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Photographs of the Western Sahara from the Mercury MA-4 Satellite†

Landform patterns hundreds of kilometers in extent are obvious.

(*Abstract is on page 353*)

Introduction

Mercury spaceflight MA-4 took place in September 1961. The photographs that it obtained are still, so far as is known, the only photographs on film recovered from space showing a continuous land area of continental proportions free of cloud and haze. They give for the first time a view of this enormous expanse of North Africa which is at once both all-embracing and comparatively detailed. (Lowman, ref. 7; Bird and Morrison, ref. 3; and references therein.)

Circumstances of the Photography

The Mercury capsule containing the camera that took these photographs was launched from Cape Kennedy and inserted into an orbit averaging 190 km (120 st. mi.) above the earth. It passed across the North Atlantic, northwest and central Africa, the South Indian Ocean, and the North Pacific. The retro-rockets were fired over Mexico, and the capsule splashed down east of Bermuda and was recovered (Figure 2). The capsule was not manned, but the interior was maintained at a pressure and temperature suitable for an astronaut.

The photographs were taken through the capsule window, with the aid of a mirror system, by a 70 mm Maurer time-lapse camera, having a 75 mm focal length and 44° angle of view, loaded with 100 feet of Super Anscochrome color film, having ASA speed 100. The exposure used was 1/500 sec at f/8. (Lobb, Nagler, Donegan, Packard, personal communications; Grimwood, ref. 4, p. 148).

The camera took photographs automatically every six seconds from lift-off until exhaustion of the film, which occurred over the South Indian Ocean. The path of the spacecraft during this time is shown in Figure 3. Frames 1 to 182 show mainly the North Atlantic Ocean and the clouds lying over it. The latter part of the film, from about frame 335 onwards, shows ocean areas which were in darkness when photographed so that no ground detail is visible. Between frames 270 and 335, the earth's surface is obscured by broken cloud, though ground detail is visible through the gaps. It is only between frames 182 and 270 that continuous areas of land are visible. The photographs studied have been confined to this strip, extending from the Moroccan coast to Lake Chad.

Once in orbit the attitude of the spacecraft was stabilized by an automatic system using horizon scanners and hydrogen peroxide jets. The camera pointed in roughly the same direction throughout the flightline, towards the north-northeast, obliquely downwards at an angle of about 70° from the vertical. All photographs show the horizon, which was about 1400 km (900 st. mi.) distant. The variation of camera height and orientation are shown in Figure 4.

Successive photographs overlap considerably, but the amount of overlap and the scale change rapidly from foreground to background. If the camera had been pointing vertically downwards, the scale of the original diapositives would have been rather smaller than 1:2,000,000. In fact, the scale in the near foreground of the originals varies from 1:3,000,000 to 1:5,000,000, while the scale in the background is much smaller.

General works on the climate (ref. 2), vegetation (refs. 5, 13), geology (ref. 8) and landforms (ref. 11) of the Sahara, which the photos illustrate so well, are listed at the end of this paper.

Interpretation

General

These space photographs show the distribution patterns of rock-type, structure, landforms, drainage and, where it exists, vegetation. These can be interpreted through the variation of tone, texture, pattern, and shape as seen in plan. The third dimension has lim-

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FIG. 1. Entire MA-4 orbit (from ref. 19).

ited use for interpretation in this series because the stereo-effect obtainable is small, but on the color photos stereo is to some extent replaced by color.

On the photos areal and linear features up to hundreds of kilometers in extent are obvious. Indeed, if the photos had been taken rather differently, a stereomodel of an area as this could have been obtained. Certainly, subtle tone and color changes can be picked out which would be lost in a mosaic of the hundreds of conventional air photos needed to cover the area shown by each space photograph. Moreover, they provide a uniform coverage across political boundaries (e.g. in Figures 11 and 1).

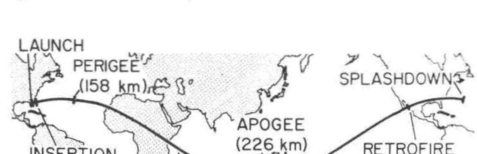


FIG. 2. Path of MA-4 satellite over Africa. The figures mark the points above which frames 182, 270, and 335 were exposed. The shading represents the area covered by one typical frame.

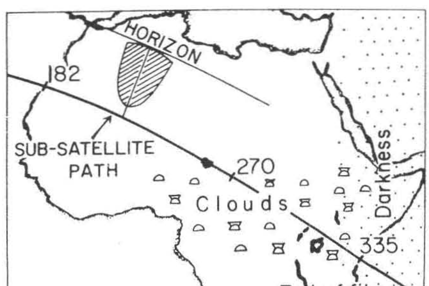
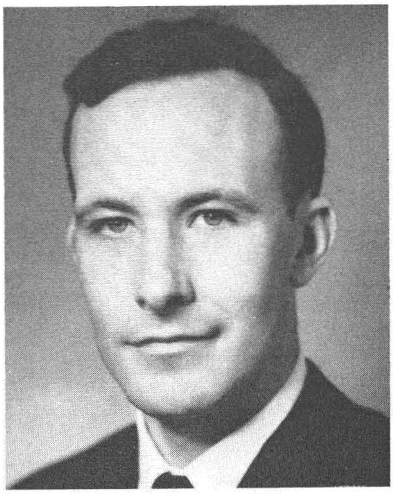


FIG. 3. Entire Atlantic coast of Morocco (frame 187). White area (left is low cloud which ends abruptly at the coast. Other clouds lie over Anti Atlas and Atlas Mts. Apart from vegetation along wadis flowing to the coast, patterns visible are geological. Banded area (foreground) is a scarpland developed on outcrops of Paleozoic rocks dipping SEE. Dark bands are resistant sandstones and limestones forming ridges up to 200 m (700 ft.) high. Shales underlie the intervening vales, but their light tone is due to a cover of Quaternary sand, gravel and lacustrine limestone. Zigzag outcrops (arrow) result from small SW–NE folds. Interference between these folds and others trending NW–SE has produced dome or basin structures (arrow). (All photographs courtesy NASA Manned Spacecraft Center.)



A. MORRISON

In the same way that a detailed survey made from aerial photos is checked by ground work in critical areas, a wider study based on these space photographs could be checked by selective use of aerial photographs or field work.

The full interpretation of these photos requires study by two groups, one group already expert on the Sahara and using the photos to piece together local studies they have made; the other group without preconceived ideas about the Sahara and viewing the photos in a worldwide context.

GEOLOGICAL

Geological patterns are usually obvious on these photos because of the absence of vegetation or an organic soil cover.

Structure is the most readily interpreted aspect of geology. The strike of bedding (Figure 5) and schistosity (Figure 11), the axes of folds (Figure 1) and elongated basin structures (Figures 1 and 5) can often be picked out. However, the direction of dip of the beds involved may not be obvious because the detailed three-dimensional form of the outcrops and the drainage pattern developed on them may not be visible. Consequently some background information on landforms, rocks, or structures from existing maps or reports is needed to establish whether structures are anticlines or synclines, domes or basins.

Most interesting of all, it is possible to map structural lineations which extend for hundreds of kilometers. These may be manifest in different places as lines of solution hollows, long, narrow salt flats, elongated volcanic outbursts, drainage lines, changes of rock type, and so forth. Nevertheless their continuity is obvious on the space photos (Figure 10) and they can be easily mapped (Figure 6).

The Hamada du Dra (Figure 5) is an especially favorable area for distinguishing structural lineaments, since it has a surface of uniform rock-type and low relief. On the original photos five families of lineaments are apparent there. The most marked of these (arrowed on Figure 5) trends northwest-southeast across the Plio-Pleistocene rocks of the hamada and the Paleozoic and Precambrian rocks to the southeast.

The trend appears again in the Eglab as the light-toned strips, arrowed on Figures 7 and 8, which resemble huge wadi beds. These do not in general correspond to present wadis and are labelled on the 1:2,000,000 geological map (ref. 15) as hamada formation (Plio-Pleistocene). Whatever their origin, it has been assumed that they follow structural weaknesses.

These previously unmapped lineaments extend for a total of 800 km (500 mi.), as shown in Figure 6. They seem to be regularly spaced about 50 km (30 mi.) apart. They parallel the Ougarta folded ranges (beyond the northeast corner of the map), formed in the early part of the Hercynian orogeny, which have been regarded as an anomaly within the area of the Saharan shield (Rod, ref. 12, p. 533). If produced, they would also parallel the 1000 km long, strikingly linear portion of the Niger River's course. Because they continue across rocks of all ages, and for such long distances, the lineaments must represent deep-seated fractures in the basement rocks.

Rock-type can be inferred from the MA-4 photographs to some extent by means of

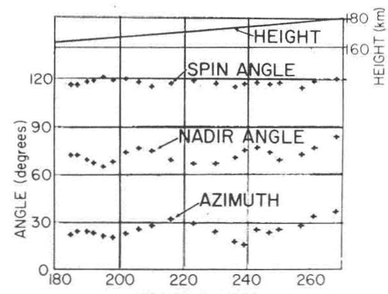


FIG. 4. Variation along the flightline of (a) azimuth of principal axis, (b) nadir angle of principal axis, (c) spin angle of camera about principal axis, measured from an arbitrary zero, and (d) height above the spheroid. Height figures were provided by NASA. Orientation figures were derived from the photographs and from maps.

tone and texture, but other clues such as gully density and details of vegetation are not evident.

Age. Very little can be deduced about the age of the rocks from the photos alone, though in the case of dune sands there is reason to think that the redder dunes were formed before the second pluvial period, i.e., in the early Quaternary, whereas the paler dunes are younger, and a similar distinction may apply to gravel deposits (Alimen, ref. 1, pp. 137–138) (see Figure 7).

Contribution to mapping. All the areas shown on the space photos have been mapped geologically on a scale of at least 1:2,000,000, and the photos rarely suggest that sweeping changes are needed in the maps, but in a few instances they have a contribution to make.

A field account of the Eglab describes rhyolite outcrops, surrounded by aureoles of microgranite, in a granite country rock, but states that they are difficult to define on the ground because of intergrading (Lapadu-Hargues, ref. 6, p. 104). On the 1:2,000,000 geological map (ref. 15) rhyolites are not distinguished from microgranites. All three types can be confidently outlined on the photos (see Figure 8b).

Figure 10 shows a striking linear feature (arrowed), evidently a low escarpment crossed by the dark beds of wadis flowing west. It is certainly a major structural feature and maybe a lithological boundary too. It does not appear on the 1:2,000,000 geological map (ref. 15) either as a fault or a continuous rock-type boundary.

The middle-distance of Figure 11 is crossed by a series of light and dark bands, continuous for 250 km (150 mi.) in a direction west-southwest to east-northeast. They resemble the outcrops of a series of sedimentary beds striking in that direction. The geological maps (refs. 15 & 16) show most of the banded area as underlain by Paleozoic and Cretaceous sedimentary rocks, but the outcrop pattern is very different from that on the photos. It is difficult to believe the maps could be so much in error, even though the correlation of geological units may have been complicated by the boundary between Algeria and former French West Africa. The bands may have been formed by wind action, mainly erosion. On frames further west, they grade into much finer lines which can reasonably be ascribed to wind action. Smith (ref. 14, p. 11) states that the wind can erode solid rock into knobs and ridges elongated in a direction independent of the strike. Even if the wind has carved them, the bands are so wide and continuous that it is difficult to believe they are not related to some type of structure, e.g., jointing.

ABSTRACT: *These high oblique photographs taken by automatic camera in 1961 remain the only generally available photographs recovered from space that show a land area of near-continental extent not obscured by cloud or haze.*

The larger geological and landform patterns of the area, as well as vegetation boundaries on the south edge of the Sahara can be mapped from the photographs. A persistent set of northwesterly-trending structural lineaments occurs in the northwest Sahara. One photo illustrates the potentiality of space photography for small-scale land-use mapping.

The original color photos (here reproduced in black-and-white) appear mainly blue because no filter was used, but other colors present occasionally distinguish between geological units which otherwise appear similar. The resolution of the original transparencies in terms of a standard test object is roughly 10–15 lines/mm. Observations and calculations show that the smallest ground features which can be seen stereoscopically on these photos are of the order of several hundred metres (1,000 ft.) high.

Much better results could be obtained using a photographic system specifically designed for mapping terrestrial distributions.

LANDFORMS

Landform patterns hundreds of kilometers in extent are obvious on these photos, for example the alternation of basins and massifs as on Figure 11, analogous in form with the basin-and-range topography of the American Southwest, but on a vastly greater scale; and the patterns typically formed by sand dunes (Figures 7, 9, and 12), and wadis (Figures 11 and 5). Maps of dune trends or drainage patterns could be rapidly constructed. The wadi

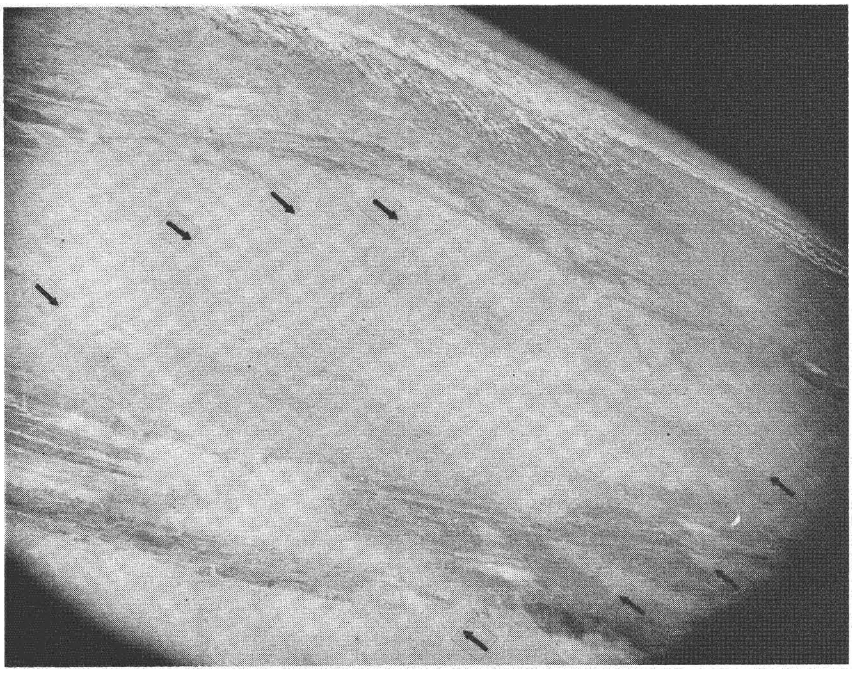


FIG. 5. Frame 193. Tindouf structural basin. Arrows indicate selected structural lineaments (see text). Light-toned area (near foreground) is Yetti, an area of subdued relief developed on Precambrian basement rocks. Dark stripes (foreground) are escarpments developed on outcrops of Paleozoic sandstones and limestones dipping away from the camera. Salt-flats occur in many of the intervening vales. Light area (middle distance) is Hamada du Dra, a plateau of flat-lying Plio-Pleistocene limestone. Beyond, forming other limb of downfold, is another scarpland (see Figure 1), and another Precambrian area, the Anti Atlas, partly cloud-covered. (For full citation of sources of this and the following figure captions (see ref. 9).) Exact locations of this and other photographs are given in Table 1.

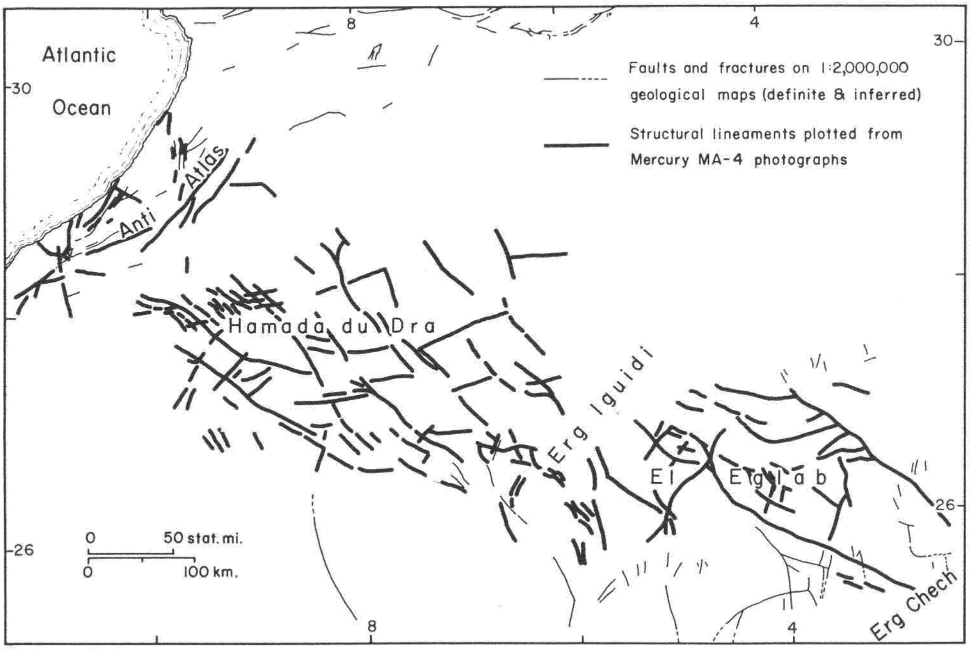


FIG. 6. Structural lineaments of the northwestern Sahara, mapped from the space photos, with the addition of all faults and fractures marked on the existing 1:2,000,000 geological map (ref. 15).

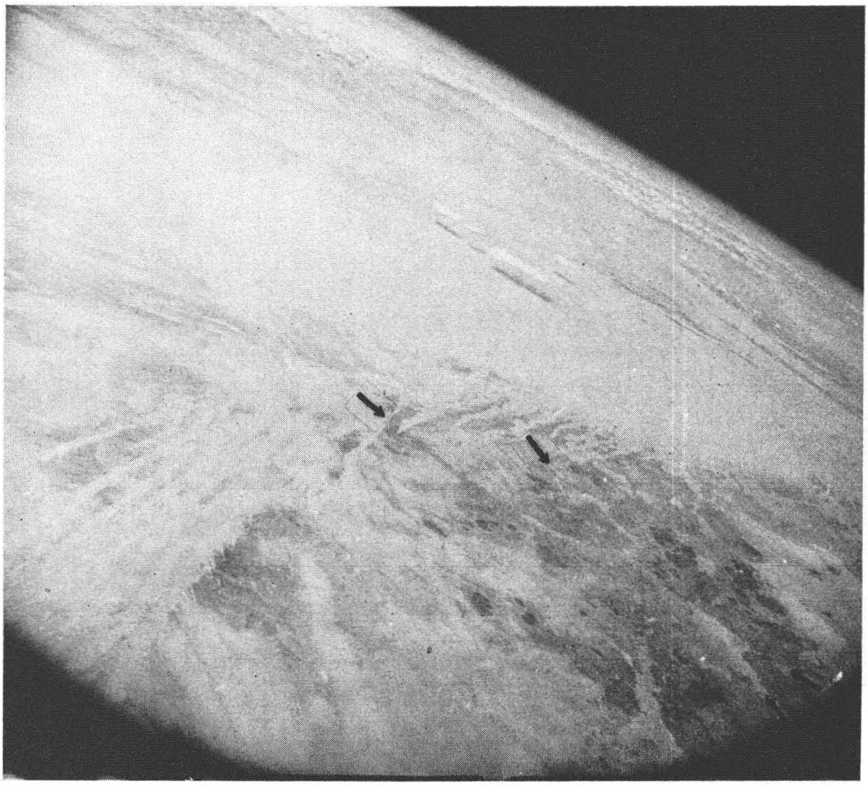


FIG. 7. Frame 199. The longitudinal sand dunes of the Erg Iguidi (left foreground). The major dune-chains, trending SW, are reddish on the original color photograph, whereas the minor dunes, branching SE from them, are almost white, and therefore younger. The two white stripes beyond the dunes are salt flats lying between Paleozoic sandstone cuestas. Light area (left middle distance) is Hamada du Dra (Figure 5). Isolated clouds cast shadows upon it. Right foreground is part of Eglab (Figure 8). Arrows indicate selected structural lineaments.

TABLE 1

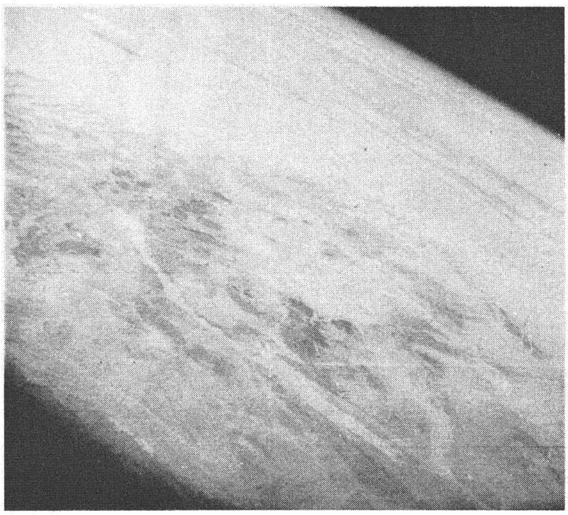
TIME, POSITION, AND ORIENTATION OF EXPOSURES REPRODUCED IN THIS ARTICLE

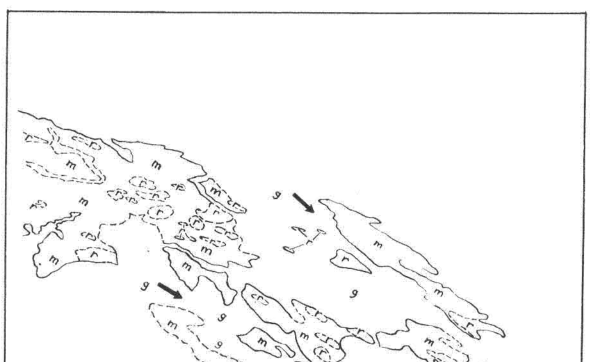
Figure number	*Frame number*	*Time G.M.T.*			*Height above an oblate earth*		*Latitude °N*	*Longitude °*	*Nadir angle of principal axis °*	*Azimuth of principal axis °*	*Spin angle about principal axis °*
		Hr.	*Min.*	*Sec.*	*Stat. Mil.*	*Km.*					
1	187	14	22	54	101.7	163.8	25.94	11.53W	72.1	24	116
5	193	14	23	30	102.2	164.5	25.05	9.13W	66.6	22	120
7	199	14	24	06	102.6	165.2	24.10	6.77W	69.6	21	119
8	203	14	24	30	103.0	165.7	23.46	5.22W	74.8	23	120
9	208	14	25	00	103.4	166.4	22.62	3.31W	76.0	27	117
10	224	14	26	36	104.8	168.7	19.79	2.66E	67.0	29	119
11	235	14	27	42	105.9	170.4	17.70	6.62E	69.3	19	115
12	258	14	20	00	108.5	174.7	13.18	14.60E	74.4	29	116
13	269	14	31	06	109.9	176.9	10.78	18.29E	85.2	38	121

Orbital data were provided by NASA. Orientation figures were derived from the photographs and from maps.

traces visible on Figures 1 and 5 may suggest that the drainage pattern in the area is consequent upon a formerly continuous cover of hamada formation, and is now becoming adjusted to the structure of the underlying Paleozoic rocks. Frame 190 (not illustrated) clearly shows that a fine pattern of parallel depressions on the Hamada du Dra is limited to the southwest part of the hamada, and makes us ask whether this is due to different dip, different rainfall now or in the past, or to the proximity of the Ocean base level to the southwestern area? Could the parallel bands in Figure 11 be formed solely by wind action, or do they reflect rock structure?

The three-dimensional form of surface features is more difficult to determine than is their two-dimensional pattern, because of the poor stereoscopic effect, and for other reasons. Thus the direction of slope of an alluvial fan would have to be deduced from the pattern of streambeds on it, longitudinal dunes (Figure 9) distinguished from narrow depressions by the direction of their shadows, and Tibesti (Figure 12) recognized as a highland by the wadis just visible on its slopes.





FIGS. 8a and 8b. Frame 203. Eglab massif (foreground), mainly composed of Precambrian crystalline rocks, especially granite. On Figure 8b, rhyolitic intrusions (*r*, almost black) have been distinguished from the surrounding micrогranite aureoles (*m*, dark grey), and the granite country rock (*g*, medium grey). Boundaries taken from the map (ref. 15) are continuous lines; those derived from the photo are broken. Arrows indicate selected structural lineaments.

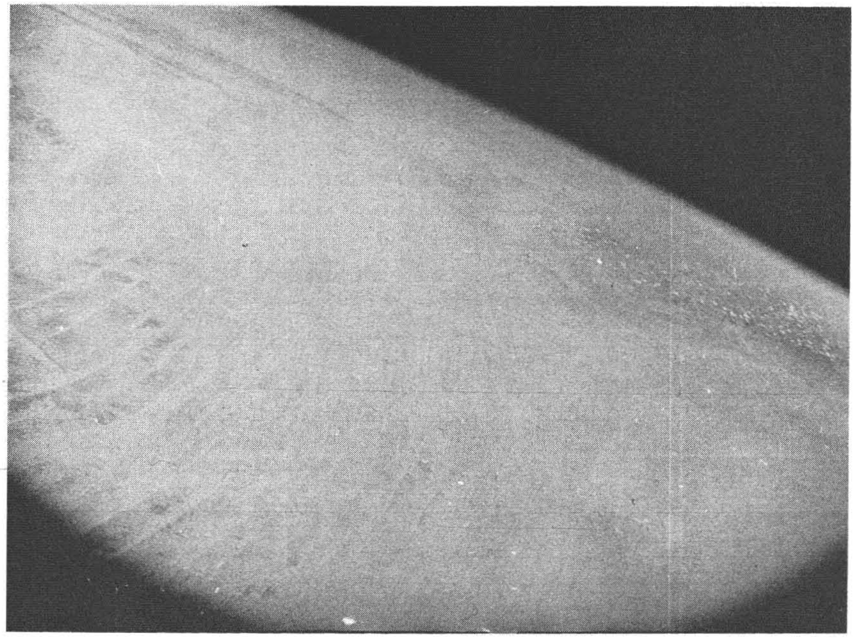


FIG. 9. Frame 208. Erg Chech (left foreground), consists of chains of longitudinal dunes 500 km (300 mi.) long and 2 or 3 km wide, separated by bare areas which here are about 10 km (7 mi.) wide. Often the sand rests directly on rock, not gravel. The dune chains parallel the dominant wind, the Northeast Trade, but this does not account for their curvature towards the *N* (middle distance). These dunes appear unchanged since they were surveyed for the French 1:1,000,000 topographic map in the 1930's. In right background clouds lie over Tademaït, a plateau of dark Cretaceous limestone. Featureless area (right foreground) is part of Tanezrouft, a gravel desert.

VEGETATION

Since most of the area photographed is desert, it is not surprising that there is no sign of vegetation on the majority of photos, apart from a slight darkening along some wadis, which may be due to moisture as well as vegetation.

South of the desert darker tones clearly indicate vegetation. By changes in tone and pattern one can distinguish successively the zones of sub-desert steppe with widely spaced low plants and grasses; wooded steppe (Figure 12) with thorny shrubs and short grasses; and finally true savanna (Figure 13) with a continuous cover of relatively tall grasses and scattered trees. In each case the whole transition from one zone to another occurs in a single frame, which enables one not only to detect the boundary, but to draw a line through the middle of the transition zone with some confidence, and also to know that the boundary has validity, since one can see that in this area there does appear to be a more rapid change in tone and pattern between vegetation zones than there is within zones.

LAND USE AND OTHER MAN-MADE FEATURES

For obvious reasons, this series is poorly suited to demonstrate the undoubted possibilities of space photography for small-scale land-use mapping. However, Figure 13 gives some idea of these possibilities. It shows, very obliquely, a patchwork pattern composed of areas of woodland and grassland, which is probably at least partly man-induced. If the photos had been taken vertically, and the areas had been say, cultivated land and forest, it would have been a simple matter for an experienced interpreter to outline them and have ready-made a land-use map on a scale of about 1:1,000,000.

LESSONS FROM THE MA-4 PHOTOGRAPHY

Study of the MA-4 space photographs prompts a number of comments about aims in the design of future satellite photographic systems intended for non-meteorological applications. These are grouped under headings which are four of the basic design parameters of a photographic system—area covered per frame, ground resolution, stereo-effect obtainable, and number of wavebands, i.e. whether to use color. However, this is *not* a discussion of the optimization of satellite photographic systems in general.

COLORS

Color is mentioned first as a matter of convenience only.

The photos are reproduced here in black-and-white, but were taken on standard Super Anscochrome color film. No filter was used apart from the effect of the spacecraft window, which was not measured, but was probably almost neutral in the visible wavelengths. Manned Spacecraft Center has issued copies of Mercury photos in three color versions: "true color rendering," "high color contrast," and "general interest." The following statements are based on examination of second generation color diapositives of "true color rendering" type. (Lobb, personal communication; O'Keefe *et al.*, ref. 10, p. 328.)

The photos were almost entirely in shades of blue because of the superimposition over the whole picture of blue light scattered by the full depth of the atmosphere. However, they are not much bluer than a high altitude aerial photo would be if taken without filters. This is to be expected, since an aircraft at 11 km (36,000 ft.) is already above 75% of the mass of the atmosphere.

The only true green or yellow color occurs in a narrow strip round the edge of the field of view, suggesting it is due to the accidental reflection of tungsten light into the lens from within the spacecraft. Green vegetation would certainly be present at the southeast end of the flightline when the photos were taken. The absence of greenish hues must therefore be due to the relatively poor ability of yellow and green light reflected from the ground to penetrate the atmosphere. The only slightly greenish tinges appear in the foreground of photos which point down more steeply than the average, so that the mass of air to be penetrated is less.

Usually the only color visible other than blue is red, always very faint. Red light, with its longer wavelength, would penetrate in larger quantities than yellow or green. Areas which appear reddish are mainly areas of Quaternary continental deposits namely, in order of redness, the longitudinal dunes of the northern Sahara (Figures 7 and 8), gravel and sand spreads in S. Morocco (Figure 1) and the transverse dune areas along the

FIG. 10. Frame 224. A few clouds lie over Ahaggar (dark area, right middle distance), central massif of Sahara, which rises to 3003 m (9900 ft.). It is mainly composed of metamorphosed Precambrian sediments. The N–S structural trend is obvious, and an E–W trend also discernible. Light-toned area (foreground) is part of Tanezrouft, a gravel desert also developed on Precambrian rocks. Tassili n'Adrar (dark area, left foreground) is a miniature plateau, a remnant of a former Paleozoic sandstone cover. Arrows indicate lineament referred to in the text.

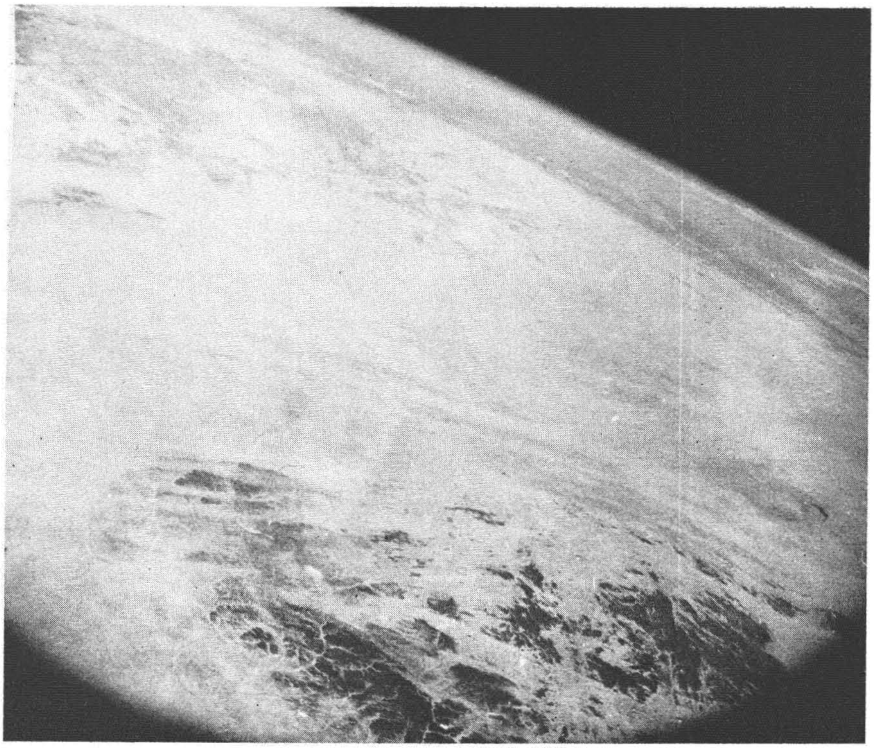


FIG. 11. Frame 235. Aïr (dark, right foreground) is a mountain area of mean elevation 800 m (2500 ft.) composed of Precambrian basement rocks. Minor wadis flow S.W. through short, deep gorges, to lose themselves in alluvial plain of Talak (light, left foreground). Between Aïr and Ahaggar (dark, left background) is a plateau of Paleozoic rocks (light, middle distance). Bands running ENE across it resemble outcrops of beds striking in that direction, but may be caused by wind erosion unrelated to structure.

southern edge of the Sahara (Figure 12). Also some rock outcrops have a reddish tinge.

The red color makes interpretation easier, but only in a few minor instances does it reveal information not obtainable from black-and-white prints. For example, on colored versions of Figure 7, in the right middle distance, longitudinal dunes (pink) can be distinguished from elongated outliers of the limestone of the Hamada du Dra (light blue, left middle distance) only by their color. On frames 239 and 243 (not illustrated) pediments surrounding inselbergs can be distinguished from the surrounding depositional areas only by the slightly warmer color of the latter. It is unlikely that instances such as these constitute an advantage which outweighs the loss of tone contrast due to using a film sensitive to blue light. Certainly if a blue-sensitive color film is to be used from space, the photos must be verticals, and a filter must be used to remove the ultra-violet and reduce the blue light.

A color film not sensitive to blue light would be more promising, for example, Ektachrome Infrared Aero. The advantage of having the data conveyed in three wavebands rather than one might outweigh the lower definition or film speed and the consequent low resolution. To establish this objectively would require a comparison of wavelength differences in the reflectivities of the surfaces involved with the distances over which total reflectivity varies. Speaking subjectively, the writers feel that, at least in areas where the relief is too low to appear stereoscopically on space photos, some kind of color is desirable.

AREA COVERED

The area covered by each MA-4 photo extends to the horizon 1400 km distant. The size of the usable area in the foreground and middle distance is about 200 or 300 km across. If the camera with its 44° lens had pointed vertically, it would have covered a roughly circular area 140 km in diameter.

Are there any particular maximum, minimum or optimum areas which space photos should cover?

If the photography is being used to photograph repeatedly a changing distribution, there is not necessarily any lower limit to the area which should be covered by a single frame.

For photography of unchanging features from space to be worthwhile, each frame should cover a larger area than could an air photo. The extreme limit for air photography may be a height of 30 km and a 120° lens, which would produce a vertical photograph of about 75 km side. Let us say the minimum area a space photo should cover has a 50 km side.

The maximum area which could be usefully covered is limited only by the extent of the largest pattern to be picked out. Judging from the region shown in MA-4, this may be as much as 2,000 km across in the case of geological structures, vegetation belts, and soil zones, 1,000 km for landform patterns and 500 km for land use, with in each case the optimum size about $\frac{1}{4}$ of the maximum. For the mapping of ephemeral distributions, e.g. the extent and effects of rain from individual storms, the state of vegetation for grazing, or the extent of savannas burned each year, the maximum useful areas would be less, in the range 200–500 km across, with again the optima being smaller.

Pictures obtained by the Tiros medium-angle television cameras cover an area about 700 km square when pointing vertically, and areas covered by the Nimbus television cameras are larger. Therefore, it appears that the size-range which could most usefully be covered by Mercury-type photos is 50 to 700 km, with optimum in the range 100 to 500 km, depending on the primary application.

Such coverage should present no insoluble technical problems.

GROUND RESOLUTION

The resolution in the MA-4 photos can be estimated from measurements on the partially resolved parallel lines making up the image of one series of longitudinal dunes. In terms of a standard high-contrast resolution test object, the resolution of the original diapositive must have been about 10 to 15 lines/mm. This figure may be in error by a factor of 2 or 3, but not by an order of magnitude.

Direct estimates of the ground resolution

FIG. 12. Frame 258. Southern edge of Sahara, N. of Lake Chad. The darkening in tone between middle distance and foreground is the transition from sub-desert steppe (low perennial plants widely spaced) to wooded steppe (drought-resistant shrubs and low trees, discontinuous short grass after the rains). Ripple-like pattern (left foreground) is area of sand-dunes formed perpendicular to the dominant wind, and now fixed by vegetation. Dark area (left background) is Tibesti, a mountainous area of basalt, which rises to over 3300 m (11,000 ft.). Borkou (entire middle distance and foreground) is a basin, only a few hundred feet in altitude, floored by lake-deposits. Clouds appear in foreground and over Tibesti.

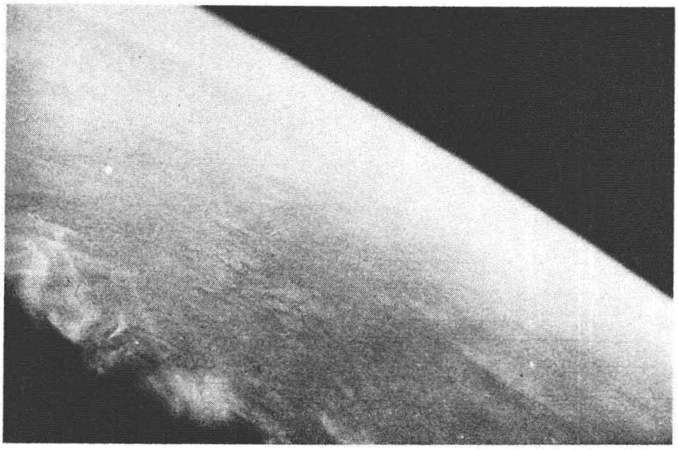


FIG. 13. Frame 269. The boundary between wooded steppe (medium-tone, left middle distance, see Figure 12) and true savanna (dark, right middle distance), where usually there is continuous grassland 1 to 1.5 m (3 to 5 ft.) high, with scattered trees 3 to 15 m (10 to 50 ft.) high.

in the foreground of the photos give figures of 200 to 800 m, depending on the contrast, shape, and orientation of the features considered, and the nadir angle of the photo. This agrees with what would be expected from a resolution of 10–15 lines/mm.

This resolution may be adequate to reveal the very broad distributions, but it is clear that better ground resolution is needed if systematic mapping of either permanent or changing distributions is the aim, particularly if we consider that the smallest mappable units are several times larger than the ground resolution, say about ½ to 3 km in the case of MA-4.

If photography had been a major aim of the MA-4 flight, the ground resolution could have been improved in several ways, apart from altering the height, focal length, or tilt: (a) by using a slower film of higher definition with a longer exposure—during the 1/500 second exposure used image movement was only 0.004 mm, which is much less than the 0.1 mm resolution attained; (b) by using a film-filter combination not sensitive to blue light, either black-and-white or false-color; (c) by reducing the number of surfaces the light encounters before reaching the lens; (d) by preventing cabin-lighting from reaching the lens.

STEREOSCOPIC EFFECT

When these photos are examined under a hand or mirror stereoscope, it is not difficult to fuse the images of adjacent photos, or of photos two frames apart, to form a stereo-image. In this image, clouds clearly appear to float above the ground, but the existence of the third dimension in the image of the ground itself is problematical in most places. It can only be seen in a few places, where the local relief exceeds 300–500 m.

The poorness of the stereo-image is due to the following factors: (i) the small scale, i.e. great height coupled with short focal length, (ii) mediocre resolution and tone contrast, (iii) small base/height ratio, (iv) oblique nature of the photos, which further decreases the scale and prevents the stereo-image from being obtained over the entire overlap at one time, (v) lack of large relief features to facilitate accurate relative placing of a pair of photos.

Calculations of the smallest relief features which should be distinguishable, based on the value for resolution estimated above, and the known values of the other parameters, also give figures of several hundreds of meters.

These figures are not a fair estimate of the ability of space photographs to reveal heights. A typical aerial camera with $f = 150$ mm, and base/height ratio 0.6, in a spacecraft at 170 km, if it attained 50 lines/mm resolution, should be able to reveal height differences of 36 m.

Obviously future photos will be most convenient if taken vertically, and film will be used most efficiently if the overlap is 60%.

CONCLUSIONS

The advantages of space photography for research and mapping arise mainly because areas hundreds of kilometers across can be shown in a single frame. Photographic tones or colors are comparable across the whole of this area. Even if the area is crossed by a political boundary, there will be no change in the type of coverage. With a suitable pair of vertical space photographs, it would be possible to obtain a continuous stereomodel over an area of this size, in which height differences of hundreds of meters are distinguishable.

The MA-4 photographs can assist mapping of the larger geological, landform, and vegetation patterns of the Sahara. Structures, especially lineaments, are particularly well shown. Photos of this kind could aid mapping of other types of distribution not present in the Sahara, such as generalized land-use.

In photography of the earth from space, ordinary color film is likely to yield less information than black-and-white, infrared, or infrared false-color film.

Much better results could be obtained by a satellite system specifically designed for photographing terrestrial distributions.

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