*Earth Satellite Photogrammetry**

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ABSTRACT: *Photogrammetry of the earth's surface from satellites, unmanned and manned, is discussed. Orbits, satellite-borne photographic cameras, and environmental conditions are considered. Television and other electronic methods for scanning the ground from a satellite are discussed briefly. It is suggested that the moon and the planets can be mapped by photogrammetric equipment in satellite vehicles orbiting around these bodies.*

INTRODUCTION

INSTRUMENTED, unmanned earth satellites are now an accomplished fact. Manned satellites are feasible, and may be an accomplished fact within a decade. In the meantime, International Geophysical Year studies of the upper atmosphere and adjacent space are providing data upon which to base the designs of future satellite vehicles, satellite instruments, and satellite-borne cameras.

Consequently it is timely for the photogrammetrist to consider the potential uses of earth satellites and space stations, manned as well as unmanned, for non-military photogrammetric purposes.[1] This paper therefore proposes and discusses future photographic and electronic methods and systems for photogrammetry from earth satellite vehicles, the advantages of such methods, and the attendant problems and difficulties.

[1] Since the first writing of this paper, it has been announced that both the U. S. Army and the U. S. Air Force are planning to launch aerial reconnaissance satellites. (E.g., the *New York Times*, 2 Feb. 1958, pages 1 and 42, article by J. Raymond; 4 Feb. 1958, pages 1 and 11, article by J. W. Finney; 19 Feb. 1958, pages 1 and 8, article by J. W. Finney.)

SATELLITE ORBITS

Prior to discussing earth satellite photogrammetry as such, it is pertinent to summarize some basic facts and data concerning satellites and their orbits.

The orbit of an earth satellite is an ellipse with the center of the earth at one focus. (The eccentricity of the elliptic orbit can be zero, in which case the orbit becomes a circle with the earth at the center.)

Once launched in its orbit, a satellite remains aloft without further propulsive force because the gravitational attraction of the earth upon the satellite is equal to the centrifugal force of the satellite's orbital motion. This balance results in an apparent weightlessness, *as if* the satellite and its payload were in a field of zero gravity. (Contrary to popular misconception, gravity acts continually upon the satellite; indeed, gravity keeps the satellite in its orbit.)

A satellite will continue to travel in its orbit indefinitely without the application of additional propulsive force (as does the earth's natural moon) if the orbit lies completely outside the earth's atmosphere. If all or part of the orbit is low enough in altitude to encounter appreciable densities of

* Cleared by the Department of Defense. The opinions expressed in this paper are the author's and not necessarily those of the Department of Defense. Part of this paper was presented at the 24th Annual Meeting of the American Society of Photogrammetry, 26 March 1958, in Washington, D. C.

EDITOR'S NOTE—Very appropriately and opportunely during the reading of this paper the press announced success for Explorer II. Later on this statement was expanded by an announcement by Dr. Rosenberg that the satellite was in orbit.

TABLE I

DATA ON THE FIRST THREE EARTH SATELLITES

	1957 Alpha (*Sputnik I*)	*1957 Beta* (*Sputnik II*)	*1958 Alpha* (*Explorer I*)
Date launched	4 Oct. 1957	3 Nov. 1957	31 Jan. 1958
Estimated life	Disintegrated 4 Jan. 1958	5 months	2 years
Weight	184 lbs.	1,120 lbs.	30.8 lbs.
Shape	Spherical	Conical	Cylindrical
Dimensions	22.8 inches diam.	19 feet long 4 feet diam.	80 inches long 6 inches diam.
Approx. perigee altitude	130 miles	143 miles	220 miles
Approx. apogee altitude	580 miles	1,056 miles	1,600 miles
Orbit period	86 minutes	104 minutes	114 minutes
Angle to equatorial plane	65°	65°	34°

air, the kinetic energy of the satellite is gradually dissipated into heat by air friction. Under the latter conditions, the orbit and the period gradually become smaller until the eccentricity of the ellipse becomes zero, after which the satellite executes a spiral orbit of decreasing radius until the satellite either intersects the earth's surface or is destroyed by aerodynamic heating at supersonic speeds.

Table I gives data concerning the first two Russian earth satellites (Sputniks I and II) and the first U. S. satellite (Explorer I). These satellites are designated respectively as *1957 Alpha*, *1957 Beta*, and *1958 Alpha*, in accordance with the artificial satellite nomenclature approved by the U. S. National Committee for the I.G.Y., in analogy to the astronomical convention for naming comets.

Figure 1 shows the sizes of the orbits of these three satellites approximately to scale in relation to the earth. The innermost circle in the figure represents the surface of the earth; the next two closed curves represent the orbits of *1957 Alpha* and *1957 Beta* respectively: the outermost curve represents the orbit of *1958 Alpha*, the altitude of which is approximately 220 miles at perigee (position of closest approach to the earth), and approximately 1600 miles at apogee (position of furthest distance from the earth). *1958 Alpha* (U. S. Explorer I) has a longer lifetime than *1957 Alpha* and *1957 Beta* because it is in a higher orbit where it encounters less atmospheric resistance.

Orbital data now being gathered and analyzed from the first satellites will give more accurate information than is now available concerning upper air densities, and will enable satellite lifetimes to be predicted more closely than is now possible. In the meantime, for purposes of discussion in this paper, it will be assumed that an altitude of 150 miles is the lowest at which a photogrammetric satellite can travel in a circular orbit with a usefully long life. This is consistent with the lifetimes of *1957 Alpha* and *1957 Beta*. This is also consistent with theoretical calculations[2] which show, for example, that for circular orbits the lifetime of a 22 lb. spherical satellite with a diameter of 21 inches, as proposed in *Project Vanguard*, is

[2] Petersen, N. V., "Lifetimes of Satellites in Near-Circular and Elliptic Orbits," *Jet Propulsion*, Vol. 26, No. 5, Part 1, May 1956, pp. 341–368.

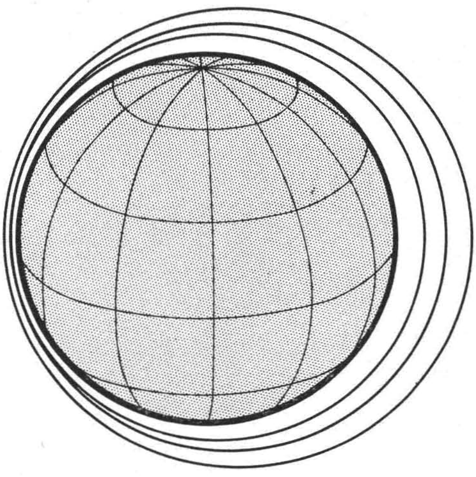

FIG. 1

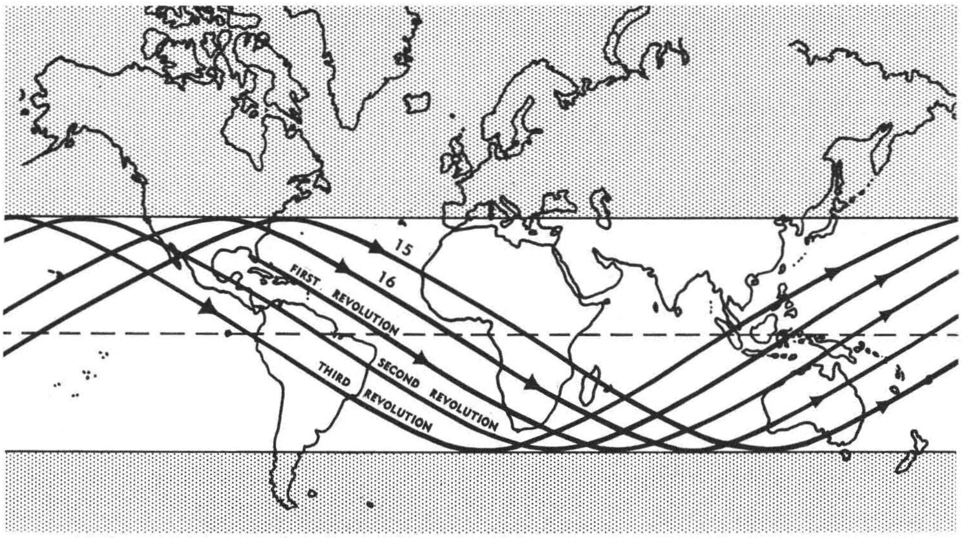

FIG. 2

approximately one month at an altitude of 200 miles, and less than one day at 100 miles. The lifetime increases rapidly for satellites with higher ratios of mass to effective cross-sectional area, such as can be expected for satellite vehicles massive enough to contain photogrammetric equipment.

The orbit of a satellite must lie in a plane passing through the mass centroid of the earth. (It is not possible, for example, for a satellite to circle the earth in a stable orbit lying in the plane of any parallel of latitude except the equator.) If there be neglected the orbit's precession (which is due principally to the non-spherical shape of the earth), the normal to the orbital plane of a satellite can be thought of as fixed in direction in space, independent of the earth's diurnal rotation.

There are three possible types of orbital planes: the plane of the equator; planes passing through the poles; and planes at intermediate angles. The equatorial orbit is least likely to be useful for photogrammetric purposes because in this orbit the satellite can view only the areas in an equatorial belt of limited width. On the other hand, a polar orbit will enable a photogrammetric satellite to survey all areas of the earth. The projection of a polar satellite's path upon the earth's surface is like a ball of string wound so that every turn of string passes over the poles, eventually covering all points on the earth; (this excludes special cases in which the synodic period of the satellite is an integral multiple or submultiple of 24 hours, in which cases the projected path on the earth's surface repeats itself).

The third type of orbital plane (at an angle intermediate between the equatorial and polar planes) was chosen for the satellites *1957 Alpha*, *1957 Beta*, and *1958 Alpha*. The angles of these orbital planes with the equatorial plane are given in the last row of Table I. In this type of orbit, the projected path of the satellite traces a basket-weave pattern on the earth, in a band between two parallels of latitude equally spaced on either side of the equator. Part of this pattern is diagrammed in Figure 2 for a satellite in a 90 minute circular orbit that crosses the equator at an angle of 40°, which is approximately the angle expected for the U. S. Vanguard satellites. The figure shows the first, second, third, fifteenth and sixteenth revolutions of this satellite, the orbital period of which is one sixteenth of the period of the earth's diurnal rotation. A photogrammetric satellite launched in the same orbital plane as *1957 Alpha* and *1957 Beta* could survey the entire area of the earth from latitude 65° North to latitude 65° South.

AERIAL PHOTOGRAPHY AND PHOTOGRAMMETRY FROM A RECOVERABLE SATELLITE

Reentry of an earth satellite into the atmosphere without harmful temperature rise (at initial speeds of the order of 18,000 miles per hour) is a difficult engineering and aerodynamic problem that must be solved before an instrumented or manned satellite can be recovered safely. Nevertheless it will be assumed in this section of the discussion that the reentry problem has been solved and that satellites can be recovered.

Satellites such as *1957 Beta*, or a manned space station, are of sufficient weight and size to carry photogrammetric camera equipment. It is therefore realistic and practical to consider the engineering problems involved in the design, construction and use of such equipment.

A camera at satellite altitude has the advantage of very wide coverage. For example, at an altitude of 1,600 miles, which is the apogee of *Explorer I*, a lens with a 90° field of view will photograph more than one-third the area of the entire earth in one exposure from horizon to horizon. Wide coverage photographs such as these should be valuable for geodetic purposes,[3] to tie in more accurate large scale surveys.

A 6-inch focal-length lens at the aforementioned 1,600 mile altitude will give photography at a scale of approximately one to twenty million. This scale is obviously too small for useful topographic mapping, unless the resolution and definition of lenses and photographic emulsions were to be improved far beyond anything presently available.

Lower satellite altitudes are obviously more desirable, or shall we say less undesirable, for topographic mapping. 150 miles was assumed to be the minimum altitude for a photogrammetric satellite, in the discussion of satellite orbits and lifetimes earlier in this paper. Even at this altitude, a 6-inch focal-length lens takes a photograph at a scale of approximately one to two million. This scale will not give a resolution or C factor high enough for topographic mapping by conventional accuracy standards. It is therefore concluded that satellite photography with conventional photogrammetric cameras would be useful only for planimetric mapping at small scales, and for tie-in of large-scale surveys made by other photography.

[3] O'Keefe, John, "Geodetic Significance of an Artificial Satellite," *Jet Propulsion*, Vol. 25, No. 2, Feb. 1955, pp. 75, 76

It is interesting to note that the aforementioned 6-inch focal-length lens, at 150 miles altitude, will photograph an area of approximately 225×225 miles on a 9×9 inch negative, using vertical photography. With this large area per frame, and a 60 per cent overlap, only 185 exposures will cover an entire flight line going completely around the world. The time interval between exposures will be 27 seconds, at the satellite's ground speed of 18,000 miles per hour.

Long focal-length cameras are obviously required if satellites are to be used for large scale photography. For example, a 180-inch focal-length camera at 150 nautical miles altitude will give photography at the same scale of 1:60,000 as a conventional 6-inch focal-length camera at 5 miles altitude (and will photograph the same ground area on the same format). For this same scale photography at altitudes of 500 and 1,600 miles, the focal-lengths of the satellite camera would have to be 50 and 160 *feet* respectively. Cameras such as these should be dubbed *VLFLI*—"very long focal-length indeed."

Presumably these long-focal-length satellite cameras can provide useful aerial photographs with ground resolution comparable to that of conventional cameras at conventional altitudes. Nevertheless it seems highly questionable whether satellite photography will be useful for relief measurement in topographic mapping because the base-height ratios will be so small. For example, if the aforementioned 180-inch focal-length camera at 150 miles altitude is used with a 9×9 inch format and 60 per cent overlap, the base-height ratio will be only 0.05. Formats of impractically huge size (e.g. 10×10 or 20×20 feet) would be required to give to the long focal-length satellite camera enough coverage to permit useful B/H values. Long focal-length convergent and trimetrogon photography should be investigated as possible solutions to the problem of using earth satellites for topographic mapping.

The lens of a long-focal-length satellite camera will have to be large in diameter to maintain conventional lens speeds. For example, a speed of *f*6 calls for lens aperture diameters of 2.5, 8.3, and 26.6 *feet* for the previously mentioned focal-lengths of 180 inches, 50 feet, and 160 feet respectively. Even for a lens speed as slow as 22, the diameters of these lens apertures must be 8, 27, and 87 inches respectively. Refracting lenses with these diameters are formidable. Reflecting mirrors may be a better means for light-gathering and image-formation for the very long focal-length satellite cameras. Such instruments are in the class of astronomical telescopes.

Aside from the lens problem, the mechanical and optical design and construction of high precision satellite cameras with very long focal-lengths would be very difficult were it not for three ameliorating factors:

1. The camera is "weightless" when in an orbiting satellite; this allows the two ends of the camera (lens and film holder) to be supported rigidly with respect to each other by relatively light connecting members of great length.
2. The satellites can be made virtually vibrationless while orbiting.
3. The camera can extend far outside the satellite proper, while orbiting, because the aerodynamic drag will be negligible, particularly at altitudes in excess of 300 miles. The camera can fold into a small space in the satellite during launching, and automatically unfold to full length outside the satellite after the vehicle is in orbit. The long space between lens and film need be enclosed only by a thin shell sufficient to keep out light; the inside of the camera need not be pressurized, and can have the same vacuum as exists outside, except for the film end as mentioned below.

Consequently, "*VLFLI*" satellite-borne cameras could be built either without folded optics, or with only a few optical folds.

Nevertheless, the design, construction, and operation of a satellite-borne camera are difficult for the following reasons:

1. The camera must be sturdy enough to withstand the accelerations and vibrations of launching and recovery.
2. An unpressurized camera must operate in nearly perfect vacuum; under these conditions, conventional lubricants fail completely, and unlubricated mechanical parts, e.g. shutter, tend to bind.
3. The film emulsion must be unaffected by vacuum; presently available emulsions are badly affected, so that the film end of the satellite camera will probably have to be pressurized.
4. The film base and emulsion must be such as to be unaffected by temperature extremes to which the satellite and its payload may be subjected.
5. The film must be shielded against intense cosmic and solar radiations outside the earth's protective atmosphere.
6. Possible collisions with micrometeorites (and meteorites) may erode or destroy optical surfaces.
7. Other problems, discussed in the paragraphs below, are stabilization, image-motion compensation, change in V/H, sensing the direction of the earth's vertical and change in altitude due to ellipticity of the orbit.

A high degree of stabilization is obviously important for cameras at altitudes of hundreds of miles. For example, an accuracy of 20 feet on the ground, from an altitude of 150 miles, corresponds to a stabilization of 5 seconds of arc. Fortunately, high stabilization may not be too difficult to achieve because an orbiting satellite moves and spins smoothly without the random accelerations that conventional airborne aircraft experience. However, it is not sufficient to stabilize a satellite camera with respect to an inertial frame of reference, because the camera will then point vertically downward toward the earth's surface only once in each revolution of the satellite around the earth. Nor is it sufficient to give the camera (or satellite) a constant spin (about an axis perpendicular to the orbital plane) in order to keep the camera pointing normal to the earth's surface; this will work for a circular orbit only; it will not work for an elliptic orbit because the radius vector from the center of the earth to the satellite does not rotate with constant angular velocity. Consequently the camera must be driven to rotate with varying angular velocity, depending upon the orbit, to make the camera always point vertically down upon the earth's surface.

Sensing the direction of the earth's vertical from a satellite is difficult because the orbiting satellite and its contents experience a seemingly weightless condition. Indirect methods of determining the earth's vertical will probably be necessary;

e.g., automatic observation of horizon position.

Image-motion compensation will be a necessity for satellite-borne aerial cameras and will be a more difficult problem than for conventional airborne cameras. Although V/H for a satellite camera at 150 miles altitude is in the range of values of V/H for conventional survey aircraft, the fact remains that the satellite ground speed will be of the order of 18,000 miles per hour. At this speed, the image will move a distance corresponding to 300 feet on the ground during an exposure of 1/100 second. Furthermore, the ground velocity vector will be changing continually in direction and magnitude (except for the very special case of a circular equatorial orbit), due to a combination of at least four factors:

(1) periodic variations in the linear speed of the satellite as it travels its elliptic orbit, the speed being a maximum at perigee and a minimum at apogee;

(2) change in speed as air friction slowly modifies the orbit;

(3) precession of the orbit;

(4) change in direction of ground velocity, which at any instant is given by the vector addition of the velocity of the earth's surface at that location due to diurnal rotation, plus the projection of the satellite's orbital velocity upon the earth's surface (both of these velocities are changing continually, the velocity of the earth's surface being a function of latitude).

For accurate image motion compensation, it will be necessary either to sense the direction and magnitude of V/H continually, or to compute it from a precise knowledge of the satellite's orbit. Doppler radar may be one solution to this problem. An ideal camera for satellite photogrammetry might be a stabilized, shutterless strip camera which automatically senses V/H, the direction of V, and the direction of the earth's vertical.

In an elliptic orbit the altitude of the satellite changes greatly during each revolution around the earth. For example, the apogee altitude of *1958 Alpha* is more than 7 times the perigee altitude (see Table I). This 7 to 1 change in altitude means that: (1) the scale of the photography will change by a factor of 7 during each half revolution of the satellite; (2) V/H will change greatly, with corresponding changes in image motion compensation. A circular or very nearly circular orbit is therefore more desirable than an elliptic orbit for photogrammetry purposes.

Corrections for atmospheric refraction will have to be made in satellite photogrammetry as in conventional aerial photography, more so because the satellite photography will be taken through the integrated density of the entire atmosphere. Local variations and fluctuations in atmospheric density also may be troublesome in accurate satellite photogrammetry. Finally, cloud cover will always present a problem in satellite photogrammetry.

If the recoverable satellites that have been postulated in the foregoing discussion are unmanned, the operation of the camera, including its orientation, must be completely automatic, or at least remotely controlled from the ground. If the recoverable satellite is manned, the problems of operation and orientation are obviously simplified because they can be controlled and monitored by an operator at or near the camera. Indeed, if the satellite is large enough and well enough equipped to be manned, many of the camera design problems become less severe, because the interior of a large manned satellite or space station will obviously provide environmental conditions that are not markedly different from the interior of a conventional aircraft.

PHOTOGRAMMETRY FROM A NON-RECOVERABLE SATELLITE

It may be possible to recover the film alone from a satellite-borne camera if the satellite vehicle itself is not recoverable. However, even if the film is not recoverable, there are still several possible methods of obtaining photogrammetric information. These include:[4]

automatic development of the photographic film in the satellite, followed by automatic facsimile transmission of the developed photograph to a ground station via a radio link;

pick-up of terrain information by a television camera in the satellite, and transmission of the televised image to the ground;

single-line-scan television pick-up in the satellite, and transmission to the ground;

[4] Rosenberg, Paul, "Information Theory and Electronic Photogrammetry," PHOTOGRAMMETRIC ENGINEERING, Vol. XXI, No. 4, Sept. 1955, pp. 543–555.

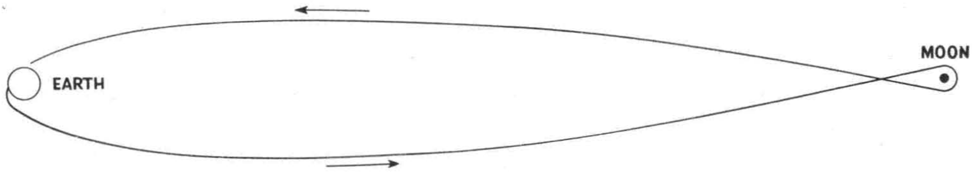

FIG. 3

photomultiplier spot-scan of the ground, e.g. the PRA TSS (terrain scanning system);[5]

infrared and radar scanning, with the video information relayed to the ground.

The methods listed above demand appreciable electric power in the satellite, in excess of the power obtainable from presently available solar batteries. The usefulness of these photogrammetric satellites would therefore be limited by the life of the self-contained power sources. These methods require a wide bandwidth for radio transmission of the information to the ground.

Satellite-borne television cameras seem to be a promising tool for reconnaissance, and for meteorological observations to aid weather forecasting. Transistorized television cameras can now be made to weigh as little as 12 lbs, and to operate on only 150 watts. However, television cameras now commercially available can give either high ground resolution with very small angular coverage, or wide-angle coverage with very poor ground resolution. Development of TV cameras that combine high ground resolution with wide-angle coverage would be highly desirable for satellite photogrammetry.

Photomultiplier spot-scan or line-scan methods[4] of satellite photogrammetry offer higher ground resolution and wider coverage than television, and have much higher sensitivity to low levels of ground illumination, especially at high altitudes. However, non-television ground scanning systems at satellite altitudes demand a higher degree of stabilization than seems feasible with presently available stabilization equipment.

PHOTOGRAMMETRY OF THE MOON AND PLANETS

At the ground speed of 18,000 miles per hour, a camera carried by an earth satellite can photograph a 3,000 mile long flight strip every ten minutes, even over the most inaccessible areas. At this rate, if the art of earth satellite photogrammetry becomes comparable to that of conventional photogrammetry, the world will be mapped completely in a short time. The photogrammetrist must then seek new worlds to conquer.

New worlds await the photogrammetrist literally as well as figuratively, in interplanetary space. It will be his task to map the earth's natural moon, the other planets in our solar system, and their moons. He can do this with photogrammetric equipment in space vehicles orbiting around the planets and their moons in much the same way as he will map the earth from orbiting satellite vehicles.

It is now technically feasible to send a rocket propelled vehicle around the moon. One such orbit for this journey[6] is diagrammed in Figure 3. Launched from outside the earth's atmosphere at approximately 24,000 miles per hour (which is less than the escape velocity of 25,500 miles per hour), the vehicle in this orbit will travel once around the moon and return to earth 157 hours after departure. The vehicle will have nearly 50 hours of useful close observation of the moon, passing within 1,300 miles of the side of the moon that always faces away from the earth.

Within our lifetime a manned, recoverable space ship may circle the moon or land there. One of the first steps in the systematic exploration of the moon will probably

[5] Williams, Ross E. and Rosenberg, Paul, PHOTOGRAMMETRIC ENGINEERING, Vol. XXII, No. 5, Dec. 1956, pp. 823–830.

[6] Ehricke, Krafft A. and Gamow, George, "A Rocket Around the Moon," *Scientific American*, Vol. 196, No. 6, June 1957, pp. 47–53.

be a photogrammetric survey from a satellite orbiting around the moon. A survey satellite can orbit around the moon at a lower altitude than it can orbit around the earth, because the moon has no atmosphere to act as a drag upon the satellite. Furthermore, moon satellites can travel at lower orbital speeds than earth satellites because the moon's mass is smaller than that of the earth (by a factor of approximately 81). For example, the vehicle in the orbit of Figure 3 will be travelling at a speed of only a few hundred miles per hour as it passes the far side of the moon at an altitude of 1,300 miles, whereas a satellite orbiting the earth at the same altitude would be travelling at speeds of the order of magnitude of 18,000 miles per hour.

For some time to come, mapping the moon, the planets and their moons will not require the same high accuracy standards that are demanded in mapping the earth. Consequently many shortcomings of satellite photogrammetry that may be intolerable for earth mapping will be acceptable for planetary and moon mapping, especially in early exploration.

It will be a momentous day in the history of photogrammetry when a photo-interpreter looks for the first time at a stereo image of the craters and mountains on the moon; or the other side of the moon, never before seen by man; or the surface of Venus; or the "canals" of Mars. The photogrammetrist still has many worlds to conquer.

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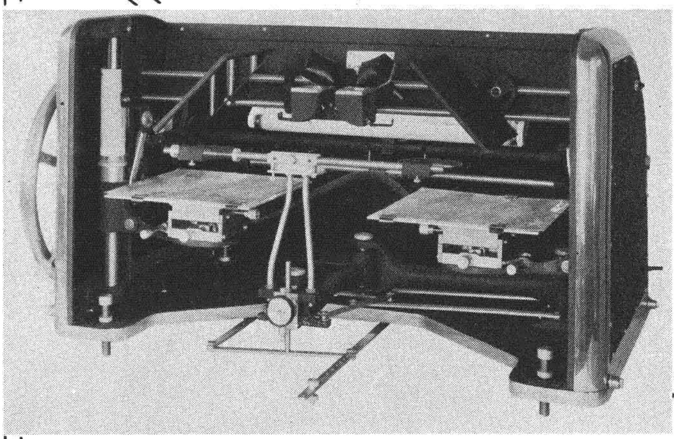

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