NASA TECHNICAL NOTE

NASA TN D-1868

NASA TN D-1868

N65 12201
(ACCESSION NUMBER)

(THRU)

26
(PAGES)

1
(CODE)

(NASA CR OR TMX OR AD NUMBER)

14
(CATEGORY)

FACILITY FORM 602

A REVIEW OF PHOTOGRAPHY OF THE EARTH FROM SOUNDING ROCKETS AND SATELLITES

GPO PRICE $ ______

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Hard copy (HC) $0.75

Microfiche (MF) $0.50

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Greenbelt, Md.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • DECEMBER 1964

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SUMMARY

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This paper reviews the methods and recent results of hyperaltitude photography, or space photography (pictures taken from space), of the earth, and discusses the potential applications and problems of space photography. Stress is placed on pictures of the earth's surface rather than cloud cover.

Numerous pictures have been taken from sounding rockets, chiefly Vikings and Aerobees, launched from White Sands Proving Ground, New Mexico, and Fort Churchill, Manitoba. These photographs include a large number of infrared pictures, taken on 4 × 5 inch film with a 25A filter, which are among the most useful for terrain analysis. In those infrared pictures taken from altitudes of 65 to 158 mi. the average scale ranges from 1:820,000 to 1:1,700,000 and the useful coverage per photograph from 2700 to 43,000 square miles.

Several score color pictures have been taken on Mercury flights with 35mm and 70mm cameras. The areas photographed include northern and central Africa, Florida, the Bahamas, the Middle East, and southern Asia. Many are of excellent quality and useful for geological and meteorological study.

The potential uses of space photography of the earth, based on its uniquely great synoptic areal coverage, include: (1) geologic mapping, (2) topographic mapping, (3) forest cover mapping, (4) icepack and iceberg monitoring, (5) hydrologic studies, (6) supplemental information for meteorological television satellites, (7) oceanographic studies, and (8) supplemental data for conventional aerial photography by the use of long focal length cameras. The potential extraterrestrial uses of space photography lie in the photographic reconnaissance of the moon and planets by fly-by probes and in the interpretation of future and presently available pictures of the planets.

The chief problem areas of space photography include: (1) delineation of specific uses, (2) determination of the best operational methods, (3) development of specialized cameras and films, (4) development of interpretation techniques, and (5) clarification of legal problems.

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A REVIEW OF PHOTOGRAPHY OF THE EARTH FROM SOUNDING ROCKETS AND SATELLITES*

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INTRODUCTION

Since World War II several thousand photographs of the earth have been taken from altitudes above 50 mi., which can be considered the boundary of space. The methods and latest results of this photography have not been reviewed recently. (For an early review see Reference 1.) The purpose of this paper is to fill this gap, and specifically to summarize the state of the art of hyperaltitude photography, or space photography, of the earth. A summary of the techniques and results of photography of the earth from the Mercury spacecraft series will also be presented. Finally, problem areas and potential uses of space photography will be discussed.

Space photography for military purposes is excluded from the scope of this paper, which contains only unclassified material. Relatively little attention will be paid to the pictures of the earth and its cloud cover transmitted by the various Tiros satellites, since this constitutes a field in itself which is adequately described elsewhere (see, for example, Reference 2). However, it should be mentioned that the Tiros pictures have been used for a number of nonmeteorological purposes (see, for example, References 3 and 4).

VEHICLES AND EQUIPMENT

The vehicles (Table 1) from which hyperaltitude photographs of the earth have been taken include a variety of sounding rockets and ballistic missiles and the Mercury spacecraft. They are described in detail in the references listed and it is unnecessary to discuss them at length. However, it should be pointed out that none of the vehicles used were specifically designed for photographic purposes, nor were any of the flights scheduled exclusively for photography, except the Arctic Meteorology Photo Probe. In most cases, the pictures were more or less an accessory experiment, although occasionally a strikingly successful one. This fact should be kept in mind in evaluating them.

*This report was presented at the annual meeting of the American Society of Photogrammetry, Washington, D. C., March 1963 and will be published in *Photogrammetric Engineering*.

Table 1

Summary of Successful Space Photography Flights.

Vehicle	Date	Cameras	Film (Filter)*	Area	Altitude (mi.)	Reference
V-2	1946	35mm Motion Picture	Super XX (25A)	SW U.S.A.	76	5
V-2	1947	K-25 Aircraft	Infrared Reconnaissance Base (25A)	SW U.S.A.	100	6
Aerobee and V-2	1946-50	K-25 Aircraft 35mm Motion Picture 16mm Gunsight	Aerographic Super XX (25A) Eastman IN Spectroscopic (29A) Kodachrome	SW U.S.A. SW U.S.A. SW U.S.A.	60-80	5, 7, and 8
Vikings 11 and 12	1954-55	K-25 Aircraft	Eastman Hi-Speed Infrared	SW U.S.A.	Up to 158	9 and 10
Atlas	1959	16mm Time-Lapse	Recordak Fine-gr. Panchromatic	Atlantic Ocean SE of Atlantic Missile Range	Up to 230	11
Aerobee	1960	Maurer 220 70mm Aerial	Kodak IR Aerographic (88A) Kodak Experimental Ektachrome (8778) Kodak High-Definition Negative (3)	North-Central Canada, Hudson Bay	47-140	12
Mercury Flight MR-1†	December 1960	Maurer 220G 70mm	DuPont Cronar Base, Black and White	Bahama Islands Vicinity	Maximum 131	
Mercury Flight MR-2	January 1961	Maurer 220G 70mm	Super Anscochrome	Florida, Bahama Islands	Maximum over 130	
Mercury Flight MA-3	April 1961	Maurer 220G 70mm	Super Anscochrome	Not Known	Low Altitude Abort Flight	
Mercury Flight MR-3	May 1961	Maurer 220G 70mm	Super Anscochrome	Florida, Bahama Islands, Mainly Cloud Covered		
Mercury Flight MA-4 (1961 αι1)	September 1961	Maurer 220G 70mm	Super Anscochrome	First Orbit Flight Path: Atlantic Ocean, North and Central Africa	86-123	
Mercury Flight MA-5 (1961 αυ1)	November 1961	Maurer 220G 70mm Milliken DBM7, 16mm (periscope observer camera)	Super Anscochrome Kodachrome EK Type II	SE U.S.A., West Coast of Mexico North Africa	86-128	
Mercury Flight MA-6 (1962 γ1)	February 1962	Ansco Autoset, 35mm	Eastman Color Negative	Florida, North Africa	87-141	13
Mercury Flight MA-7 (1962 τ1)	May 1962	Robot Recorder, 35mm	Eastman Color Negative	West Africa, Atlantic Ocean, and other areas	87-145	14
Mercury Flight MA-8 (1962 βδ1)	October 1962	Hasselblad 500C, Modified 70mm	Anscochrome 200	Western U.S.A., Mexican Gulf Coast, South Atlantic Ocean	87-145	15
Mercury Flight MA-9 (1963 15A)	May 1963	Hasselblad 500C Modified 70mm	Anscochrome 200	South-Central Asia, Philippine Islands, Pacific Ocean, Middle East, North Africa	87-144	16

*Wratten filter numbers.

†MR refers to suborbital flights with a Redstone launch vehicle; MA to flights with an Atlas launch vehicle. The MR-2 flight carried the chimpanzee Ham; MR-3, A. Shepard; MR-4, V. Grissom; MA-4, a simulated man; MA-5, the chimpanzee Enos; MA-6, J. Glenn; MA-7, M. Carpenter; MA-8, W. Schirra; MA-9, L. Cooper.

A summary of the cameras, films, and filters used to date in space photography is also presented in Table 1.* The information has been grouped according to vehicle-camera combinations; each entry may represent one or more flights. Detailed information is presented in the references cited.

QUALITY OF THE PICTURES

The immediate results of photography are, of course, the pictures. Representative photographs of the earth as seen from space are presented in Figures 1-11. Some general comments can be made about their quality and the effectiveness of the equipment, although this is somewhat difficult because of the incidental nature of the photography. None of it was taken for specific photogrammetric purposes, and therefore it cannot be evaluated in these terms.

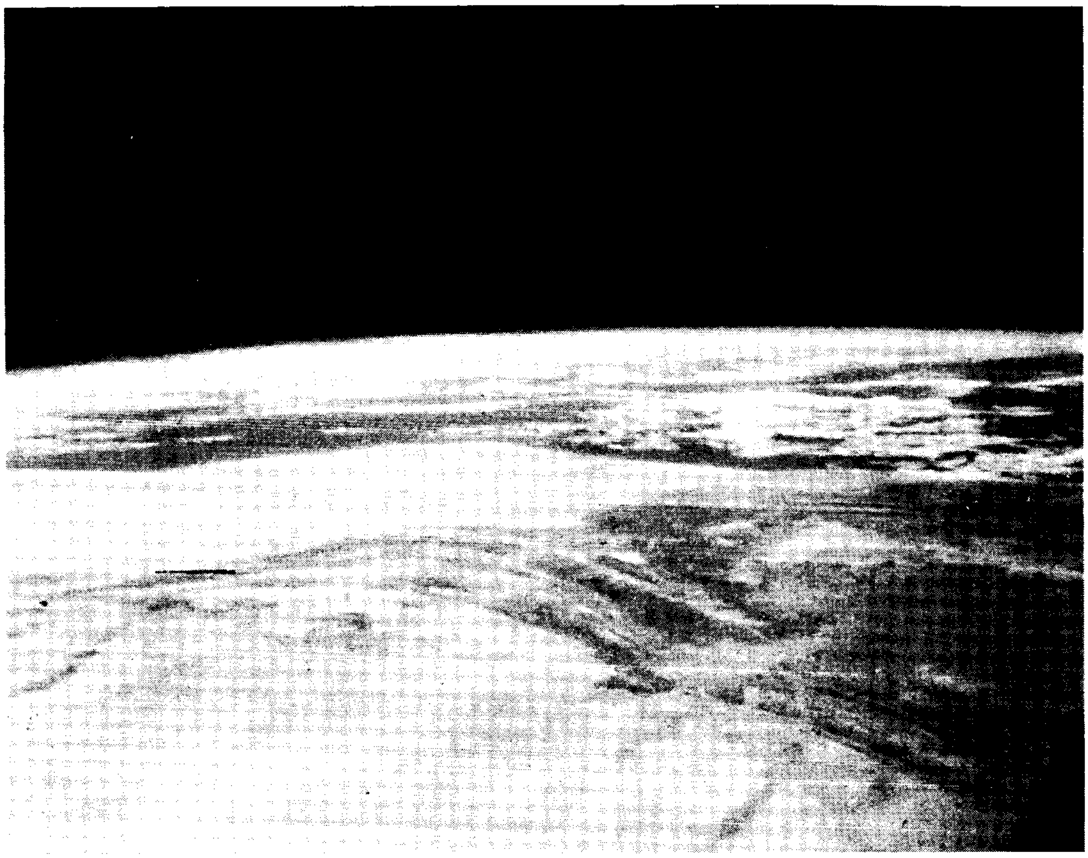


Figure 1—The Atlantic Coast and northern Spanish Sahara, view to west, Anti-Atlas Mountains are at the far right. This is a black-and-white print of a 35mm color transparency taken by Glenn during the MA-6 orbital flight.

*None of the camera equipment mentioned herein was specifically designed for use in space.

Figure 2—The Atlantic Coast and southern Spanish Sahara. Cap Blanc is at the lower left. This is a photograph of an image transmitted by Tiros V from an altitude of about 450 mi.

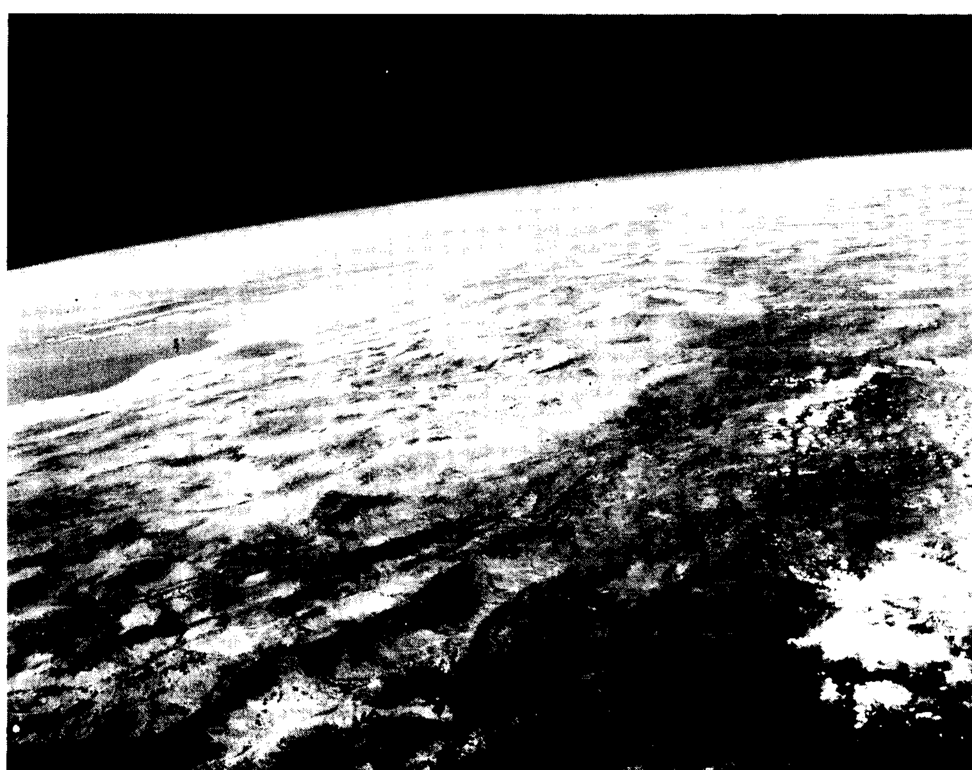
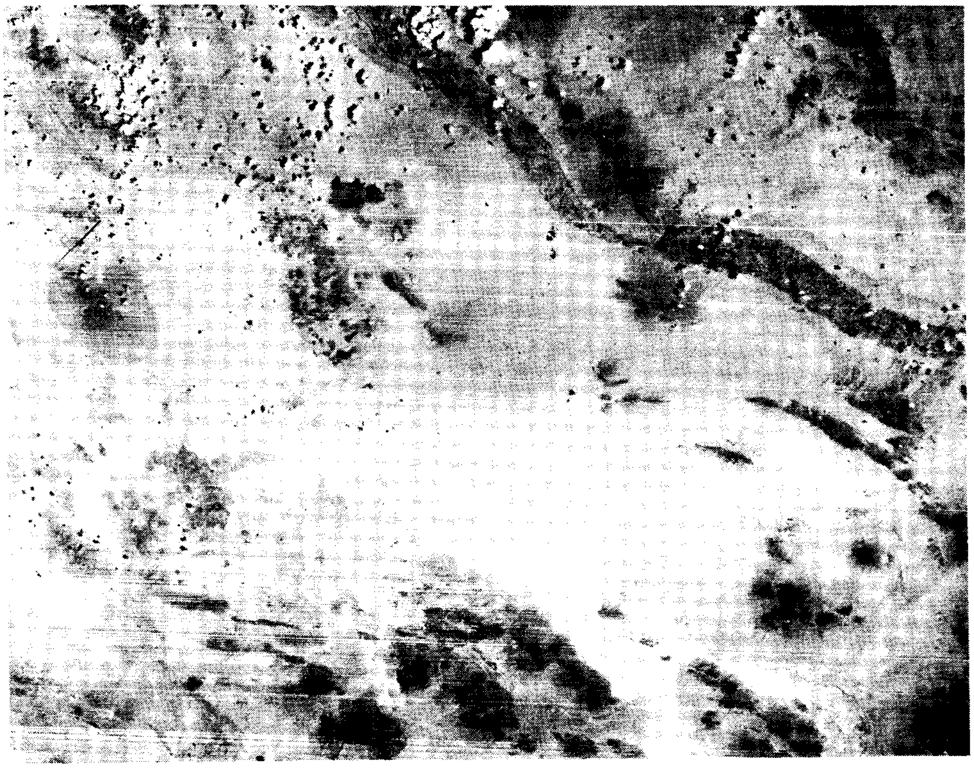


Figure 3—Southwestern Arizona, northern Sonora, and the Gulf of California (left). The Pacific Coast is in the distance; view to southwest. This is a print of a 4 x 5 black-and-white photograph from Viking 12 at about 140 mi.

Figure 4—Southern New Mexico and northern Chihuahua, Mexico. The Rio Grande Valley and the city of El Paso, Texas are at the upper right; north is to the top left. This is a print of a 4 x 5 black-and-white photograph taken from Viking 11 at about 158 mi.



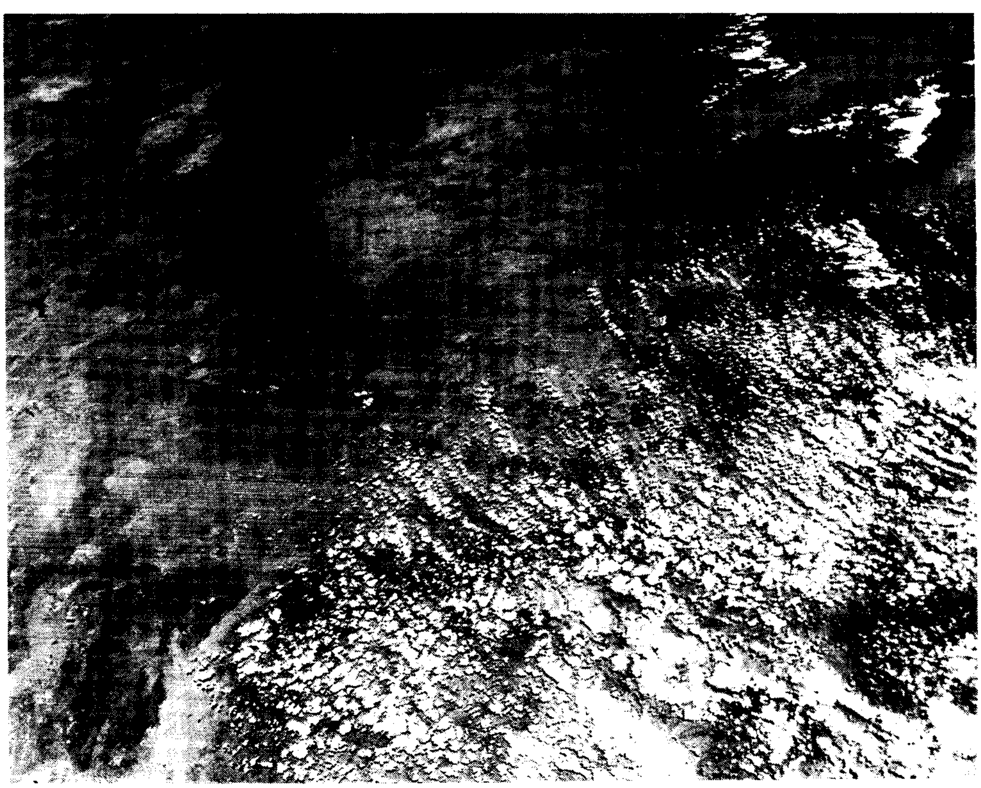


Figure 5—Eastern Arizona; the San Francisco Mountains and the Mogollon Rim are in the center; view to west. This is a print of a 4 x 5 black-and-white photograph from Viking 11 at about 150 mi.

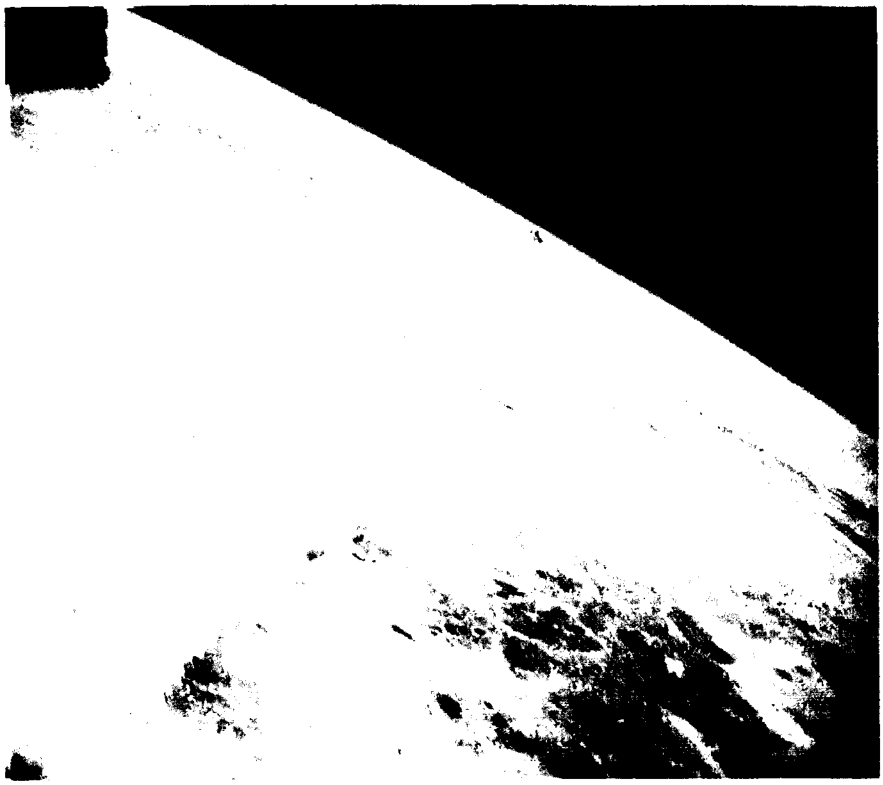


Figure 6 — South-west Algeria showing seif dunes at the lower left; view to north. This is a print of a 70mm color transparency taken by an automatic camera during the MA-4 orbital flight.

Figure 7 — Southern Morocco. Anti-Atlas Mountains are in the foreground, High Atlas in background under cloud cover. The Atlantic Coast to the left coincides roughly with the edge cloud cover. This is a print of a 70mm color transparency taken by an automatic camera during the MA-4 orbital flight.

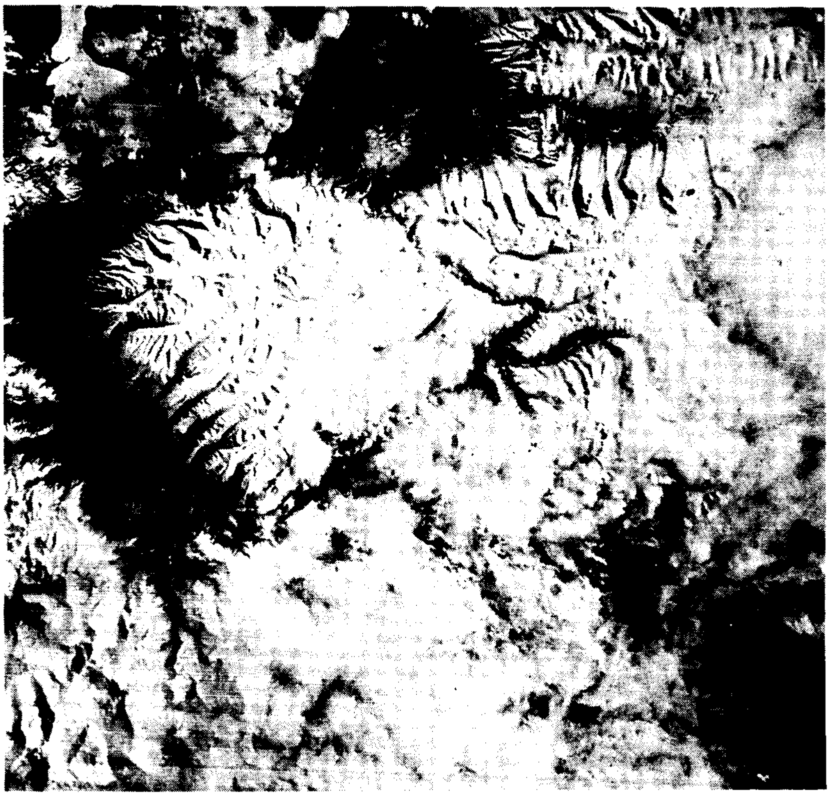


Figure 8—Southwestern Tibet. Rakas Tal and Manasarowar (lakes) are at the upper left; vertical view; north is to the top. Note the valley glaciers in the snow-covered mountains in the center. This is a black-and-white print of a 70mm color transparency taken by Cooper during the MA-9 orbital flight.

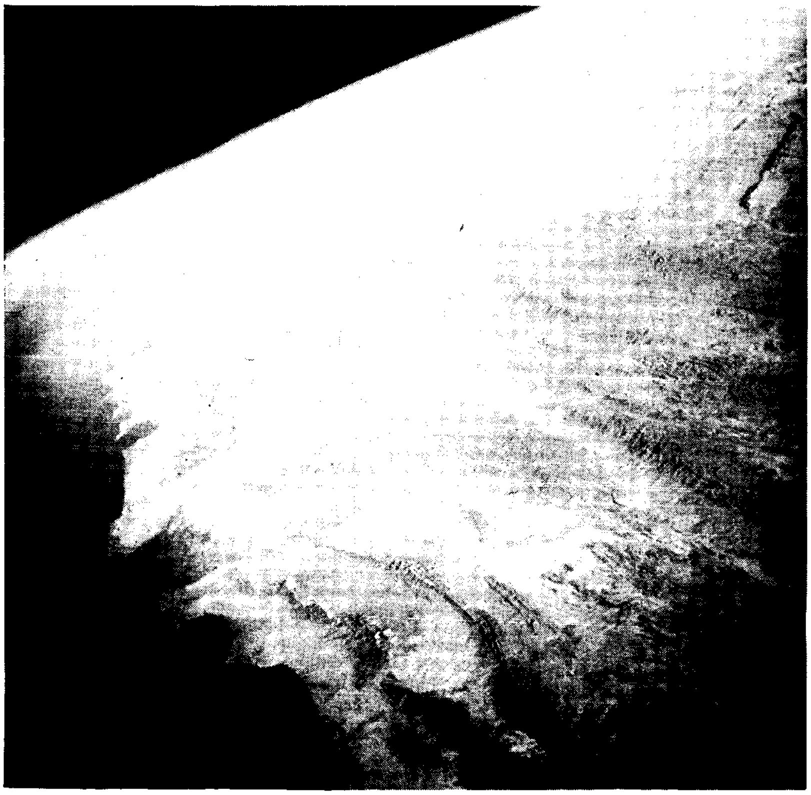


Figure 9—The north shore of the Arabian Sea and the Gulf of Oman. Western Pakistan is in the foreground and southeast Iran is in the background; view to west. This is a black-and-white print of a 70mm color transparency taken by Cooper during the MA-9 orbital flight.

Many of the space photographs are of relatively good to excellent quality. Because of the great scale difference, it would be misleading to compare these pictures with conventional air photographs; the proper standard would seem to be similar images transmitted from space by other means, in particular by the television cameras on the Tiros satellites.

Most of the photographs taken by the vehicle-camera combinations in Table 1 are clearly superior in image sharpness and tonal contrast to those transmitted from the Tiros satellites. This is demonstrated by Figures 1 and 2, which show roughly the same part of northwest Africa photographed from a Mercury spacecraft and from Tiros V (1962 $\alpha\alpha$1). These pictures are not strictly comparable; for example, the Mercury pictures were taken from about 100 mi. as opposed to 450 mi. for those from the Tiros satellite. Nevertheless, the fact that the high oblique photo taken by Glenn with a hand-held 35mm camera retailing for $69 shows more detail and tonal contrast than the vertical photo taken by the highly refined Tiros camera strongly suggests the inherent superiority of actual photographs over telemetered images. Some of the pictures taken by the narrow-angle cameras on Tiros I (1960 β2) and Tiros II (1960 π1) approach the resolution of the Mercury photographs, but at a great sacrifice in area coverage.

The reasons for this superiority are not hard to find, the chief one being the fact that the film itself is returned. This rather obvious fact has been mentioned because it suggests that in planning future lunar and planetary probes, considerable effort to bring back the film itself would be justified. In principle, television images can be made to equal the resolution and spectral range of film, but the transmission rate, bandwidth and complexity of the system must be correspondingly increased. Of course the unique advantage of space-borne television systems, that of immediate picture transmission, compensates for their limitations in many applications. A detailed evaluation of the relative advantages of film return and telemetry should be made for each mission.

CAMERAS

The most successful camera used to date, with respect to picture quality, seems to have been the K-25 aircraft camera. Some specific characteristics of this camera can be mentioned that contribute to its usefulness:

1. Optical specifications — the combination of focal length (163mm) and field of view (34° × 43°) appears to provide a reasonable compromise between resolving power and scale when only one camera can be used.

2. Physical specifications — the weight (15 lb) and construction of the K-25 permit its use in a variety of rockets. A useful modification is the addition of an armored film cassette, permitting film recovery even from hard landings in which the camera itself is destroyed (Reference 10).

3. The K-25 takes a picture 4 × 5 inches, permitting greater resolution, other factors equal, than smaller film sizes.

Other cameras which have produced good results are the Hasselblad and Maurer cameras, both of which use 70mm film. The high quality of the pictures taken with the 70mm camera carried during the MA-9 flight indicates that detailed photogrammetry from space vehicles can be accomplished with this film size. Holliday obtained good 35mm pictures (Reference 17); this seems to be the smallest film size which has produced pictures useful for photo-interpretation of land areas, on the basis of a comparison with the 16mm pictures presented by Conover and Sadler (Reference 18). However, no comparative study of different cameras has been made, and it is possible that the smaller sizes might be useful. For best results, cameras should be tailored to specific vehicles and missions.

All the space photographs taken to date have been made by what are considered "small" cameras in modern photogrammetry (Reference 19). Improvements in the already-acceptable quality can be expected when weight and space allowances make it possible to mount the equivalent of standard aerial mapping cameras in spacecraft.

FILM

Space photography as defined here is simply an extension of aerial photography to extreme altitudes, and the problems encountered in selecting film and filter types differ mainly in degree. Experience to date in space photography tends to verify earlier judgements, based on aerial photography, of the effectiveness of different film types.

Holliday (cited in Reference 7, by Newell) found Eastman Aero-Super XX film, used with a 25A filter at 1/500 second and f/8, to be the best combination with respect to terrestrial detail and film speed. Infrared films have been found to give the best haze penetration; the combination used on the Viking 12 flight (Reference 10) of Kodak Hi-speed Infrared film with 25A filter, at 1/500 second and f/8, has produced some of the best terrain pictures published.

Early color pictures taken from space were not as useful as black and white pictures; this was largely due to the greater resolution possible with the latter. Holliday (Reference 17) found color film to be "not too successful from altitudes over 30,000 feet." More recent color photographs, such as those taken during early MR and MA flights, showed indifferent haze penetrating ability and excessive blueness. The latter problem is also encountered in aerial photography at altitudes as low as 2000 ft (Reference 19), but can be partly overcome by filters or viewing techniques (Reference 20).

The color pictures taken by L. G. Cooper on Anscochrome 200 during the MA-9 flight (Figures 9, 10, and 11) were a great improvement over previous efforts, with respect to resolution and color rendition. Part of this improved quality apparently stems from the location of some of the areas photographed, such as the Tibetan plateau, which are characterized by high altitude and dry air. However, these pictures clearly demonstrate that the usefulness of color photography can be extended beyond the atmosphere.

From the results obtained so far with a variety of films, it appears that low light intensity will be no problem in photographing the day side of the earth. O. E. Berg (personal communication) has obtained excellent pictures from an Aerobee using Kodachrome, with an ASA rating of 24.

If possible, space vehicles should carry equipment for simultaneous photography with a variety of film and filter types. The great value of multiband photography is discussed in several references (Reference 21), and there are good reasons to think that its usefulness will not stop at the ionosphere.

SCALE AND RESOLUTION

A few approximate figures can be given on the scale and ground resolution of the space photographs taken to date. The most useful pictures available are those taken by the K-25 camera during the Viking 11 flight (Figures 4 and 5). To permit easy comparison of the scales and areas covered under various conditions, Table 2 has been prepared from Reference 9.

Table 2

Scale and Coverage of Viking 11 Photographs.

Altitude (mi.)	Approximate Average Scale	Useful Area per Photograph ($mi.^2$)	Comments
65	1:820,000	2700	Exposure 1, nearly vertical
86	1:3,300,000	43,000	Exposure 34, high oblique
146	1:1,100,000	40,000	Exposure 25, low oblique
158	1:1,700,000	16,000	Exposure 19, nearly vertical

In this table the approximate average scale was estimated by measuring known distances between points roughly halfway from the near edge of the picture to the far edge, or in the case of the obliques, to the limit of useful resolution. The limit of useful resolution is defined here as the maximum distance at which, on the published picture, Baumann and Winkler identified major topographic features such as rivers and individual mountains. Scales listed in the table are based on the original negative size (4 × 5 inches) rather than the published size (7 × 9 inches).

The useful area per photograph is the portion of the photographed terrain bounded by the three near edges of the picture and the limit of useful visibility, or the fourth edge in the case of the nearly vertical photographs. No correction was made for clouds, which covered from about 2-3 percent to well over 50 percent of the useful area of the photographs. This relatively high coverage was slightly surprising, in view of the prevailing dry climate of the area photographed (southwest United States and northwest Mexico).

The Viking 11 pictures have also been used for a test of ground resolution by the Army Map Service (C. S. Spooner, unpublished consultation brief, 1959). Four of the negatives showing the El Paso area were printed at 7X, and the resolution was estimated by comparison of the appearance of two "natural" resolution targets: the parallel runways at Biggs Air Force Base, and the New Orleans Railroad and Alameda Avenue. The results are summarized in Table 3.

The comments on ground resolution in the Army Map Service report are of considerable interest. First, it was noted that on exposure 4, taken from 94 mi., most of the streets, railroads, and canals shown on the AMS 1:250,000 map of the area could be recognized after a study of the map. Second, it was concluded that these features could not be identified unambiguously by use of the photographs alone. Finally, it was tentatively concluded that if rocket photography were to be used for planimetric mapping without supplemental larger-scale photographs, resolution of about 100 ft would be necessary.

Table 3

Estimated Resolution at Various Altitudes.

(Reference 22; based on photographs presented in Reference 9)

Exposure Number	Altitude (mi.)	Estimated Resolution (ft)
4	94	300
8	122	400
14	151	500
20	158	600

It should be mentioned that the planimetric mapping under consideration in the AMS report would have been intended for, among other things, delineating cultural features. It seems likely that considerable geologic information could be extracted from photographs with lower resolution than necessary for this purpose. For example, study of the 7X enlargement of exposure 14 (500 ft resolution) showed that it is possible to trace contacts between cultivated and uncultivated alluvium and between bedrock and alluvium, as well as a sedimentary rock contact in the Franklin Mountains. Furthermore, the drainage patterns are probably clear enough to permit structural mapping to the extent that they reflect the structure. The usefulness of relatively-low-resolution pictures is further demonstrated by the various Project Mercury photos, such as Figure 6.

Before leaving the subject of resolution, it is of interest to compare the figures given in Table 3 with those given by Stroud (Reference 23) for the optical system carried by Tiros I and II. Stroud states that the ground resolution of the wide angle camera is about 3 to 4 mi., and of the narrow angle camera, about 0.4 to 1.0 mi., for points directly under the satellite at its nominal 400 mi. altitude.

PHOTOGRAPHY FROM MERCURY SPACECRAFT

Apart from a few pictures published in popular magazines, little information on the terrain photography carried out during the various Project Mercury flights has appeared. The following is a brief general summary of the methods and results of this photography; specific aspects are discussed elsewhere in the paper. The opinions expressed herein are the writer's, and are not necessarily those of Goddard Space Flight Center or the National Aeronautics and Space Administration.

All the "earth-sky" pictures taken from the Mercury spacecraft on the unmanned flights were taken by automatic cameras (see Table 1) for general information purposes, as were those taken during the two manned suborbital flights. Starting with the first manned orbital flight, however, the cameras were operated and held by the astronauts. The earth photographs taken by J. H. Glenn during the first flight (MA-6) were of general interest subjects, although the astronomical and meteorological photography was specifically planned.

For the second orbital flight (MA-7), flown by M. S. Carpenter, a list of selected areas for terrain photography was prepared, including representative physiographic provinces and features of special geologic interest. The press of in-flight operations prevented Carpenter from taking many terrain pictures, but some of the astronomical photography was very successful.

A similar list was prepared for the MA-8 flight, and both pilots, W. M. Schirra and L. G. Cooper (backup) were briefed in some detail on areas and features to be photographed. Unfortunately, cloud cover and other difficulties made it impossible to get useful terrain pictures, although Schirra, using his own discretion, did take a number of meteorologically useful cloud photographs.

Astronaut L. G. Cooper, during the MA-9 flight, took 29 color pictures of the earth, as opportunity permitted. This was the most successful series taken during Project Mercury; all the photographs are usable for geographical, geological, or meteorological purposes, despite the fact that neither time nor attitude control fuel was specifically allotted for photography (all the pictures were taken during drifting flight). Cooper made a number of interesting observations on visibility and color, including the following:

1. Although terrain as seen from space has a distinct bluish tinge, it is not difficult to distinguish major color variations visually. This suggests that successful color photography is inherently possible with proper equipment; photographs taken on earlier flights showed such an extreme bluish cast that the feasibility of hyperaltitude color photography seemed doubtful.

2. Visibility is very sensitive to atmospheric conditions; Cooper could not see San Diego or Los Angeles because of haze, but he could distinguish individual roads in the southwestern United States desert areas.

3. Shadows along the earth's terminator (the twilight zone) are very distinct, at least in areas of good general visibility. Earlier photographs, in particular those of the terminator taken during the MA-4 flight, suggested that diffusion might blur out shadows.

4. Apparent ground motion from the altitude of this flight (about 85-140 mi.) is very rapid; Cooper was unable to keep individual objects in view for longer than 1 minute, and in general saw them for even shorter times. This has obvious implications for the planning of future photography from orbiting vehicles.

5. The haze penetrating ability of the human eye is about the same as that of the color films used to date. It had been predicted, on the basis of the MA-4 color pictures, that Cooper would be able to see details as far north as Cape Hatteras while flying over central Florida; this was verified at the scientific debriefing.

Other aspects of Mercury photography will be discussed under appropriate headings. The scientific results of the project as a whole are summarized in Reference 24.

INTERPRETATION OF SPACE PHOTOGRAPHS

To the best of the writer's knowledge, no comprehensive study has been published on the interpretation of hyperaltitude photographs of the earth. Such would be beyond the scope of this report. However, a brief summary will be presented of what can be recognized in various pictures, and of techniques which may be useful.

Recognizable Features

As pointed out in the discussion of resolution, cultural features can be recognized as such on some photographs with extremely small scale, even if they cannot be identified with certainty. There seems to be little danger of confusing natural and artificial terrain features. It is interesting to note that with the exceptions of an irrigation canal and some roads in India, no man-made structures have been recognized to date on color photographs; for example, Figure 10 shows the area of Calcutta, but the city itself cannot be distinguished.

It is not possible to put a lower limit on the physiographic and geological detail which can be delineated on space photographs without an extensive study. However, a rough idea of the useful resolution can be gained by examination of pictures of the southwestern United States and other areas (Figures 4 and 5). An interesting aspect of some of these pictures is that linear features much narrower than the estimated resolution can easily be seen in the pictures. For example, railroads whose width could hardly be over 100 ft can be seen on Viking photographs (Figure 4) whose resolution was estimated by Spooner to be 600 ft. The fact that lines are seen much more easily than other shapes is well known, but is of particular importance in the present discussion because many geological features of importance, such as faults and contacts, are essentially linear. This suggests that space photography with resolution too low for most purposes of conventional aerial photography may be valuable nevertheless for geological mapping.

Bodies of water are among the most easily distinguished features on these pictures, especially on those taken with infrared film. In Figure 3 (Viking 12) taken from 143 mi., the Salton Sea, the Gulf of California, and the Pacific Coast can be seen clearly over 550 mi. away. On the same picture, Baumann and Winkler identified the San Jacinto and San Gorgonio peaks to the north of the Salton Sea.

In most parts of the Basin and Range province shown, it is fairly easy to distinguish bedrock from alluvium, although it might be difficult to draw precise contacts. On Figure 5, it is possible

Figure 10—The Hooghly River on the western part of the Ganges delta, India; north is to the top. This is a print of a 70mm color transparency taken by Cooper during the MA-9 orbital flight.

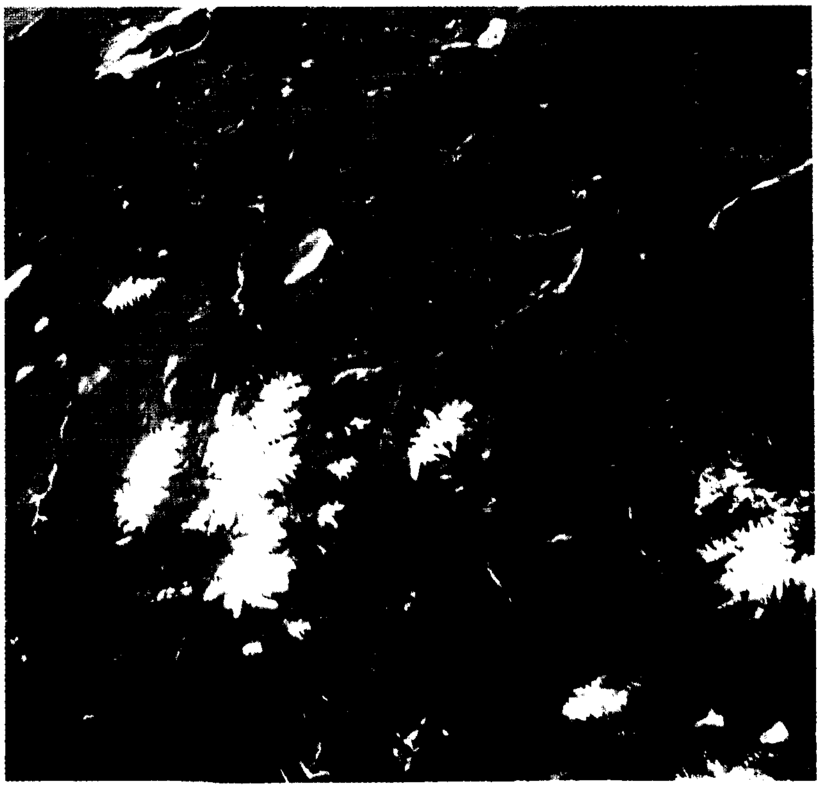


Figure 11—North-central Tibet (details are in Figure 12). This is a print of a 70mm color transparency taken by Cooper during the MA-9 orbital flight.

to trace the Mogollon Rim and to identify the San Francisco Mountains and Meteor Crater, which are over 300 mi. from the rocket subpoint. Individual volcanic necks in the Hopi Buttes region can be delineated easily. On Figure 4 (Viking 11) which shows the El Paso region from an altitude of 158 mi., igneous and sedimentary rocks can be distinguished with the help of the geologic map of Texas (Reference 25), by tonal differences, and contacts can be located approximately. Lava flows are identified easily; the lava looks very much like black ink spilled on the film, and could probably be identified from altitudes of several hundred miles or more.

The MA-4 photographs of North Africa are of considerable interest because they are among the best color pictures showing unobscured terrain. The Anti-Atlas Mountains are especially striking (Figure 6) in the amount of structure which can be seen. The folded nature of the mountains is obvious, and many individual plunging folds can be traced (see also Reference 3). A linear feature suggestive of the Zemmour fault (Reference 26) can be seen intersecting the coast south of Agadir, but can not be identified with any certainty. To the southeast, farther along the flight path, seif dunes and various unidentified (bedrock?) structures can be clearly traced (Figure 7); there is little doubt that these pictures, as they are, could be used for mapping dune distribution if it were desirable.

Many of the MA-9 photographs show abundant topographic and geologic detail. Figure 9, taken over Pakistan, encompasses an area of folded mountains in which many geologic contacts are visible. Figure 11, taken over the Tibetan plateau, is even more useful because of the favorable camera angle. A geologic sketch map has been prepared from this photograph (Figure 12) which shows a number of structures of possible economic interest. For example, the domes and anticlines represent potential oil-bearing areas, and the intersections of some of the lineaments might be the loci of mineral deposits.

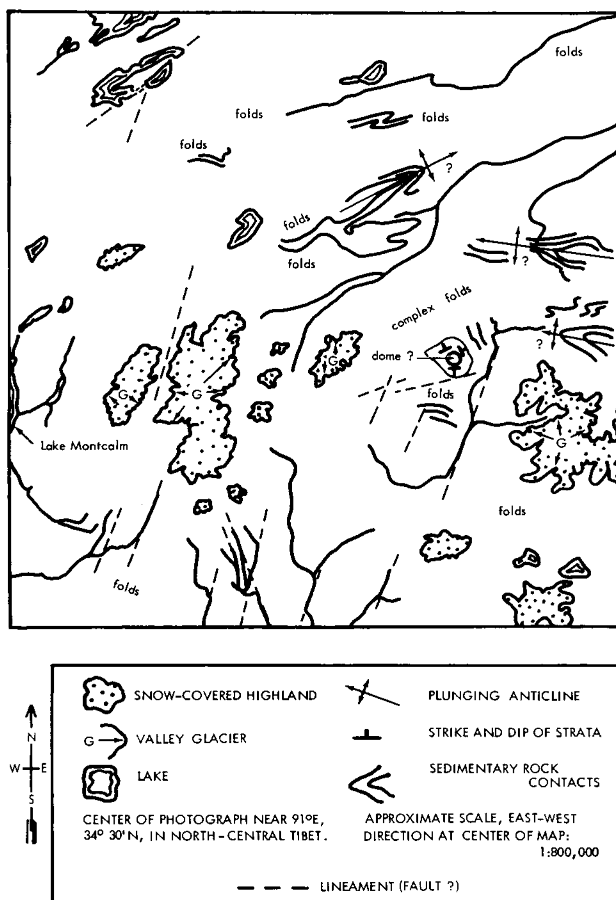


Figure 12—The geologic-physiographic sketch map of Figure 11.

Techniques of Interpretation

In contrast to the wealth of experience accumulated in interpreting cloud pictures from the Tiros satellites, interpretation of terrain photographs is still in an elementary stage.

Stereoscopes have been used successfully on many space photographs despite the fact that none of these have been planned for such use. It is possible, even without a stereoscope, to recognize relatively minor topographic features on good pictures. None are available yet, however, which are suitable for topographic mapping.

Many of the best space photographs are high or low obliques. To interpret such pictures, it will be helpful to rectify them, taking into account the earth's curvature. Glaser (Reference 27) has described a method of rectifying hyperaltitude photographs by means of a modification of the Canadian grid system. It seems likely that some such method could be applied to pictures used for geologic purposes.

POTENTIAL APPLICATIONS OF SPACE PHOTOGRAPHY

With the exception of the cloud cover pictures from the Tiros satellites, the main use to which space photography has been put so far is the satisfaction of our curiosity on what the earth looks like from space. Nevertheless, it seems certain that more specific tasks exist, a few of which will be suggested here.

Terrestrial Uses

Before considering specific applications of space photography of the earth, it is worthwhile to discuss the more general question of what it has to offer that cannot be duplicated by conventional aerial photography.

The most obvious unique property of space photographs is that of providing a synoptic picture of a large area. This has been of course the basis for the great success of the meteorological satellites, and may find application in other fields to be discussed.

A second property of space photographs is the extremely great area which can be covered by each picture. This difference can be illustrated by a comparison of the scales listed in Table 2 with the usual 1:20,000 or 1:40,000 scales used in aerial photography. The area covered increases with the inverse square of the scale, and is so much greater for space photographs that it is virtually a qualitative difference. As Hemphill points out in a valuable review of the geologic uses of small-scale photographs (Reference 28), this great coverage permits a continuity of observation which may lead to the discovery of many geologic features which would be overlooked on conventional large-scale air photos. The geologic sketch map of part of the Tibetan plateau (Figure 12) illustrates this possibility; some of the linear features are scores of miles long and might easily be missed on photography showing only small portions of them. This example strongly supports Hemphill's suggestion that "photographs of even smaller scale than are now generally available would be desirable for many photogeologic interpretation problems . . . where diagnostic features must be viewed collectively in order to recognize their geologic significance."

A third advantage is that space photography shows a large part of the earth from an extreme altitude *as it is* (subject to the limitations of visibility and resolution). This statement requires some amplification, since it touches directly on the question of whether photographs taken from space can be simulated essentially by mosaics of conventional air photographs, as frequently suggested (see, for example, Reference 29).

A standard mosaic, whether controlled or uncontrolled, is a patchwork of individual pictures, usually taken in good weather with vertically oriented cameras. An uncontrolled mosaic has little resemblance to the actual appearance of the terrain because of tonal differences between photographs, overlapping margins, etc., and is of little use for precise measurements. Controlled mosaics frequently give the impression, especially when dodged, of a single picture, and as such could be used, in principle, to simulate or replace the small scale pictures taken from space vehicles. However, the dodging itself may reduce the geologic usefulness of the mosaic because it must destroy some tonal differences. Miller (Reference 30) specifically warns against trying to draw geologic inferences from dodged mosaics because tonal clues to the structure may be lost. It is seen then that a controlled mosaic is essentially different in tone and has greater uniformity of scale than a space photograph of equal scale. Furthermore, mosaics cannot provide stereoscopic coverage on the extremely small scale of hyperaltitude photographs; this is of vital importance for geologic interpretation, and can be provided by even roughly oriented space photographs such as those from the MA-4 flight.

Bird (quoted in Reference 31) reports that mechanically reduced low-altitude air photographs do not show the same patterns seen on high altitude photographs. It seems highly probable then, that, contrary to popular opinion, space photographs cannot be simulated by degraded or reduced mosaics of conventional air photographs. It should be added that large, controlled mosaics require thousands of square miles of photography of areas with fourth-order ground control. This may not be available for parts of the earth such as the portion of Central Africa photographed on the MA-4 flight.

The potential applications of space photography include use in geologic reconnaissance, topographic mapping, forestry, ice pack reconnaissance, hydrology, supplemental weather photography, and oceanography, and as a supplement to conventional aerial photography.

Geologic Reconnaissance

The wealth of detail on the MA-4, MA-9, and Viking photographs suggests strongly that high quality space photography from satellites would be useful in geologic reconnaissance mapping of remote areas such as Central Africa (see, for example, Reference 3), and oceanic islands, for which aerial photography is not available or is obtainable only at great expense. Such reconnaissance could serve as a guide for geophysical surveys, for conventional photography, and for additional space photography at higher magnifications. The resolution achieved by the K-25 cameras flown from White Sands suggests that considerable geologic detail could be distinguished even with moderate magnification.

An even more exciting possibility than the mapping of previously unphotographed areas is that of photographing previously mapped areas from space to show major geologic structures unnoticed at large scales. It is well known that aerial photography was a qualitative breakthrough in many fields, in that the new perspective it afforded permitted recognition of features which might never have been discovered by ground methods. It seems very possible that space photography will be a similar breakthrough in geology, for it permits us to see entire mountain chains, wrench fault systems, and volcanic fields at a glance. Harwood (quoted in Reference 31) has suggested that satellite photography might eliminate the mysterious faults which seem to follow national and state boundaries; more important is his suggestion that we could begin to learn something of the broad structure of continents, and even of intercontinental tectonics.

Topographic Mapping

The Army Map Service study previously referred to (Reference 22) concluded tentatively that 1:1,000,000 scale topographic mapping might be done with satellite photography with good accuracy, and that somewhat larger scales might be possible with lower accuracy. The requirements for attitude and altitude control of a cartographic satellite are considerably more stringent than those for one used only for reconnaissance mapping. However, the present Mercury spacecraft would meet most of these requirements.

Forestry

The fact that aerial photography has become a nearly indispensable tool of the modern forester (Reference 19) makes it seem likely that space photography will have application in this field. The scale and resolution possible with small cameras would prevent the use of space photographs for detailed studies such as crown counts, but reconnaissance forest mapping might be possible. The fact that color film adds a negligible amount to the cost of space photography further indicates its possible usefulness in forestry. The great potential value of multispectral photography (Reference 21) in detecting changes in vegetation suggests that it would be useful to carry out such photography from space using instruments such as the recently-developed 9-lens Multiband camera (Reference 32).

Ice Pack Reconnaissance

It was discovered shortly after Tiros I was put into orbit that sea and river ice could be seen on the telemetered images despite their relatively low resolution. This led rapidly to the joint Canadian-American Project Tirec to investigate the application of weather satellites to ice reconnaissance. Using Tiros photographs in conjunction with aircraft photography and ground observations, the project demonstrated that satellite ice reconnaissance in areas such as the Gulf of St. Lawrence was clearly feasible and of great potential value (Reference 31); Singer and Popham (Reference 4) report that as much as $1,700,000 might have been saved in 1961 by the United States and Canada through ice observations from a Nimbus satellite if one had been in orbit. It may be pointed out that a figure of this sort is misleadingly conservative; an operational Nimbus satellite could provide similar ice reconnaissance over the approaches to western Europe, Russia, and Antarctica at very little extra cost.

Film photography would have the advantage of greater resolution than television. But in day-to-day ice pack monitoring, methods of rapid image retrieval would have to be utilized, such as facsimile transmission of films developed in flight. It seems safe to say that both television and photography from orbiting vehicles promise to be immensely useful in ice studies.

Hydrology

Although relatively little application has been made of space photography to hydrology, it might be useful in several ways. One of these is the measurement, over large areas, of snow cover; the National Weather Satellite Center and other agencies in the United States and Canada are currently investigating the use of Tiros pictures for this purpose. As shown by the MA-9 photographs, deep snow, light snow, and valley glaciers can be distinguished easily, indicating that methods involving film recovery should also be valuable because of the high resolution of the film.

The fact that entire drainage basins of major rivers can be photographed quickly from satellites suggests that many other hydrologic applications can be found for space photography.

Supplemental Weather Photography

The greater resolution obtainable with film-recovery methods of space photography makes space photographs valuable for synoptic studies of the fine structure of cloud systems (S. Soules and K. Nagler, personal communication), similar to those already conducted from airplanes (Reference 33). The Arctic Meteorology Photo Probe (Reference 12) further demonstrated the usefulness of rocket photography in supplementing and supporting meteorological satellites.

These applications would not be considered photogrammetry in the usual sense, but are worth mentioning because a surprisingly large part of the earth's surface is covered with clouds at any one time This will obviously hamper terrain photography, but the pictures of the cloud cover itself will be of value.

Oceanography

The ability to take individual photographs covering scores of thousands of square miles should prove invaluable in oceanographic studies. In addition to the obvious benefits of weather observations over remote oceanic areas, the following applications may be possible:

1. Multispectral photography covering the near infrared, visible, and ultraviolet can show the distribution of currents and possibly of areas with differing salinity. That such photography is possible even from space vehicles was suggested by Glenn's ability to see the Gulf Stream during the MA-6 flight (Reference 13). A knowledge of the structure of such major near-surface currents would obviously be of value to the fishing and shipping industries, and from a broader viewpoint to nations whose climate is strongly influenced by these currents, such as Iceland, England, and Chile.

2. The discovery by Cameron (References 34 and 35) that water currents in oceans, bays, and rivers could be mapped by stereoscopic time-lapse air photography opens another possible application of space photography. Small areas can of course be mapped with low altitude photography, but to map large currents, such as those in the Bay of Fundy, Cameron (Reference 36) has found it necessary to use photographs with scales of 1:85,000. He suggests extension of the method to major currents such as the Gulf Stream (and to large physiographic features) by the use of 1:270,000 photographs taken from altitudes of 80,000 ft or higher, or by the use of satellite photography.

3. L. G. Cooper, during the MA-9 flight, noticed striking color differences in the water around islands in the Bahamas, which he attributed, presumably correctly, to water depth. Conventional air photos have been used to study this, and it is interesting to note the possibility raised by Cooper's observation that space photographs can also be used to map bottom topography.

Supplementing Conventional Aerial Photography

The review to this point has dealt primarily with small scale (i.e., on the order of 1:1,000,000) photography because these scales are uniquely attainable from space vehicles, and because most published space photographs have scales in this range. The latter fact results from the relatively small size and short focal lengths of the cameras flown to date. It is apparent, from optical laws alone, that if it were possible to fly large cameras with focal lengths on the order of several meters, photographs with scales on the order of 1:50,000 and correspondingly high ground resolutions could be taken. This possibility is discussed at length by Katz (Reference 37) in relation to military surveillance systems and by Rochlin (Reference 38) in relation to arms control inspection. Its importance for the present discussion is that it should be possible, if problems such as image motion can be overcome, to duplicate conventional aerial photography to a large degree. Should this prove possible, space photography could be put to many of the innumerable uses of conventional methods, in addition to its unique potential applications already discussed.

Extraterrestrial Uses

The most immediate use for space photography of the earth is probably its application to the study of pictures of other planetary surfaces, that of Mars in particular. It is interesting to note that all the efforts to interpret the thousands of available pictures have been made in essentially complete ignorance of what the earth would look like under similar conditions. The problem of deducing the nature of the Martian surface is complicated by the fact that experience gained by the study of lunar features cannot be applied reliably to Mars, because the existence of a Martian atmosphere and an intermittent hydrosphere may have produced physiography more nearly terrestrial than lunar.

Another important application of space photography lies in the planning of future planetary photographic probes. It seems likely that unmanned probes to Mars and Venus will carry television pickups; the design of the optical systems and choice of the trajectory will be greatly aided by experience gained in space photography of the earth. Another type of mission in which photography will play a major role is the manned Mars fly-by, under study by NASA (Reference 39). In such a flight, the spacecraft could stay in the vicinity of the planet for about 10 hours. Obviously the cost of a planetary fly-by would be substantial, and the photography should be very carefully planned for maximum value. Experience in earth orbiting photographic missions will be essential in selecting the equipment and methods for investigations of the other planets.

PROBLEM AREAS OF SPACE PHOTOGRAPHY

The major need in space photography of the earth at this time is simply for more experience in taking, processing, and interpreting photographs. The field is now at roughly the same stage as aerial photography was before World War I. Study is needed in several specific areas if we are to make full use of space photography:

1. Delineation of uses for space photographs — The chief need here is for specialists in various types of photogrammetry to study existing pictures in order to determine potential applications in each field. Such study will lead in turn to better specifications of optimum flight methods, camera and film types, etc.

2. Operational problems — Some fundamental questions remain to be answered on how space photography is best carried out. For example, the relative values of sounding rockets and unmanned and manned satellites are not definitely known, largely because specific applications have not been clearly established. Further questions requiring answers include those of film recovery vs. television, color vs. black and white film, the nature of optimum trajectories and orbits, and the optimum combinations of focal lengths.

3. Development of specialized cameras and films — As mentioned previously all space photography to date has been done with adaptations of conventional equipment and films. It seems self-evident that, after specific applications have been developed, equipment designed expressly for rocket and satellite photography will produce better pictures than available at present.

4. Development of interpretation techniques — It is obvious from the previous discussion that this is one of the biggest gaps in space photography. Interpretation of space photographs can use many of the techniques and tools of aerial photography. However, problems such as curvature and the extremely small scale of the pictures will necessitate considerable modification of the older methods.

5. Legal problems — The pictures taken from the Viking and V-2 rockets fired at White Sands show large areas of Mexico, illustrating the fact that it is possible to photograph foreign territory in considerable detail without violating the air space of the country in question. A further problem in this respect is the fact that satellite photography will hardly be economical if restricted to national borders. So far no objection has been made to the

Tiros satellites, one possible reason being that the pictures obtained this way are of little use for military reconnaissance purposes. However, space photographs with resolutions of a few feet can be taken (Reference 38).

The position has been taken (Reference 40) that "observation of the earth from outer space is a legitimate and permissible activity in the peaceful exploration and use of space." This opinion is based on the resolution passed by the United Nations General Assembly (Resolution 1721 XVI) that "Outer space (is) free for exploration and use by all States . . . . and (is) not subject to national appropriation."

ACKNOWLEDGMENTS

A number of people and organizations have generously contributed material and advice for this review. Dr. P. M. Merifield of the Lockheed Aircraft Corporation, a pioneer in the use of space photography, brought the potential usefulness of space photographs to the writer's attention, and made many useful suggestions. Mr. R. C. Baumann and Mr. O. E. Berg of Goddard Space Flight Center provided pictures from Viking flights and related material. Dr. A. Nowicki, Mr. S. W. Dossi, and Mr. L. Kosofsky of the Army Map Service provided unpublished data and advice on mapping satellites. The writer had several invaluable discussions of the subject with Dr. W. A. Fischer, Dr. S. J. Gawarecki, and Dr. H. Holt, and Mr. R. J. Hackman of the U. S. Geological Survey. Mr. P. Backer, Mr. R. Mercer, Mr. L. Fischer, Mr. R. Murphy, Mr. W. Armstrong, and Mr. H. Higgins of Project Mercury cooperated fully in providing pictures taken during the orbital flights referenced. The writer had many valuable discussions on the interpretation of Mercury photography with Dr. J. O'Keefe and Dr. J. Gill of NASA, and with Mr. S. Soules and Mr. K. Nagler of the U. S. Weather Bureau.

Mr. B. C. Schuler of Goddard Space Flight Center provided many useful Aerobee pictures. Mr. J. F. Cronin, Air Force Cambridge Research Laboratory, made several useful suggestions. Mr. P. Mikoda of the Ansco Corporation provided much useful information on film types. Finally, thanks are due to Dr. Robert Voas, formerly of the Manned Spacecraft Center, for his cooperation and encouragement in regard to the terrain photography planning during the Mercury project.

(Manuscript received May 1963; revised April 1964)

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