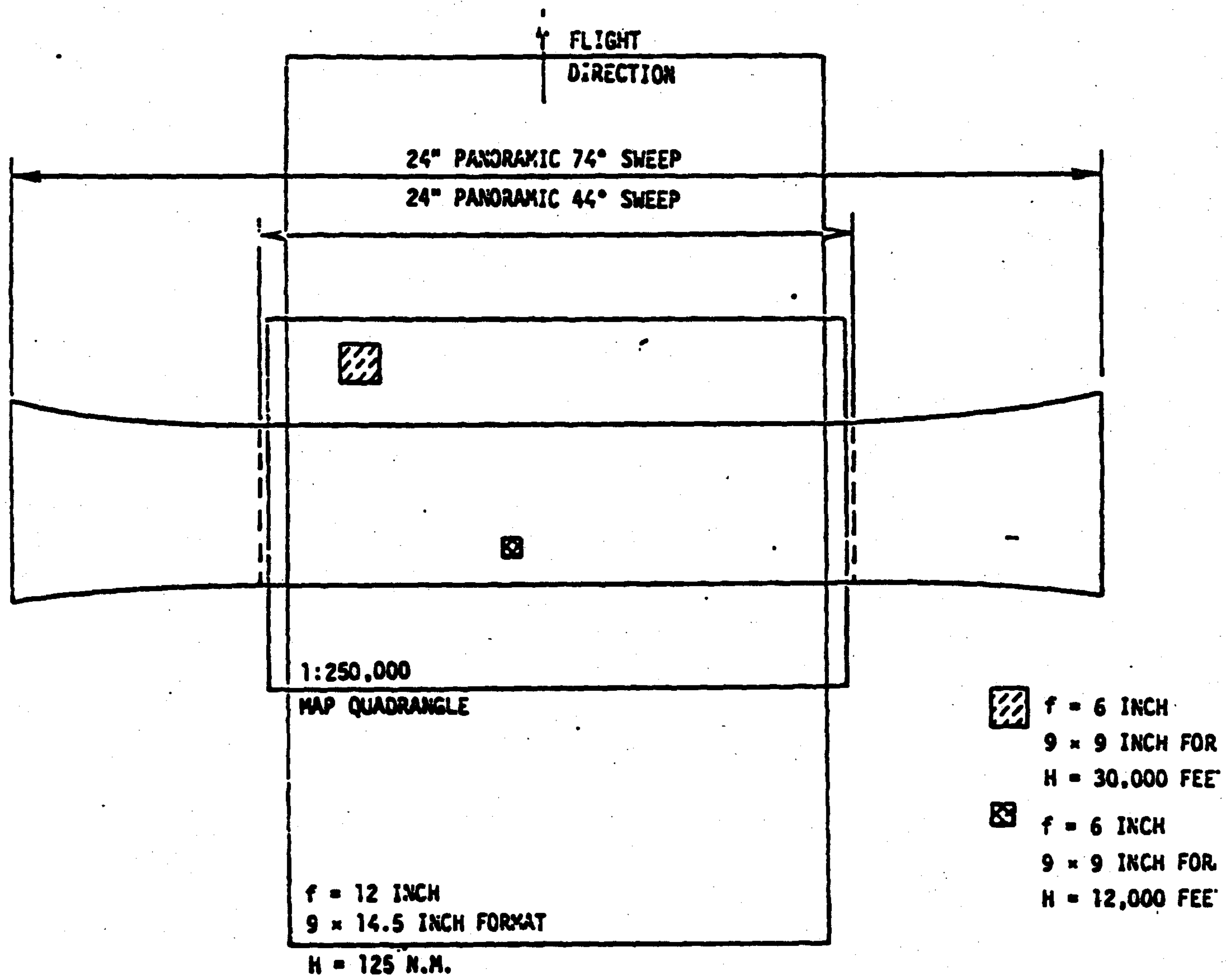


Figure 5 Comparison of Coverage Obtained From Aircraft and Satellites

the control points for the space photography could be established by triangulation of the photographs themselves. This is not possible with the conventional photography because the errors in the triangulation accumulate with the square of the number of photographs involved. This is basically what makes it possible to predict that space photography will be able to do the job at all.

The remaining question is whether the 500 stereo pairs will do the same mapping job as the 100,000. This is the great imponderable, because there is no experience in mapping from space photography. The figures indicate that the proposed systems will probably do the job, if other parts of the mapping system are given the same attention as the spacecraft and its cameras.

The final fact is that with space photography, useful products can be made which are totally impossible from conventional aerial photography. These include:

a) A synoptic mosaic of continental areas at scale of 1:1,000,000 or 1:500,000 which is obtainable from the 6 inch photography.

b) Photogrammetric control for maps at scale 1:24,000 anywhere in the world. This is obtainable from the proposed 12 inch photography.

c) Compiled maps at scale 1:250,000 anywhere in the world. This is also obtainable from the proposed 12 inch photography.

d) Large scale, rapid response, mosaics and revised maps for any selected area in the world. These are obtainable from the proposed 24 inch photographs.

No economic analysis of space cartography would be complete without consideration of the data processing part of the map production routine. Only about one third of the current processing involves the photographs. A cartographic satellite does not improve the remaining two thirds. But it drastically alters the inputs, both in type and in quantity. The formats and focal lengths of space photography may be, to a large extent, incompatible with the current data reduction instrumentation. Clearly, if satellite photography is to be useful on a production basis, detailed consideration and planning is required throughout the whole course of the map making cycle. This extends as far as a re-education of map users who may find it necessary to revise their notions of what is an acceptable map.

Conclusion

We see before us both an opportunity and a challenge. We have the prospect of obtaining a knowledge of the Earth's surface and its resources in detail which we could not have imagined ten years ago. Our generation may be in the position to complete the world mapping task which was started 5000 years ago when the Babylonians first put stylus to clay to guide a caravan across the desert.

PHOTOGRAMMETRIC GEODESY
ON THE
MOON

[redacted]

Raytheon Company
Space and Information Systems Division
Alexandria, Virginia

Annual Meeting
American Society of Photogrammetry
March 1968

8041804

PHOTOGRAMMETRIC GEODESY ON THE MOON

[redacted]

Introduction

There can be little doubt that the major technological achievement of this decade will be the landing and recovery of men from the surface of the Moon by NASA's project Apollo. The recent successful tests of the Saturn V booster, the Apollo capsule, and the Lunar Module have made it evident that it is only a matter of a few months until this accomplishment will take its place in history beside the travels of Marco Polo, the discovery of America, the exploration of the Pacific, and the voyages to the North and South Poles. Every one of these historical ventures was followed by a sustained program of exploration and eventual utilization of the areas discovered. Unless the initial Moon landing is followed by a similar cycle of exploration and utilization of its resources, our generation's technical triumph will go down as nothing but an enormously expensive grandstand pla

NASA has, of course, recognized this fact and has been actively studying the course of future lunar and planetary exploration. The ultimate goals of the nation's space program have been defined by the President's Science Advisory Committee [1] as a search for the answers to the questions:

- Does life abide in places other than the Earth, and if so what is its nature, how did it evolve and what are its probable forms elsewere?
- What is the origin and evolution of the universe, and what is its ultimate destiny? What is the place of our Sun and solar system in it? Do natural laws as we know them on Earth indeed govern the behavior of every observable part of the vastness of space?
- What are the physical conditions on the Moon and on the other planets in our system, and how did our solar system evolve? What dynamic relationships between the Sun and the planets shape their environments?

These broad objectives will be achieved by systematic pursuit of more limited specific objectives in the scientific disciplines of geology, geophysics, geochemistry, bioscience, particles and fields, and astronomy. Although geodesy and cartography are considered valid sciences in their own right, they also serve as essential base knowledge for the other disciplines, and in general, other scientists simply presume that adequate cartographic support will be available for their experiments.

The Space Science Board of the National Academy of Science met at Woods Hole, Massachusetts, during the summer of 1965, to relate these broad goals to the lunar exploration program in the post Apollo period. The specific objectives which they defined for the Moon are:

- Determine the origin and history of the Moon;
- Determine the composition, structure, and processes of the lunar surface;
- Determine the composition, structure and processes of the lunar interior;
- Determine the existence and the structure of any organic compounds indicating the presence of life on the Moon.

In order to recommend experiments which would implement these basic objectives, a conference of scientists interested in lunar exploration was convened by NASA in Falmouth, Massachusetts, July 19 - 31, 1965 [2]. A second conference on lunar science and exploration was convened at Santa Cruz, California, July 31 to August 13, 1967, to update and revise, as necessary, the findings of the Falmouth conference [3]. Both conferences contained Geodesy and Cartography Working Groups whose reports document a set of scientific objectives in this area. In addition, the Geology and Geophysics Working Groups at the two conferences imposed requirements for cartographic support of their own programs. In many instances, this cartographic support is implied rather than stated explicitly.

Requirements for Lunar Geodesy and Cartography

At the Falmouth conference the Geodesy/Cartography Working Group outlined the essential steps in the development of cartographic knowledge of the Moon:

- Establish a selenodetic coordinate system related unambiguously to the right ascension-declination system.
- Describe, in sufficient detail, the gravitational field of the Moon.
- Derive a reference figure with respect to a point which is representative of the Moon's center of mass.
- Establish a three-dimensional geodetic control system over the entire lunar surface in terms of latitude, longitude, and height above the chosen reference figure.

To complete these tasks it would be necessary to:

- Define and develop systems for the collection of raw data which are suitable for compilation of topographic maps of various scales, using photogrammetric methods.
- Define and develop techniques and instruments for the reduction of acquired data and presentation of these data in useful form.
- Select and implement additional geodetic measurements to provide complementary results for analyzing in depth such phenomena as rotation and physical librations of the Moon, lunar tides, etc.
- Establish specific research and development programs which show promise of effecting significant improvements in knowledge of lunar geodetic parameters.

At the Santa Cruz conference the Geodesy/Cartography Working Group recognized the common metric character of a group of vitally interrelated topics:

- The lunar ephemeris describing the position of the center of mass of the Moon.
- The angular orientation and motion of the Moon about its center of mass.
- The gravitational field of the Moon.
- The size and shape of the Moon's surface.

They described the present state of knowledge on these topics, and, most importantly, defined the types of measurements which would result in a compatible accuracy for each of the parameters.

The Geology Working Group of the Falmouth conference recommended a systematic program of lunar mapping at various scales. At the Santa Cruz conference, the group modified their earlier recommendations, and the current map requirements are:

- Orthographic, Mercator, and Polar Stereographic projections of the whole Moon (approximately 10 sheets) at scale 1:5,000,000.
- Complete topographic coverage of the Moon (144 sheets) at scale 1:1,000,000.
- Coverage of approximately 20 areas of interest as Apollo Applications Program (AAP) landing sites and traverses (approximately 100 sheets) at scale 1:250,000.
- Coverage of central parts of 20 areas of special interest (approximately 20 sheets) at scale 1:50,000.
- Coverage of landing sites in the central portion of AAP sites (80 sheets) at scale 1:5,000.

Contour intervals were not specified for any of these map series, but are expected to be compatible with the character of the terrain.

In addition, the Geology Working Group spelled out the requirements for an Earth based Scientific Data Center which would have, among others, the capability of producing large scale topographic maps in near real time from TV or electromechanical scanner data obtained from landed and mobile vehicles.

Before defining systems for producing map data it is appropriate to translate these map requirements into photogrammetric terms. Based on U. S. map accuracy standards, the standard error of positional coordinates may not exceed:

$$\sigma_p = 0.03 \text{ mm x map scale number,}$$

and the standard error of elevations should not exceed:

$$\sigma_h = 0.3 \text{ x contour interval.}$$

The ground resolution required for compiling terrestrial maps is dictated primarily by the cultural features (roads, buildings, etc.) which must be included. These are nearly independent of map scale, and hence required resolution is not linearly related to map scale. On the Moon, however, cultural features are expected to be absent, so that a linear relation seems justified.

The smallest feature which could be depicted on a map would have a least dimension of about 0.25 mm. In order for an object to be photographically identifiab it must be imaged by about 5 resolution elements. The required surface resolution for photography is thus:

$$\text{ground resolution} = 0.05 \text{ mm x map scale number.}$$

The reasonableness of this figure may be judged by noting that it means the map should have a resolution of 20 ℓ/mm. This is a little better than the resolving power of the unaided human eye. Consequently an orthophotograph (which seems the most useful representation of the lunar surface) made to this criterion would contain all the information which a human could extract without enlarging the map scale by magnification.

The criteria represented by these formulas may be applied to the standard map scales and contour intervals. The results are given in Table 1.

Table 1
MAP ACCURACY REQUIREMENTS

Map Scale	σ_p (meters)	resolution (meters)	c.i. (meters)	σ_h (meters)
2,500,000	760	125	1000	300
1,000,000	300	50	500	150
250,000	76	12.5	100	30
100,000	30	5.0	50	15
50,000	15	2.5	25	8
25,000	7.6	1.3	10	3
10,000	3.0	0.5	5	1.5

These represent the numbers against which the performance of a photogrammetric system should be evaluated.

Lunar Camera Systems

It is abundantly clear that many of the geodetic objectives and most of the cartographic requirements can be satisfied by using orbiting spacecraft as a platform for metric cameras and other sensors. A great number of proposals for lunar camera systems have been made ranging from 1 1/2 inch to 144 inch focal length and including both transmitted and recovered photography. These various suggestions may be played against the geodetic and cartographic requirements and the restraints on photography imposed by lunar photometric response and illumination, vehicle attitude and stability, lunar rotation, image motion, film response, etc. Without going into detail on all the analysis involved, several camera systems emerge as clearly desirable:

- For complete lunar coverage and small scale mapping, a 3 inch focal length, 4 1/2 x 4 1/2 inch format vertical camera.
- For complete lunar coverage and medium scale mapping, a 12 inch focal length, 9 x 14 1/2 inch format vertical camera.
- For independent determination of mapping camera orientation, a pair of synchronized stellar cameras of 6 inch focal length, 70 mm format.
- For large scale site mapping, a pair of 24 inch, 4 1/2 x 9 inch format convergent cameras.

Because of the wide availability of 6 inch focal length, 9 x 9 inch format cameras, they are considered an acceptable substitute for the 3 inch cameras, and a fall back solution in case vehicle or mission restraints make it impossible to employ the 12 inch camera system. Physical film recovery is considered essential to assure cartographic integrity of the photography.

In addition to the cameras, the spacecraft will require transponders to permit accurate orbital tracking, a vehicle clock capable of being related to ephemeris time with an accuracy of ± 0.001 second, and a pulsed altimeter capable of about ± 2 meter accuracy. The clock and altimeter readings should be synchronized with the camera exposure and recorded in a data block on the film.

In order to provide complete coverage of the lunar surface, it is apparent that the spacecraft will have to be in a near polar orbit, and if total coverage is desired from a single mission, the time in orbit would be a complete lunation of 28 days. Furthermore for efficient coverage, the altitude should be such that the width of the area covered by the photography is some multiple of the approximately 33 km separating consecutive orbital passes as they cross the equator. For the proposed camera systems this altitude works out to be 93 km. Obviously if the sidelap is near zero at the equator it will be 50 percent at latitude ± 60°. The cameras may therefore be turned off at this latitude on alternate photographic orbits.

The capabilities of these camera systems are summarized in Table 2.

Table 2

CAPABILITY OF CAMERA SYSTEMS

Item	3 inch	6 inch	12 inch	24 inch
Orbit altitude, km	93	93	93	93
Photograph on orbits	1,5,9	1,5,9	1,3,5	any
Photograph scale	1:1,225,000	1:612,000	1:306,000	1:153,000
Stereo model ($\ell \times w$)(km)	63 x 140	63 x 140	50 x 70	19 x 36
Content for map scale	1:250,000	1:100,000	1:50,000	1:20,000
Control for map scale	1:100,000	1:50,000	1:25,000	----
Contour interval (m)	100	50	30	10
Frames for 100% cover	6000	6000	14,700	----
Film wt. for 100% cover (lb)	23	82	322	----
Geodetic positions σ_p (m)	35	17	8	----
Geodetic elevations $^{p}\sigma_h$ (m)	36	18	11	----

It is appropriate to say a few words about the camera systems in the recently successful Lunar Orbiter series. As is well known, the spacecraft contained a medium resolution (MR) 3 inch focal length camera, and a high resolution (HR) 24 inch focal length camera. The pictures were transmitted and reconstructed on Earth in framelets which were subsequently assembled into full or partial frame pictures. The system was designed to photograph potential Apollo landing sites. It was not designed with cartographic objectives in mind, and efforts to perform photogrammetric operations with the records have been time consuming and produced accuracies far below those anticipated for the 3 inch and 24 inch systems listed in Table 2. The organizations charged with measurement of the Lunar Orbiter records have achieved 0.030 mm standard error in image coordinate residuals; this is to be compared with the 0.005 mm customarily obtained in comparable measurements of actual film. In addition to the decrease in accuracy, the division of the record into a large number of scanned segments has imposed a tremendous data reduction load. In the triangulation of a single 16 photograph strip it has been found necessary to measure over 12,000 separate points in order to remove image nonlinearities, to tie the individual framelets together, and to provide the required geometrical distribution.

Lunar Cartographic Spacecraft

At this point in time there are no firm approved programs for new lunar exploration spacecraft. Many scientists feel that it would be more economical to develop unmanned, but recoverable, orbiting spacecraft specifically designed and optimized for particular missions even if this means delaying the exploration by some few years. However, the Apollo systems hardware already exists, and the only serious study to date has been performed by Martin-Marietta Corporation to define the integration of the cartographic cameras with other sensors and the spacecraft [4]. They have proposed a new equipment carrier module which would replace the Lunar Module. As shown in Figure 1, it will consist of a welded aluminum truncated cone enclosure 84 inches in diameter at the experiment mounting end and 110 inches long overall. A truss, which will support the cone in the spacecraft adapter, will also serve to support all experiments not requiring in-flight access or pressurization Among these may be unmanned subsatellites and landers to emplace experiments on the lunar surface. The cone itself will be pressurized and the camera systems will be among the experiments in the pressurized section. The astronaut will have access to the experiment section through the air lock for such functions as changing the film magazines.

As shown in Figure 2, the command and service module with the equipment carrier module will have its longitudinal axis normal to the Moon's surface and the cartographic camera will look down through the base of the cone. This

Figure 1 - Apollo Equipment Carrier in Lunar Configuration

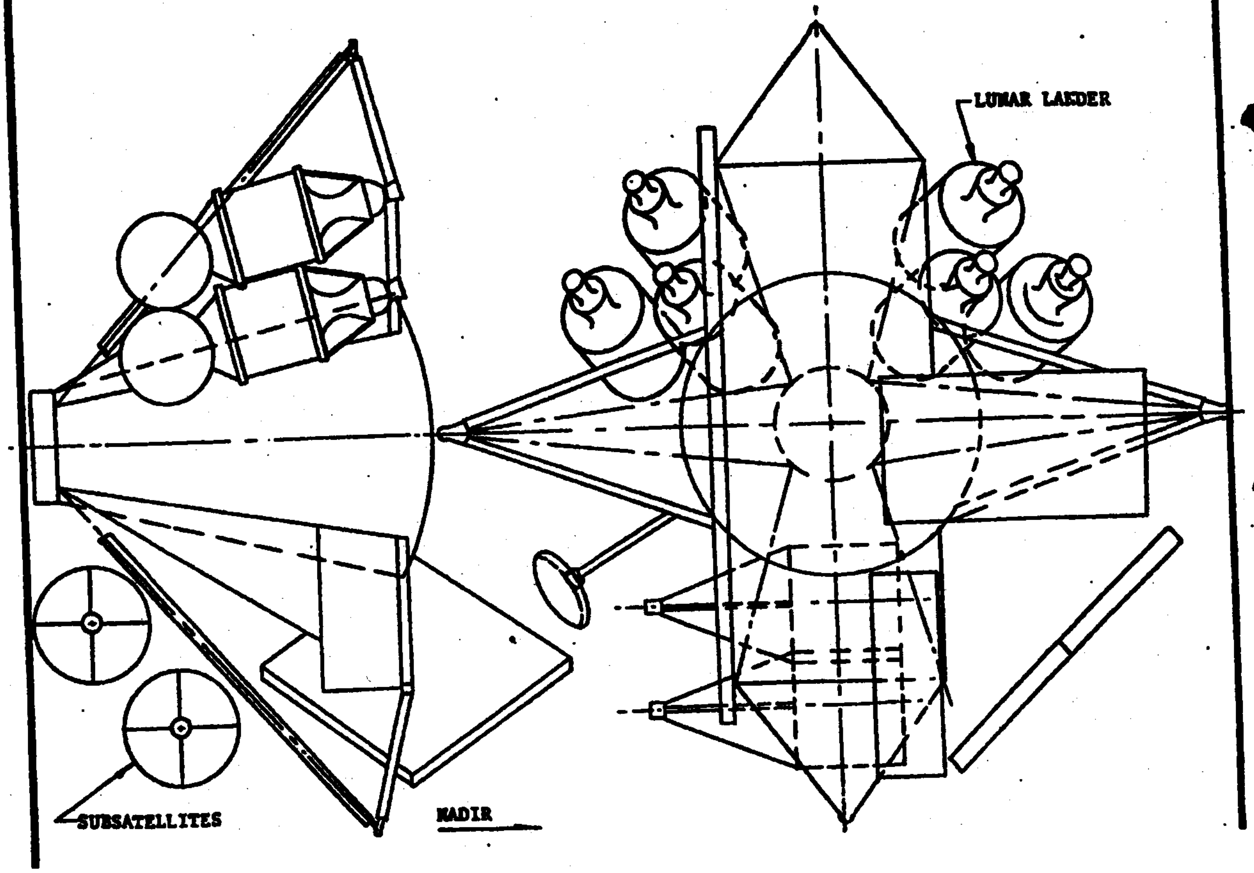
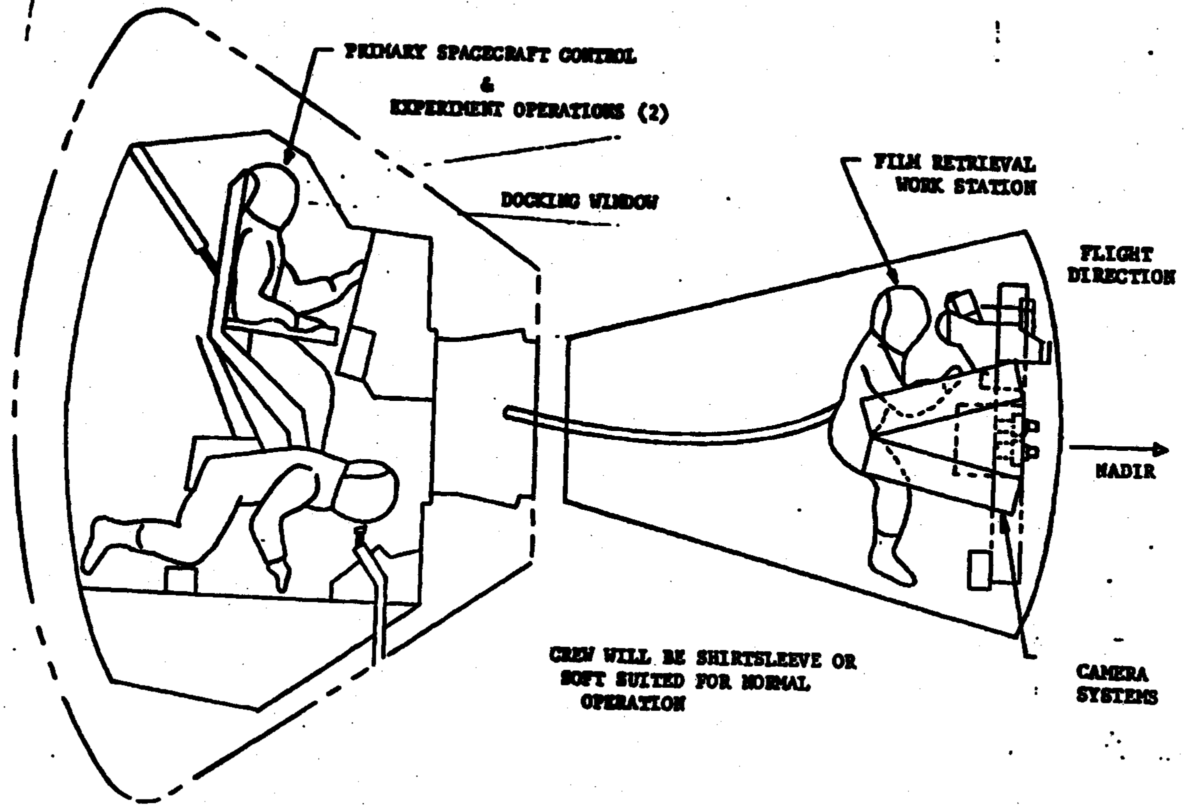


Figure 2 - Crew Positions for Apollo Lunar Mission



configuration will provide the astronauts maximum terrain visibility through the Command Module windows. In 12 days of operation the system would acquire cartographic quality photography of 40 percent of the Moon's surface. It could perform all the required special site photography.

Data Reduction of Lunar Photography

The Lunar Orbiter records are the only Moon photography which will be available for several years to come. The Manned Spacecraft Center, the Army Map Service, and the Aeronautical Chart and Information Center are making valuable map products from these records:

- Site Geometry - Triangulation of the MR photography of the first three Lunar Orbiter missions and the scientific sites photographed by Orbiter V provides photogrammetrically established control for the individual areas covered by the missions. The resulting topographic data points are internally consistent by virtue of the photogrammetric constraints, but are related to the Moon's center of mass only to the extent that the input spacecraft positions are given with respect to the center of mass. Relative uncertainties of the positions and elevations so determined are presently on the order of 150 meters in position and 300 meters in elevation. Uncertainties of elevations with respect to a lunar mass centered coordinate system are on the order of 500 meters. These uncertainties apply to all map and mosaic products based on this triangulated control.
- 1:100,000 scale uncontrolled mosaics. These are produced on a quick response basis using the MR photography to provide an overall view of the area photographed at a common scale.
- 1:25,000 scale uncontrolled mosaics. These are produced on a quick response basis using the HR photography.

- 1:100,000 controlled mosaics. These are produced utilizing the control established by the triangulation of the MR photography.
- 1:25,000 controlled mosaics. These are produced from the HR photograph utilizing the control established by the triangulation of the MR photography.
- 1:100,000 topographic maps. These are produced utilizing the MR photography and the control established by the triangulation of the MR photography. Compilation is by conventional stereoscopic plotting instruments. They contain 100 meter contours and shaded relief rendition.
- 1:25,000 topographic maps. These are produced from the HR photography of Mission I, and are scaled to the control established by triangulation of the MR photography. Originally, contour data was to be provided by photometric analysis of the HR photography, but this has not yet become operationally feasible. Contours (or more appropriately, form lines) at 25 meter intervals are compiled from the MR photography at the same time the 1:100,000 maps are produced. The maps also contain shaded relief rendition. These map products have been dropped from the later missions.

From Orbiter IV photography and the high altitude photography of Orbiter V, the following products are under consideration:

- Lunar Control Net - Although the geometry of Orbiter IV and V MR photography is poor from a photogrammetric point of view, the fact that nearly the whole Moon is covered makes it attractive to attempt to establish a complete lunar control net. This net should be more extensive and consistent than the present nets established by the Department of Defense Agencies from Earth-based telescope photography. The accuracy is expected to be comparable with the best positions and elevations in the current network.

The approach is to use strip triangulation to provide initial values for a more comprehensive block adjustment program. An alternate approach to the development of a complete lunar control net is to employ the HR pictures from Orbiter IV and V. These pictures have inadequate overlap to permit a conventional photogrammetric triangulation, and consequently will be totally dependent upon orbital position data. However, incorporating them in a triangulation program with adequate orbital constraints will produce consistent results. Preliminary analysis indicates that accuracies of about 250 meters may be expected.

- Controlled Mosaic - Based on the triangulated control net, it is feasible to produce a controlled mosaic of the near side of the Moon at a scale of 1:1,000,000 using the HR photography of Missions IV and V.
- Atlas - A photographic atlas of all Orbiter IV and Orbiter V far side photographs is obviously feasible. This would simply be an assembly of the photographs, indexed and keyed to a lunar coordinate system.
- Lunar Astronautical Charts - The current lunar map series is the Lunar Astronautical Charts (LAC), scale 1:1,000,000 consisting of 44 sheets covering most of the visible face of the Moon. This series is produced from Earth based telescope photography supplemented by visual observations. One of the most valuable applications of Lunar Orbiter photographs would be the revision of this series, and extension of coverage to the polar areas and back side. This should be feasible using the control net described above, and the surface detail from both the MR and HR photographs from missions IV and V.

When new lunar photography of high geometric integrity, supported by stellar attitude photography, and laser or radar altimetry becomes available, a whole new set of photogrammetric problems will require attention. No matter how sophisticated the sensors, or how elegantly the data are acquired, their usefulness can be either negated or enhanced by careful consideration of the data reduction problems.

The principal objective will be to provide a unified geodetic control system related to the Moon's center of mass, and serving as a framework for compilation of high accuracy maps. Involved in this problem are several other considerations:

- Celestial orientation of the Moon's axis and short term rotation (physical librations);
- Mathematical reference surface;
- Relation of center of mass to center of figure.

Contributions to knowledge in each of these areas can be obtained from the photogrammetric reductions, and in theory at least, they could all be included as additional unknowns in one grand least squares solution. However, other types of observations and analyses will also be contributing to determination of these quantities. It therefore seems advantageous to solve the photogrammetric problems individually so that the values obtained thereby may be compared and combined with those from other observations systems.

Refinement of Lunar Ephemeris by Star-Surface Photography

Present knowledge of the orientation of the axis of the Moon in the celestial system and the rotation about the axis is not better than approximately 30 seconds of arc. To fully exploit the directional accuracy of the stars in a Moon centered system, considerable improvement in determination of the Moon's axial orientation is needed. This can be provided to a level of accuracy comparable to the angular accuracy of the photography by analysis of simultaneous star-surface photography covering a large part of the Moon's surface.

The basic approach is to compute in a Moon fixed coordinate system by classic photogrammetric techniques the relative orientation between two terrain photographs exposed at some interval of time. The relative orientation of the same two terrain photographs can also be computed in the celestial coordinate system from the corresponding stellar photographs. The differences between the two relative orientations can only be ascribed (apart from inaccuracies in the solution) to the Moon's motion in the time interval between the two exposures. Every pair of conjugate photographs would provide a set of observation equations. A least squares solution would be employed. The initial values would be the Moon's orientation and rotation rate as extracted from the American Ephemeris for the midpoint of the mission. The unknowns would be corrections to the initial values plus the constants in a time polynomial for each of the angles. Although a linear polynomial should be sufficient for missions of short duration, second degree terms might be employed for missions up to a full lunation since 80 percent of lunar motion anomalies have a period of one lunation.

Not all photographs would be used. At latitude ± 60° photographs from adjacent orbits will have 50 percent sidelap and 4 to 8 hours will have elapsed between adjacent photographs. A solution involving these two lateral bands of photography would have good geometric strength and time distribution.

Orientation of Lunar Photography by Simultaneous Stellar Photography

The purpose of stellar photography is to provide an independent determinati of the attitude of the cartographic camera at each exposure, and thereby reduce the error propagation in a photogrammetric triangulation. The orientation values required are those with respect to the principal axes of the Moon, and their calculation must take into account the parameters of the lunar ephemerides, as determined in part by the preceding analysis. This simply means that stellar coordinates must be related to the Moon's equator, and a time scale determined by the lunar rotation rate.

Photogrammetric Triangulation Program Optimized for Lunar Application

To properly exploit the total photographic coverage of the Moon, synchronized stellar photography, and laser or radar altimetry, expected to be provided by the Apollo Applications Program, a new integrated triangulation program is indicated. What is required is a photogrammetric triangulation program which will be self-sufficient, which will absorb all observations of accuracy comparable to photogrammetry, and which will not be dependent upon control points on the surface in order to reach a solution.

To develop such a program, a detailed study is required to determine precisely the requirements and the means for implementation. In this analysis, consideration should be given to the following:

- A choice must be made in the type of photogrammetric condition equations. Collinearity equations are simpler to administer programmatically. However, they require approximations for all ground points, and corrections to these initial ground point coordinates become additional unknowns in the solution. (They do not, however, increase the order of the matrix to be solved.) Coplanarity and scale restraint equations involve only the exposure station parameters without requiring ground point approximations. However, they result in complicated program bookkeeping because each equation involves several exposure stations. A system based on these equations would also include collinearity equations to accommodate ground control points if they were available. It may be necessary, for example, to enforce the ground coordinates of one point in order to relate the triangulation to a lunar latitude and longitude graticule.

  If the triangulation is based on coplanarity and scale restraint equations, it would be necessary to perform space intersections to determine ground point coordinates subsequent to the computation of air station positions and camera attitudes.

- The system must be capable of absorbing measured scale distances. The most probable source of these will be the laser, or radar, altimeter readings taken in conjunction with the photography. However, tracking data may also provide scale distances which may eventually be comparable in accuracy to altimetry. Either type of observation should be acceptable.
- The system should accommodate weighted, functionally described, or enforced camera attitude data. If preceded by proper analysis of lunar motions, camera attitudes obtained from stellar photography may be sufficiently accurate to be enforced rigidly in the solution, thus eliminating three unknowns per photograph. Spacecraft attitudes usually vary slowly, and a valuable approach is to describe the change in each attitude angle by a Fourier or polynomial function. The constants of these functions then replace the actual angles as unknowns. To make the system flexible enough to handle small blocks or situations where star camera or other attitude data may not be available or useful, it should be possible to solve for the attitudes, but even in this situation, it should be possible to weight the initial approximations.

  A modular program permitting either of these approaches to the computation of orientation angles would be desirable.
- It should be possible to impose orbital constraints on the air stations. This will both reduce the number of unknowns in the solution and will strengthen the geometry. It is the obvious way of introducing tracking data into the solution.

  Considerable study is needed to determine the best way of introducing such constraints. Initial Keplerian elements with time polynomials for changes in the elements is an appealing approach. Such time series are capable of absorbing the effects of large scale gravity field anomalies. The number of orbital passes to be included in a single orbital function is also a subject for serious study.

Continued tracking of lunar satellites will provide gravity harmonics independent of any photogrammetric triangulation. Depending upon the magnitude of the effects which this gravity field will have on exposure station positions, it may be desirable to include the gravity model coefficients as weighted parameters in the orbital model.

There is no thought that the development of such a computer program would start from scratch. Many elements of the program are already available. But a thorough analysis is required to provide an optimum operational program.

In addition, study needs to be devoted to define the data handling routine for a task of this magnitude. Undoubtedly, it would not be advisable to start out initially with a large solution involving the total Moon coverage. A probable procedure would be as follows:

(1) Correction of observed image coordinates for film distortion, reduction to principal point, blunder eliminations, etc.
(2) Computation of stellar attitudes and transformations to terrain camera attitudes.
(3) Sequential strip triangulation of individual half orbits to edit data and obtain good approximate values.

(4) Triangulation of blocks containing up to a few hundred photographs. These could either be parallel strips of half orbit length, or shorter but wider blocks consisting of adjacent parts of several orbits. Probably both would be tried, but in either case considerable overlap would be provided between adjacent blocks.

(5) Simultaneous solution of all photographs utilizing all available constraints.

The output of this program would be a geometrically homogeneous set of coordinate values for all points on the lunar surface included in the data reduction scheme, and position and orientation of the exposure stations in the same coordinate system. With the stellar attitudes based upon analysis of the Moon's axial orientation, absolute lunar latitudes of the triangulated points will be correct within the errors of the orientation computation and the triangulation variances. Relative lunar longitudes will be correct to the same tolerances. Absolute longitude values will be related to a defined meridian based upon a photographically identified point. A landed spacecraft seems to be a good choice for such an initial meridian.

If a 12 inch focal length metric camera constitutes the basic cartographic system, the predicted standard error of photogrammetrically established control points will be about 10 meters in position coordinates and 15 meters in elevation. This is more than an order of magnitude more precise than a control system which might be obtained from the current Lunar Orbiter records.

Lunar Mathematical Reference Surface

Once a homogeneous set of coordinates values for points covering the lunar surface is established by the photogrammetric triangulation, it will be feasible to establish a mathematical reference surface, essentially by a surface fitting procedure. A sphere, spheroid, or three axis ellipsoid could be fitted by minimizing the sum of the squares of discrepancies between the triangulated points and the selected reference surface equations. The equation type providing the minimum residuals could be adopted. If the triangulation is based on stellar directions, the orientation of the reference surface will be with respect to the Moon's axis of rotation. If, furthermore, the lunar gravity model or orbital tracking data are imposed in the triangulation, the origin of the reference surface will be the Moon's center of mass.

Cartographic Plotting

It is apparent that some of the parameters of proposed lunar photography are not directly adaptable to the types of photogrammetric plotting equipment generally available. Consideration needs to be given to the problems:

- Accomodation of new focal lengths and formats.
- Handling of lunar surface curvature.
- Restrictions imposed by shadows in low sun areas.
- Orthophotomap, pictomap, or mosaic presentation of planimetry.
- Contours, slope zones, surface texture, shaded relief presentation of topography.
- Automatic correlation of lunar photography.

Studies of plotting equipment adaptability should be carried out in parallel with development of camera systems and mission plans to provide the basis for selection of available instrumentation, or the justification for new development.

Lunar Surface Photogrammetry

Much of the work to be performed by astronauts on the lunar surface, and by manned and unmanned mobile vehicles operating from a landing site, has cartographic and photogrammetric implications.

- Landing vehicle imaging systems:

  The Lunar Module (LM) may be equipped with TV or film cameras, or an electromechanical scanner whose function would be to record the landing site. The design, installation, operation, and reduction of these records will require research and development.

- Astronaut camera and survey equipment:

  A wide variety of photographic and survey equipment has been proposed for use by astronauts [3] in mapping a landing site. Mono and stereo cameras, Jacob's staff, distance measuring equipment, zenith camera, etc. are included.

- Imaging systems for mobile vehicles:

  Proposals have been made [3] for Local Scientific Survey Module (LSSM) and Lunar Flying Unit (LFU) for mobile operation from a landed spacecraft. The LSSM may have an operating radius of around 100 km in the manned mode and 1000 km in the unmanned mode. The LFU will have an operating radius of a few kilometers. Both vehicles can carry imaging systems which could produce useful cartographic data. The LSSM would probably have a TV system, the LFU a camera. The LSSM system may be required to provide real time navigation data, particularly in the unmanned mode. This would require near real time mapping at an Earth based Data Center from TV or electromechanical scanners as a means of providing guidance and control data to the active system operating on the lunar surface. A complete analysis of such a system is required. It should consider the sensor system, the down and up data links, the ground data processing equipment, procedures, and manpower.

AMERICAN SOCIETY OF PHOTOGRAMMETRY 105 N. VIRGINIA AVE., FALLS CHURCH, VIRGINIA 22046, TELEPHONE: 534-6617

Dr. William T. Pecora
Director
U.S. Geological Survey
Washington, D. C. 20242

Dear Dr. Pecora:

The American Society of Photogrammetry (ASP) is concerned by recent cancellations of lectures and withdrawals of articles that deal with the use of satellites for surveying earth's resources.

Your past support, interest in earth resources satellites (as evidenced by the EROS Program), and your established leadership in earth science, lead me to seek your help in clarifying the situation.

[redacted] the Head of the Department of Geodetic Sciences at Ohio State University, and now Chief Scientist of the Raytheon Corporation, [redacted] Operation, was selected as our distinguished lecturer for 1967-68. [redacted]s his topic 'Mapping from satellite photographs'.

The ASP Distinguished Lecture series is jointly sponsored by the National Science Foundation. [redacted]cture was similar, in content, to that he presented and distributed in reprint form before the Annual Meeting of the AIAA, in Dallas, Texas, November 1967. The first of his series of Distinguished Lectures was presented before the Potomac Region of ASP, November 13, 1967. A comprehensive summary of the paper was published in the January 1968 issue of Photogrammetric Engineering.

[redacted] found it necessary to cancel presentation of his paper before the Annual Meeting of the Canadian Institute of Surveying and Mapping; later he cancelled his scheduled lecture at the University of Delaware, and finally, withdrew entirely from our Distinguished Lecture series. Concurrently, [redacted]written version of his lecture was also withdrawn; this paper had been set in type and was scheduled for publication in the March issue of Photogrammetric Engineering.

It is hard for us to reconcile [redacted]actions with his long history of support to our Society and his reputation for scientific excellence. The scientific facts and extrapolations contained in [redacted]paper are generally known among workers in his field but need wider distribution in the form of publication in journals and texts, and in oral presentation in lecture series. We feel, therefore, that it is very regrettable that [redacted]as found it necessary to cancel additional presentation of his excellent paper.

S&T Cont. No. 1611

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Enclosure

The aim of our Society is to disseminate scientific information and we pursue this aim with vigor. [redacted]s assembled information that is scientifically sound and should be disseminated. I would like guidance from you and any assistance you can provide in making it possible to make [redacted]paper available to the scientific community.

We look forward to hearing from you in the near future.

Sincerely,

Heinz Gruner

Heinz Gruner, President
American Society of Photogrammetry

[redacted] [redacted]

DIRE[illegible]R OF DEFENSE RESEARCH AND ENGINE[illegible]NG
WASHINGTON, D. C. 20301

RAK - 13 - 10
PCL - A - 4
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25 MAY 1968

Dear Mr. Gruner:

This is in response to your recent letter to Dr. Pecora, in which you discussed [redacted] paper, "Mapping from a Satellite System."

I have looked into the matter and find that we imposed the constraints to which you refer because of national defense considerations. As an employee of Autometrics working on Department of Defense projects, [redacted] publications are necessarily reviewed, in order to protect the national interest, as well as his own.

Our representatives discussed the security analysis in detail with [redacted] in December and he concurred in their findings. Recognizing the potential awkwardness of the situation -- very much as described in your letter -- we worked with [redacted] in preparing a clearable paper which has been available since February, and which could very well be considered as a candidate paper for your Distinguished Lecturer series.

I certainly share your interest in disseminating scientific information to the fullest extent possible within considerations of national security. I believe our action with [redacted] has been in consonance with both criteria.

John S. Foster, Jr.

Mr. Heinz Gruner, President
American Society of Photogrammetry
105 N. Virginia Avenue
Falls Church, Virginia 22046

804/8042