*A Satellite's View of the Earth**

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ABSTRACT: *Photography of the earth taken from beyond the atmosphere will include distortions not encountered in conventional aerial photography. Known information on these distortions is presented and remedial measures are proposed.*

I. INTRODUCTION

IN MAN'S attempts to record and map areas of the earth's surface by photogrammetry, cameras have progressed through many phases. First, there was the limited environment and small field of view of the fixed terrestrial camera. Next, photogrammetrists turned to balloons and later to aircraft as elevated camera platforms. Recently, we have given attention to the rocket as the camera vehicle, and our advances in space technology indicate that it may be possible to use an artificial earth satellite as a camera platform.

The altitudes above the earth at which it may thus be possible to photograph the earth with cameras are such as to raise some natural questions as to the quality of this small-scale photography. Experience in obtaining photography suitable for cartographic purposes from extremely high altitudes is meager indeed! Up to the present time our highest cartographic photography was taken at an altitude of 158 miles. This was the height reached by the Viking 11 Rocket bearing a modified K-25 camera (Figure 1) and balloon-borne mapping cameras exposed at altitudes of approximately 38 miles (1, 2, 3).

Attempts to produce acceptable maps with photography taken to date have indicated that specially designed high-acuity camera systems will be needed if we are to achieve any except small-scale mapping accuracies.

We should not be so naive as to expect that a high-acuity, low-distortion camera system designed for mapping from conventional altitudes will perform equally well in a space environment of, for example, 300 miles. I shall therefore present some of the considerations involved in obtaining extremely high-altitude photography.

II. DISTORTION

It may be well to define what is meant by the term distortion in this presentation. Basically photogrammetry is based upon the theory of "perfect optical systems." (4) This concept in turn rests upon two basic assumptions: first, that in any homogeneous medium the geometrical rays of light are absolutely straight lines; and second, that objects in any plane which is perpendicular to the optical axis are depicted sharply and without distortion in a conjugate image-plane also at a right-angle with the optical axis. The development of the theory proceeds from these two assumptions and conventional geometry.

It should be noted that the laws of reflection, refraction and the properties of light are not required in the development of the theory and that rectilinear propagation of light is assumed. Thus there exists the possibility that the results obtained by applying conventional photogrammetric concepts may be incompatible with the properties of light in the atmosphere. The difference between conventional photogrammetric theory and the actual behavior of light in the atmosphere camera system will be simply referred to as distortions in the photogrammetric system.

III. OPTICAL PROPERTIES OF THE EARTH'S ATMOSPHERE

When the physical properties of light are examined we are faced with the dilemma that light exhibits a dual nature. That is, under some conditions light behaves as if it were composed of a beam of particles (photons), while under other circumstances, it exhibits the properties of wave motion. As an example, the primary action of light on the photographic emulsion is to make the haloid grains photo-conductors, in accordance with

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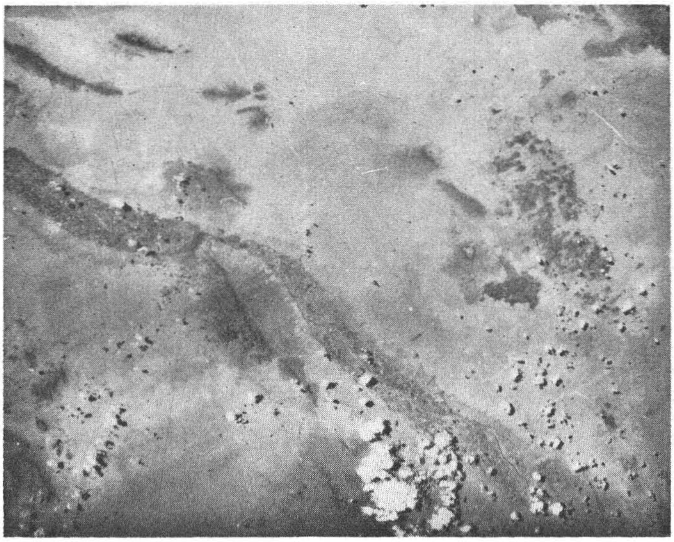

FIG. 1. Photograph taken with a modified K-25 camera from an altitude of 158 miles. Taken from a Viking 11 Rocket launched on May 24, 1954. Film used infra-red, shutter speed 1/500 sec., f/8 with red filter. Lens Ilex Paragon Anastigmat, f/4.5, focal length 163 mm. Photograph by U. S. Naval Research Laboratory.

the quantum nature of light. (5) However, when we describe the propagation of light through the atmosphere the wave nature of light is used.

Since we are mainly concerned with the transmission of light through the earth's atmosphere, we will deal with the wave nature of light.

The interaction of light in the earth's atmosphere creates many phenomena so spectacular as to have drawn the attention of outstanding physicists (6). Of these phenomena the question that concerns us is how does the atmosphere affect the "photographic visibility" (7).

To appreciate the complexity of the problem of photographic visibility it may be well to note some of the highlights in the development of present day knowledge in this field. (8).

Mention should be made of the experiments of Pierre Bouguer, often called the founder of photometry. In 1792, he published his work "Essai d'Optique sur la Gradation de la Lumiere" in which he studied the quantity of light lost by passing through a given extent of the atmosphere. He established, that.

" . . . when the distance increases through which light must travel, then the light intensity is reduced according to the terms of a geometrical progression."

Thus the general form of light extinction was presented. However, such extinction gave only a clue to what was happening to the image-forming properties of light. We know from photometric theory for an object to be photographed, it must present some contrast to its surroundings. The lowest contrast of luminance that will produce a visible boundary in the negative is the threshold of luminance contrast for our camera system. (9)

Two processes are at work which tend to decrease the luminance contrast and light intensity of a light beam as it passes through the earth's atmosphere. First: absorption decreases the intensity of the light beam by converting it to another form of energy (heat). The second process: scattering by the molecules of air, haze, fog and dust has the effect of decreasing the luminance contrast between an object and its background.

Thus the limiting condition in "seeing" through the atmosphere will be imposed by the scattering of light. Absorption will be the critical factor only for the smoky haze that occurs near large industrial centers (10, 11).

Scattering effects are classified according to two criteria—by the nature of the scattering particles, or by the number of scattering processes taking place. The explanation of multiple scattering from a mathematical standpoint is extremely complex (10). Although there are theories to explain the scattering processes, the use of these theories to obtain values for photographic visibility has not been possible because of the lack of sufficiently good photometric measurements.

However, from the theory of light scattering, we can arrive at some general conclusions.

The transparency of the atmosphere depends directly upon its composition. If the light traverses a perfectly homogeneous medium, no scattering is present. However, even in a so-called pure or Rayleigh atmosphere which contains only the molecules of the permanent gases, statistical fluctuations in the arrangement of the molecules cause a scattering. In 1899, Lord Rayleigh demonstrated that this scattering was in proportion to the inverse fourth-power of the wave-length, which incidentally, accounts for the blue color of the sky, since the blue end of the spectrum is scattered to a greater extent. However, Rayleigh's law is valid only for particles much smaller than the wave-length of light. Since much of the non-homogeneity of the lower atmosphere is caused by smoke, dust, water droplets and living organisms suspended in the air, the scattering of light rays by the various particles is additive. The photographic visibility thus is a function of the amount and size of the "aerosols" present in the optical path. Limited studies have in dicated that less attenuation of contrast by scattering can be expected when the longer wave-lengths of light are transmitted through haze that is composed of small particles. For fogs and mists that are composed of large-size particles, no preferential transmission for the longer wave-lengths has been indicated. It then appears that there is very little that can be done regarding the attenuation of contrast caused by the atmospheric aerosols, except to use the longer wave-lengths of light under special conditions. For example, photographing in the infrared regions.

The second distortion which should be considered is the effect of scintillation and shimmer on the resolution of our camera system. From considerations of optical design, the theoretical maximum limit for the resolving power of a perfect lens can be specified. As a perfect lens is never realized in actual practice, the resolving power consequently will be a function of the design of the actual lens. Conventional mapping camera design criteria will have to be modified to account for: (a) change of index of refraction for environment of space, for example, vacuum-to-glass-to-gas used for pressurizing camera, and (b) the wave-lengths of the energy spectrum used. In theory, a high resolution lens could be constructed. This is a problem in optical design; to achieve the ultimate in resolution will require a lens specially designed to operate in a space environment.

When the optimum lens is put into the space environment, the design resolution probably will not be realized because of degradation in the resolution caused by: (a) movement of the camera during exposure; (b) vibrations in the camera during operation; (c) combination of film and filter used and (d) effects of non-homogeneity of atmosphere such as shimmer and scintillation. The first three are "old hat" in conventional aerial photography, but the last factor may not be well known among photogrammetrists.

Astronomers, especially since the development of the telescope, have been aware that celestial objects change their appearance during observation. These changes in intensity and steadiness of the image originate from rapid changes in the atmospheric density causing irregularities of the refractive index (12). The effect of these changes in refractive index can be explained as follows: After travelling through the atmosphere, rays originating from an object may not be parallel when they strike the objective lens, and thus cannot be focused as sharply as parallel rays. Since the focus of the object is defined along the direction of the normal of the incoming wave surface, rapid differential changes of the atmospheric refractive index, in small segments of the area photographed, will result in the formation of a distorted and oscillating image; if the image is a star, the so-called "tremor disk" familiar to astronomers is formed. The magnitude of the displacement and the effect on resolution of this "tremor disk" has been the subject of many studies, especially in determining the suitability of sites for astronomic observatories.

It should be noted in passing that seeing through the atmosphere is a poor criterion for use in determining the steadiness of the atmosphere. It is believed that this unsteadiness consists of two components, one developed in the upper atmosphere, and assumed constant with respect to time and space, and the other of local character and developed irregularly near the earth. Here again the magnitude of these errors depends upon a knowledge of the distribution and magnitude of atmospheric irregularities. Limited measurements have indicated that the unsteadiness can amount to from one to four seconds of arc. Thus it appears that the camera system resolution will be limited by the unsteadiness of the atmosphere.

The nature of the variations in the intensity of light, or brightness scintillation, may also be of interest. For point sources of light, such as a star, the brightness scintillation has been studied by placing a sensitive photocell at the principal focus of a telescope (13). Investigations have indicated that the amplitude of fluctuation is approximately inversely proportional to the aperture over the range of 36 to 3 inches. However, for extended sources of light, such as a planet, the amplitude of scintillation was less than that of a star at the same altitude. This results from the averaging effect of the light being received from the extended area. It should be expected that in this averaging of light intensities from "point sources on the surface" that the brightness contrasts will be decreased with resulting loss in resolution.

Astronomers believe that the brightness scintillation is largely independent of the "tremor disk." The feeling is that the "tremor disk" arises from refraction of the rays in their passage through turbulent elements that are relatively large; while brightness scintillation is mainly a diffraction effect arising from the presence of much smaller irregularities along the light path. The various colors fluctuate independently of one another in time. No definite conclusions as to the coherence of the fluctuations have been developed.

In the field of atmospheric refraction we are fortunate in having much literature on this subject. On the specific field of photogrammetric refraction for precision work, we presently have theories that are sufficiently general. However, their accuracy is dependent upon a knowledge that the index of refraction profile is error free, and that the profile accurately represents all portions of the atmosphere under consideration.

III. Summary and Conclusions

It may be well at this point to retrace the factors discussed and to draw some conclusions on what can be expected from photogrammetric space photography. In its most general terms, a photogrammetric distortion can be considered as the failure to satisfy the colinearity condition between the object point, center of projection and the image point—the image points being co-planer. In addition, there must also be considered the photometric and physical properties of light as it passes through the object space which is the atmosphere.

Since there has been extended the optical distances through which the light must travel from our ground objects to the photographic plate, and the theory upon which our photogrammetric procedures are based does not consider the properties of light in the atmosphere, certain distortions will occur. First, the scattering of light by the molecules of the permanent gases and aerosols will cause a degradation in our image contrast, the amount of attenuation of contrast will depend upon the size and amount of particles in the atmosphere. Even in a pure or so-called "Rayleigh atmosphere" some attenuation of contrast will occur. In the "pure atmosphere" the scattering can be minimized by using the longer wave-lengths of energy such as photographing in the infrared regions. If the atmosphere contains large size scattering particles then very little can be done to eliminate the attenuation to the contrast caused by scattering.

The second effect of photographing through the atmosphere will be a loss in resolution resulting from the atmospheric turbulence of the air. Here again there is very little which can be done to increase the resolution limit imposed by the "optical shimmer" of objects.

To quantitatively evaluate the effects of scattering and shimmer on the photography is a difficult task. Charting photography has been taken from rockets at 168 mile altitudes with satisfactory results. Our next step is to obtain special cameras for space photography. When this has been accomplished, we can come to grips with the optical problems of the atmosphere.

References

1. Baumann, R. C., and Winkler, L., Rocket Research Report No. XVIII, "Photography from the Viking 11 Rocket at Altitudes Ranging up to 158 Miles," U. S. Naval Research Laboratory, Washington, D. C., 1 Feb. 1955, p. 1.
2. Griffing, P., "Strato-Lab Balloon Photography," Photogrammetric Engineering, Vol. XXIII, No. 3, pp. 582–587.
3. Di Pentima, "High-Altitude Small-Scale Aerial Photography," Rome Air Development Center, Technical Note 58–156, ASTIA Document No. AD 148777, July 1958, p. 2.
4. Longhurst, R. S., *Geometrical and Physical Optics*, Longmans, Green and Co., New York 1957, Chapter II.
5. Mott, N. F., and Sneddon, I. N., *Wave Mechanics and its Applications*, Oxford University Press, 1948, Chapter VIII.
6. Minnaert, M., *The Nature of Light and Colour in the Open Air*, Dover Publications Inc., New York 1954, Chapter IV.
7. Middleton, W. E., "The Attenuation of Contrast by the Atmosphere," Photogrammetric Engineering, Vol. 16, p. 163 (1950).
8. Middleton, W. E., "Random Reflections on the History of Atmospheric Optics," *Opt. Soc. Am.*, Vol. 50, No. 2, p. 97 (1960).
9. Middleton, W. E., *Vision Through the Atmosphere*, Univ. of Toronto Press, 1958, pp. 134–136.

10. Van De Hulst, H. C., *Light Scattering by Small Particles,* John Wiley and Sons, Inc., New York 1957, pp. 3–10.
11. Van De Hulst, H. C., *The Atmospheres of the Earth and Planets* (2nd Ed), G. P. Kniper, Ed., Univ. of Chicago Press, 1952, Chapter III.
12. Hanssom, N., Krislenson, H., and Reiz, A., "On Atmospheric Unsteadiness," *Meddelande fran Lunds, Astronomic Observations,* Series II, Nr. 129.
13. Kopal, Zednek, Editor, "*Astronomical Optics and Related Subjects,*" Chapter V, Resolution Problems and Scintillation, pp. 265–341, Interscience Publishers, Inc., New York.

*Photogrammetry, Navigation, and Space Problems**

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In the past, photogrammetry was mostly used to produce topographic maps. It is, however, a well-known fact that photogrammetry—due to the versatility of this method—can be applied not only for producing such maps but with equal advantage as a measuring method in many other fields of science and technology. Photogrammetry applied for non-topographical purposes is normally designated as Non-Topographical Photogrammetry.

Photogrammetric methods are closely related to geodetic methods because both sciences in their practical application are greatly concerned with performing measurements of various kinds. As far as concerns the accuracy, which can be attained by both measuring techniques, one was of the opinion—at least in the past—that geodetic measuring methods would yield a higher accuracy than photogrammetric measuring methods. It seems, however, that in the future this conception must be modified to a certain extent because of the remarkable progress which has been made in recent years in improving photogrammetric measuring techniques. The use of high-performance cameras, high-quality photographic material and high-precision measuring or plotting instruments already permits one for certain measuring tasks to obtain an accuracy which is considered as standard geodetic accuracy. An example is the photogrammetric determination of numerical coordinates for boundary points in land surveying, in which photogrammetric methods are today capable of replacing certain geodetic methods.

The universal acceptance of photogrammetry as a measuring method and its increasingly high degree of accuracy have permitted applying photogrammetric methods in the most recent time to such diverse fields as flight testing and navigation, satellite and missile tracking, and lunar investigations. It is the purpose of this paper to discuss these three applications.

A. Stellar Photogrammetry

The application of this method is at present being studied to produce information on the pitch, roll and heading of an aircraft in flight for instrument testing. For this purpose star photographs are made with a special photogrammetric camera, namely, a stellar camera or star camera. From these star photographs pitch, roll and heading can be computed at the exposure stations by means of formulas which have been derived at the Institute of Geodesy, Photogrammetry and Cartography of The Ohio State University.

One of the main problems in stellar photogrammetry is that regular aerial cameras are unable to produce useful star pictures. There are three reasons for this: first, the relative aperture is too small to produce star images, especially of stars of smaller magnitude; second, the exposure time has to be kept very short because of the aircraft motion and oscillation; and third, the resolution of the combination of camera objective and photographic emulsion is not always sufficient to produce pictures of a sufficiently large amount of stars. [Figure 1]

To overcome these difficulties a system is being worked out at this Institute consisting of high-performance camera and a stabilized camera mount. In order to obtain correct information on pitch, roll and heading, the rela-

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