Noting that

$$\dot{x}_f = f\dot{\beta}, \qquad (42)$$

we can drop the prime on t, substitute (42) in (41) and obtain by integration the amount of parabolic image movement, a_α, for a point off-axis, at an angle α, as

$$a_\alpha = \left[\frac{1}{2}\left(\frac{v}{h}\right)\dot{x}_f \sin\beta + \frac{1}{2}\dot{\beta}\dot{x}_f \tan\alpha\right] t_e^2. \qquad (43)$$

Comparing equation (43) with equation (15), it is clear that the magnitude of off-axis motion is greater than axial motion, but it remains parabolic; and thus its modulation transfer may be evaluated by means of equation (28) or Figure 5.

Conclusions

The transfer function for image-motion arising from the finite slit-width of transverse-scanning panoramic cameras has been derived and investigated, subject to the assumption of small angular slit-width. This motion degrades the system's resolution in the direction perpendicular to the scan.

The contrast loss depends on the sine of the scan-angle, so nadir and near-vertical photography is not likely to be affected although the contrast loss at high-oblique angles can be very large. Furthermore, reducing either the film's transport velocity or its exposure time will always increase the modulation transfer. Contrast loss also depends on the v/h rate, but this is not under the designer's control. Finally, it was shown that the amount of image-motion is greater for points off the optical axis than for points on axis.

Acknowledgements

The author has benefited from many helpful comments by colleagues at The Perkin-Elmer Corporation, especially those of Cran H. Barrow and Richard C. Babish.

*Environmental Effects of Supersonic and Hypersonic Speeds on Aerial Photography**

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and
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ABSTRACT: *Certain environmental effects may degrade the quality of photography taken from vehicles flying at supersonic and hypersonic speeds. Among those associated with the immediate environment of the vehicle are: (1) Metric distortion caused by refraction of light rays by flow field surrounding the vehicle; (2) Loss of resolution by scattering of light by turbulent boundary layers over the camera window; (3) Loss of contrast between ground object and its background by presence of luminous air in flow field; and (4) Metric distortion caused by temperature-induced window curvature. In addition to the above environmental effects, Rayleigh scattering between the ground and the vehicle can cause large reductions in contrast. This effect was also taken into account in determining the additional reduction in contrast caused by the luminous air in the flow field.*

Introduction

In recent years, much evidence has arisen to indicate that important effects of the aerodynamic and thermodynamic environments can occur in aerial photography taken for mapping or reconnaissance purposes at supersonic or hypersonic speeds. For instance, photography taken in the F101 airplane at

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Mach numbers approaching 1.4 and altitudes of about 35,000 feet indicated some interesting results when examined by the U. S. Army Engineers at Ft. Belvoir, Virginia. When viewed in stereoscopic pairs, these photographs indicated sudden changes in ground elevation of the order of 50 feet where it was known that no such discontinuities existed. This result and other known effects led GIMRADA[1] to sponsor an analytical study of the effects of supersonic and hypersonic speeds on aerial photography. Phases I and II (Refs. 1 and 2) of this study have now been completed by Vidya, Inc. of Palo Alto, and this paper is a brief résumé of some of the important effects encountered.

In this paper, some of the effects of boundary layers and shock waves on the metric distortions introduced into mapping photography as well as the metric distortion caused by aerodynamic heating of the camera window are discussed. Turbulent boundary layers, which occur in supersonic flight over a wide altitude range, can cause serious reductions in the resolution of photography taken through these boundary layers. An indication of the size of these reductions is presented. It is known that scattering of the Rayleigh type can cause significant reductions in contrast in photography taken from high altitudes. This subject is discussed as a background for evaluating the importance of luminosity on aerial photography. This environmental effect will also be covered in the paper.

[1] This work was sponsored by the U. S. Army Engineer Geodesy, Intelligence and Mapping Research and Development Agency, Ft. Belvoir, Virginia under contract number DA-44-009-ENG-3990.

EFFECTS OF BOUNDARY LAYERS AND SHOCK WAVES ON METRIC DISTORTION

In Figure 1, the general effects of boundary layers and shock waves on metric distortion are illustrated for a camera mounted in the conical nose of a high-speed vehicle. It will be noted that the flow field of the cone is represented first by a boundary layer, then an area between the boundary layer and the shock wave, and finally, the shock wave. These parts are termed the near-flow field of the vehicle. There is also the atmospheric refraction caused by the far field. Consider a light ray traveling from the window to the ground. Within the boundary layer, the ray can be bent either toward or away from the normal to the window, the direction depending on whether the temperature of the outer surface of the window is higher or lower than the temperature at the edge of the boundary layer. The density decreases as the ray passes from the outer edge of the boundary layer to the inner edge of the shock wave. This causes a bending in the direction indicated by the arrow. Across the shock wave there is a further decrease in density, and from the outer edge of the shock wave to the ground, the density increases. These cause further refractions in the directions indicated by the arrows.

In general, at altitudes under 100,000 feet, the influence of the near-flow field is significant. However, because of the decreasing density, it becomes rapidly smaller as the altitude increases, and at altitudes above 100,000 feet, the influence is negligible. Some calculated metric distortions are illustrated in Figure 2 for flight at an altitude of 35,000 feet and at a Mach number of 1.6. Contours of constant metric distortion, shown as ground

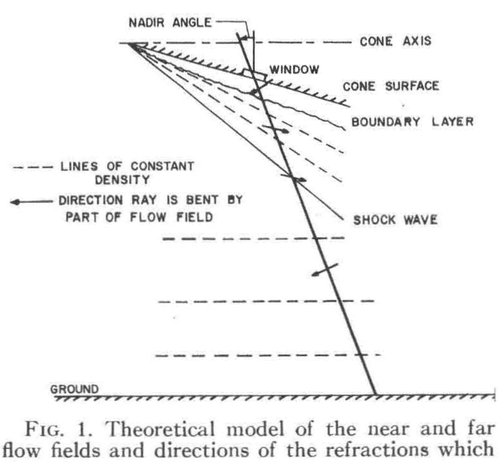

FIG. 1. Theoretical model of the near and far flow fields and directions of the refractions which they cause.

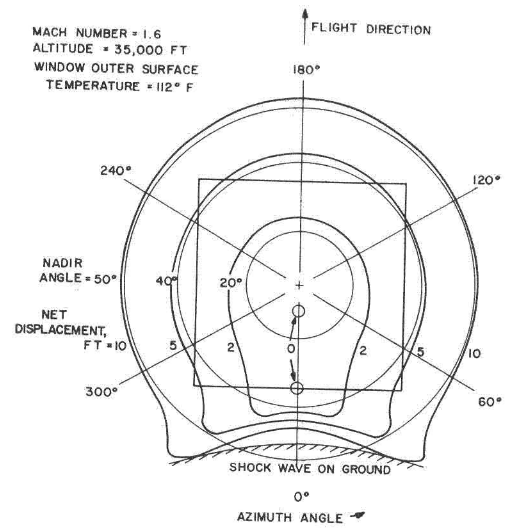

FIG. 2. Metric distortion over complete field of view of camera.

displacements, are plotted as functions of nadir and azimuth angles. These are the net displacements due to distortions in the lateral and longitudinal directions. The square outline represents the area covered by a camera with a 45° field of view. The intersection of the shock-wave from the airplane with the ground is also shown. It is interesting that the contours are nearly circular on the forward part of the photograph, but are greatly distorted as they approach the position of the shock-wave. At the very high altitudes, where atmospheric refraction is the dominant source of refraction error, the contours will be nearly circular.

Bearing in mind the large distortion effects in the immediate vicinity of the shock-wave, let us examine Figure 3. The bow shock-wave shown in this figure is curved because of the variation in shock-wave strength and atmospheric temperature with altitude. A direct light ray from the camera to a ground point is indicated.

There exists another ray at near grazing incidence to the shock-wave which is internally reflected by the shock-wave and also arrives at point P. When this phenomenon is considered in connection with stereoscopic formulas, the calculated altitude varies with distance from the nadir-point in the vertical plane of symmetry as shown on the right side of the figure. Clearly this effect indicates the presence of a discontinuous change in ground elevation where none should exist. This is the phenomenon observed by GIMRADA in the aforementioned aerial photography.

Effect of Window Curvature Caused by Aerodynamic Heating on Metric Distortion

Among the configurations studied in the analytical studies (Nielsen and others, 1960, 1961) are the supersonic configuration and the hypersonic configuration shown in Figure 4. The supersonic configuration, which is taken to be generally representative of supersonic aircraft, is a simple, pointed cone shown here with a 15° semiapex angle with the camera window mounted 6 feet behind the apex. The hypersonic configuration is a highly swept wing with blunt leading edges. This configuration which is representative of hypersonic glide vehicles is assumed to be at 20° angle of attack. These two configurations are treated in this and the following sections of the paper.

Consider aerodynamic heating of these configurations. At supersonic and hypersonic

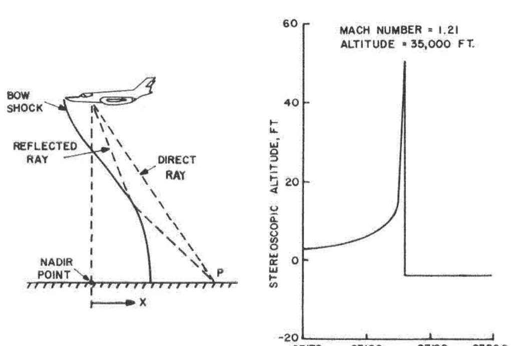

FIG. 3. Effect of grazing incidence with bow shock on stereoscopically determined altitudes.

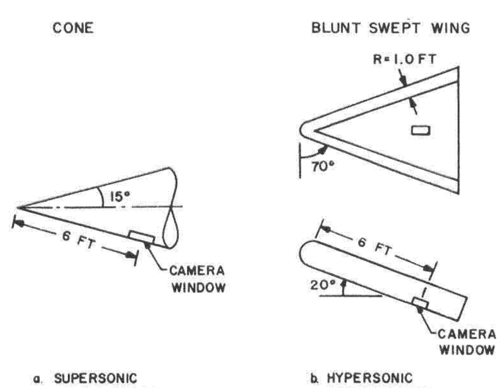

FIG. 4. Configurations studied.

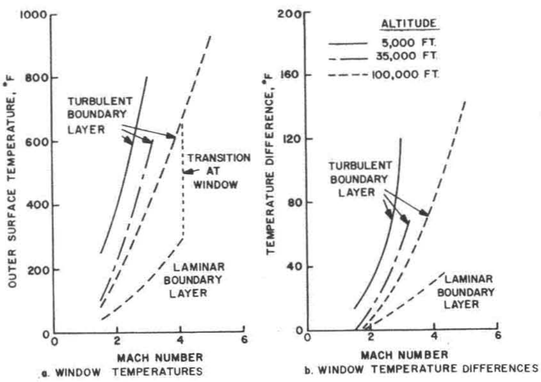

FIG. 5. Aerodynamic heating of camera window for cone configuration.

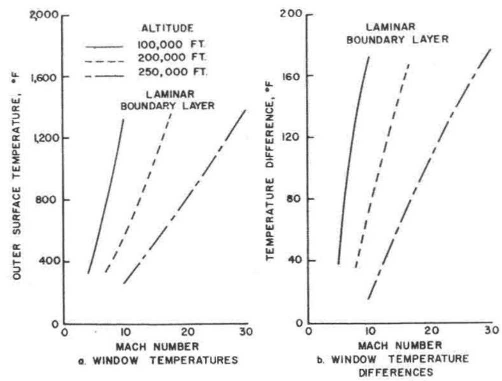

FIG. 6. Aerodynamic heating of camera window for blunt swept wing configuration.

speeds, fluid friction occurring in the boundary layer adjacent to the vehicle can cause serious heating of the camera windows. Sufficiently high temperatures can be reached to cause structural failure and even luminous radiation from the window itself. The importance of aerodynamic heating depends on Mach number, altitude, and whether the boundary layer is laminar or turbulent. As an example, the calculated outer surface window temperatures are shown in Figure 5 for the supersonic cone configuration described in Figure 4. The variation of the window temperature with altitude and Mach number for a turbulent boundary layer is shown. At high altitudes, the atmospheric density is very low so that long lengths of laminar boundary layers are possible. Thus, at 100,000 feet these are laminar boundary layers at the window for Mach numbers below 4 and have much lower window temperatures than for a turbulent boundary layer. For Mach numbers above 4, the boundary layer turns turbulent in front of the window and much higher window temperatures occur.

One of the important parameters in assessing the effect of aerodynamic heating is the temperature difference acting across the window. This temperature difference is important because it determines how much lens effect is introduced by aerodynamic heating, and also how much heat is conducted into the camera cavity through the window. The temperature differences shown in Figure 5 are for a quartz glass window $\frac{1}{2}$-inch thick. It is generally true that the temperature difference through the window increases in almost direct proportion to the increase in the external surface temperature of the window.

In Figure 6, the window temperatures and window temperature differences are shown for the hypersonic swept wing previously described. Because hypersonic flight generally occurs in the very high atmosphere, the results shown here are for altitudes above 100,000 feet. For all the cases calculated, the boundary layer was predicted to be laminar. Even though the laminar boundary layers cause considerably less aerodynamic heating than turbulent boundary layers, the window temperatures and temperature differences for this case are considerably greater than those for the cone configuration. This effect is principally due to the considerably higher Mach numbers. A comparison of the window temperature shown in Figure 5 for the sharp cone with a laminar boundary layer flying at an altitude of 100,000 feet, and a Mach number of 4.0 with the temperature shown on Figure 6 for the same conditions shows that they are nearly the same.

In Figures 7 and 8, the metric distortions introduced into the aerial photography by these temperature differences are shown for a

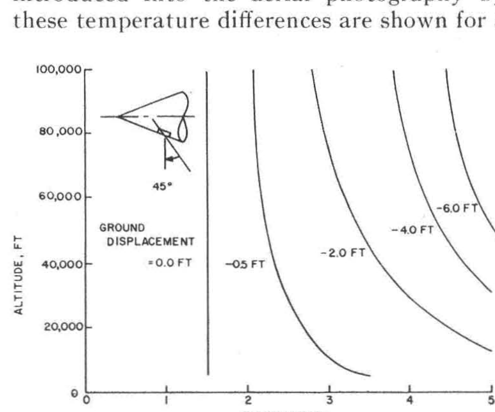

FIG. 7. Metric distortion at a nadir-angle of 45 degrees caused by temperature induced window curvature on the cone configuration.

light ray traveling at a nadir-angle of 45°. These results all apply for a simply supported circular window of 6-inch diameter and $\frac{1}{2}$-inch thickness. The longitudinal ground displacements for this light ray are shown in Figure 7 for the conical configuration for various altitudes and Mach numbers. Generally speaking, increases in Mach number and altitude both cause increases in temperature-induced distortion. This distortion is, of course, additive to that caused by boundary layers and shock-waves. There is possibly a further additive distortion because of a difference in air pressure between the camera cavity and the outer edge of the window. Such pressure difference causes window curvature and also a difference in the refractive index of the air at the two surfaces of the window.

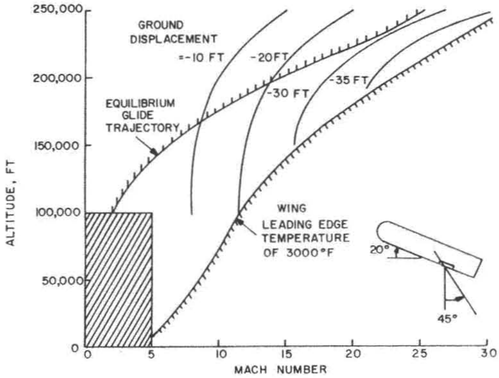

FIG. 8. Metric distortion at a nadir-angle of 45 degrees caused by temperature induced window curvature on the blunt swept-wing.

The temperature-induced metric distortion is shown in Figure 8 for the swept-wing configuration. First observe that the hatched area of this curve covers the entire range of Figure 7. The upper hatched line on Figure 8 indicates the upper boundary below which the glider must operate if it is to have sufficient aerodynamic lift to sustain gliding flight. The lower boundary represents a lower limit above which the glider must fly if it is not to exceed a surface temperature of 3000°F. The corridor between the two hatched lines is called the *corridor of continuous flight.* It is observed that, at high altitudes in the corridor of continuous flight, very large ground displacements occur because of temperature-induced window curvature. Part of this effect is due to the large incidence angles which occur in rearward viewing from the window mounted in the glider which is at 20° angle of attack. If the glider were at 45° angle of attack, the nadir-angle of 45° would place the line of sight parallel to the boundary layer and it would be impossible to see anything. It is thus clear that angle of attack is a very significant parameter controlling metric distortion due to temperature-induced window curvature and, in fact, due to the other sources previously discussed. Angles of attack of 45° for hypersonic gliders are not unusual.

EFFECTS OF TURBULENT BOUNDARY LAYERS ON RESOLUTION

One of the significant effects of turbulent boundary layers at any speed is to limit the resolution that can be obtained in photographs taken through the turbulent boundary layer. A light ray traversing a turbulent boundary layer will encounter regions of variable density which are more or less statistically random. Since the index of refraction for air is directly proportional to density, the light ray will be refracted in a statistically random fashion due to the inhomogeneities in the turbulent boundary layer. This refraction is in addition to the systematic refraction which would occur if the boundary layer were laminar. As a result, if the boundary layer is turbulent, a previously parallel bundle of light rays will be scattered into a small element of solid angle in traversing the boundary layer. This phenomenon sets a definite limit on the resolution in seconds of arc that can be obtained by taking photographs through the boundary layer with a photographic system otherwise giving perfect resolution. It was shown by Stine and Winovich (1956) that the amount of scattering depends on the general density level of the boundary layer, together with the optical path length of the light ray through the boundary layer. It is possible, based on their work, to make approximate calculations of the amount of scattering due to turbulent boundary layers.

As an indication of the effects of Mach number and altitude on the resolution limit of a turbulent boundary layer, the results shown in Figure 9 have been calculated. These results are for a camera with a 6-inch focal-length and a flat image-plane and are expressed in lines-per-millimeter on the film. The actual resolution depends on the incidence angle of the light ray measured from the normal to the boundary layer. For large incidence angles, significant reductions in resolution limit are indicated. The general reduction in resolution with increases in Mach number is due principally to the increase in density in the boundary layer accompanying such increases in Mach number. Comparison of the curves for a 5,000-foot

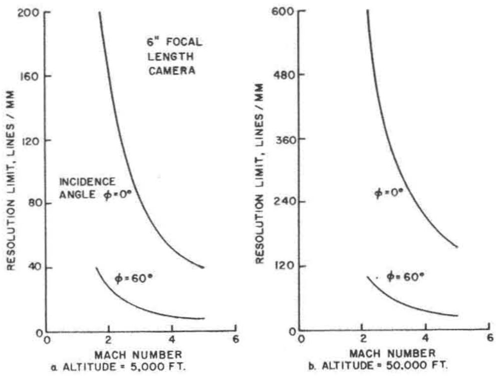

FIG. 9. Resolution limit for viewing through turbulent boundary layer on cone configuration.

altitude and a 50,000-foot altitude indicate substantially greater limits for the higher altitude. This result is due to the decreased densities at the higher altitude. When measured in lines per millimeter, the resolution limit is inversely proportional to the focal-length. This is true since the boundary layer introduces a resolution limit which is basically one of angular measure.

The general treatment of resolution limits for turbulent boundary layers is based upon a semiempirical correlation of wind-tunnel data (Stine and Winovich, 1956). The foregoing curves have been based on application of these data to flight conditions. In this procedure, the assumption must be made that the change in the thermodynamic condition of the boundary layer from adiabatic in the wind-tunnel case to highly cooled in the flight case does not affect resolution. Also, the general turbulence level of the flight boundary layer is assumed equal to that for which the wind-tunnel data was taken. Whether or not these assumptions are conservative is not known. All that can be said is that carefully designed flight tests to measure resolution limits of turbulent boundary layers are definitely needed, particularly in view of the advent of high-acuity reconnaissance cameras.

EFFECT OF RAYLEIGH SCATTERING ON CONTRAST

As a prelude to a rational discussion of luminosity effects on aerial photography, it is important to consider the effects of Rayleigh scattering on contrast at the window of the reconnaissance or mapping vehicle. In this discussion, it is assumed that the atmosphere is free of haze and other scattering particles, except scattering centers of the Rayleigh type. To illustrate the general phenomenon of Rayleigh scattering, the sketches of Figure 10 have been prepared. In the left sketch, light is shown emanating from a point on the ground of different brightness than its background. Some of the light rays beamed toward the camera window are scattered out of the cone by molecules of air, and the brightness of the image and background are both reduced. The contrast is the ratio of the brightness difference between the object and the background divided by the brightness of the background. Since these quantities are all reduced proportionally by attenuation, there is no change in contrast.

The phenomenon illustrated on the right-hand side of the figure does cause a deterioration in the contrast. Consider an external light-ray from any source which enters the cone of view and is scattered. Part of the scattered light will be beamed toward the window and will increase the brightness of both the background and the object. It is clear that a loss in contrast will result.

The loss of contrast due to Rayleigh scattering depends on the wave-length of the light, the altitude of the vehicle, and the nadir-angle. A scattering parameter can be defined for a Rayleigh atmosphere as shown in Figure 11. The importance of scattering depends upon the value of this parameter which is shown as a function of wave-length and altitude in this figure. The scattering parameter decreases rapidly with wave-length and increases with the altitude of the vehicle. Above 40,000 feet, there is not much increase in the scattering parameter with altitude.

The importance of the scattering parameter on the change in contrast between the ground and the camera is illustrated in Figure 12. Actually, the importance of the scattering parameter in reducing the contrast at the camera to a value below that at the ground, depends on the ratio of sky brightness to ground brightness. The actual parameter used to measure this quantity in the present

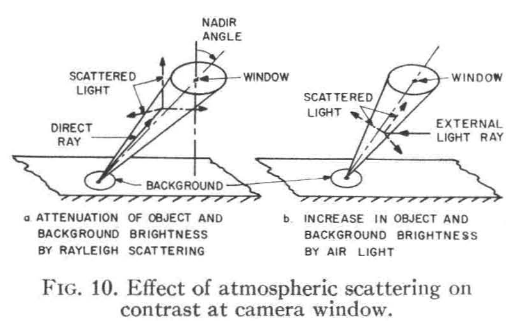

FIG. 10. Effect of atmospheric scattering on contrast at camera window.

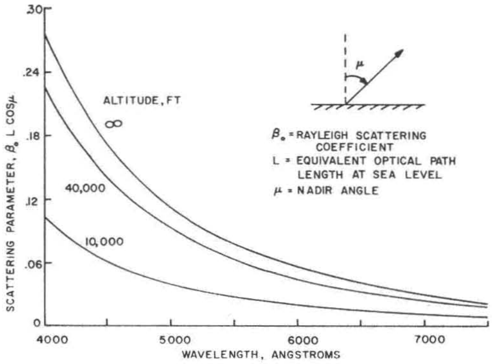

FIG. 11. Scattering parameter for Rayleigh atmosphere.

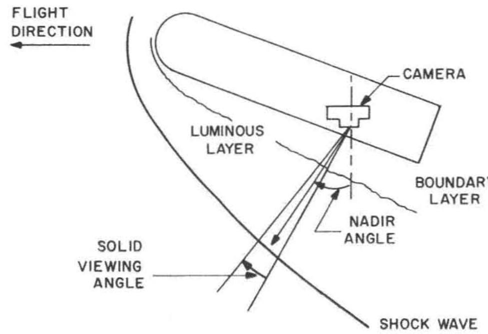

FIG. 13. Effect of flow field luminosity on contrast at camera.

case is the ratio of horizon brightness to ground brightness. For a wave-length of 4,000 angstroms and an altitude of 40,000 feet, the scattering parameter is about 0.2 for a nadir-angle of zero degrees. For a ratio of horizon brightness to ground brightness of even 1, substantial reductions in contrast are shown by the figure.

EFFECT OF AIR LUMINOSITY AT HYPERSONIC SPEEDS ON CONTRAST

Under certain combinations of pressure and temperature the equilibrium thermodynamic state of air is such that the air is radiating energy in the visible spectrum. It is possible in hypersonic flight to heat the air up as a result of shock-wave compression and/or fluid-friction to the point where it is luminous. The importance of such luminosity as it affects aerial photography and even ordinary viewing is clear and has been analyzed for the hypersonic swept-wing configuration previously described. The significance of air light

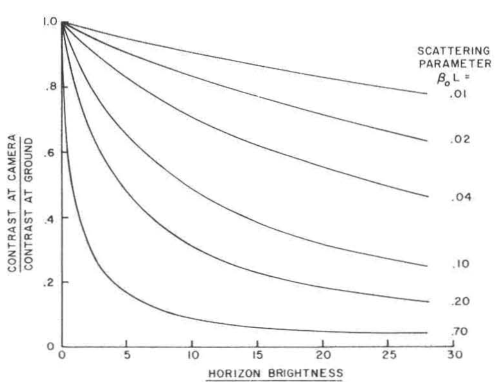

FIG. 12. Contrast-reduction ratio due to air light and Rayleigh scattering for a clear atmosphere.

due to Rayleigh scattering has been evaluated in terms of contrast reduction between an object and its background. Similarly the significance of air luminosity can be evaluated.

Consider Figure 13 which depicts the swept-wing glider with blunt leading edges at 20° angle of attack. A strong bow shock-wave due to the blunt vehicle is shown. The flow field between the shock-wave and the vehicle lower surface can be hot enough to be almost entirely luminous. This occurs when the Mach number is high. The principal effect of the luminous air is to reduce the contrast of any object against its background when viewed through the luminous layer. The loss of contrast will depend on the brightness of the luminous layer, the length of the optical path through the luminous layer, the wave-length of the light, and the brightness of the background of the object being photographed.

An analysis (Nielsen and others, 1961) has been made to evaluate the reduction in contrast for the hypersonic, blunt, swept-wing. In this analysis it was first necessary to calculate the shape of the shock-wave, the boundary layer thickness, and the pressure and temperature distributions thoughout that part of the flow field through which the light rays will pass. Then thermodynamic data must be used to evaluate the total brightness of the luminous air along the optical path. Brightness data are available in Reference 2 as functions of density, temperature, and wave-length. From the brightness of the luminous layer, together with the known quantities, the contrast reduction due to luminosity can be calculated.

In Figure 14, some general curves are shown to illustrate the significance of luminosity. The contrast with luminosity divided

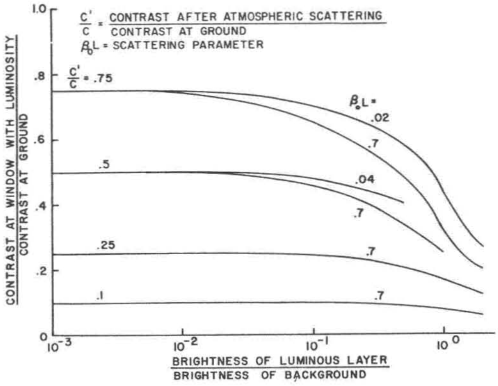

FIG. 14. Contrast reduction caused by luminous layer.

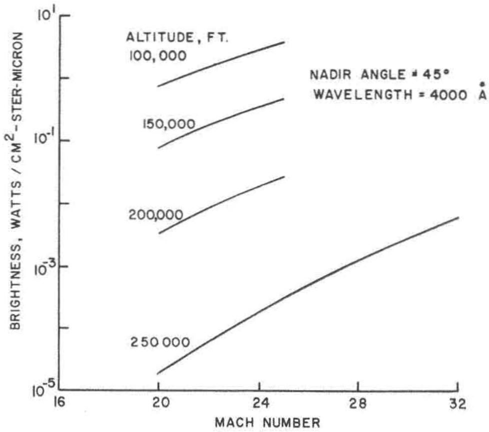

FIG. 15. Brightness of the luminous layer around the blunt swept-wing.

by the contrast at the ground is shown as a function of the ratio of the brightness of the luminous layer to the brightness of the background. The curves shown are for various values of the scattering parameter and of the contrast reduction ratio due solely to air light. It can be seen that when the loss of contrast due to air light is not large the influence of the luminous layer starts to become important when it is only one-tenth the brightness of the background. By the time the luminous layer is as bright as the background, serious losses of contrast due to luminosity have been incurred.

In Figure 15, some typical brightnesses are shown for the luminous layer under the swept-wing configuration. These brightnesses are for a wave-length of 4,000 angstroms and a nadir-angle of 45° rearward. The general variations with altitude and Mach number are to be noted. At lower Mach numbers the curves will turn sharply downward as the air becomes less luminous.

The foregoing brightnesses of the luminous layer under a blunt swept wing have been used to examine the importance of luminosity on aerial photography taken from this vehicle. Figure 16 shows the results of these calculations. This figure first shows the corridor of continuous flight previously described in connection with Figure 8. A set of parameters for the calculations have been chosen as indicated on the figure. It is assumed that the threshold contrast at the camera is 0.02. Then, the minimum values of ground contrast which will just produce a contrast of 0.02 at the window are shown on the diagram. At 200,000 feet in the corridor of continuous flight, a contrast of about 0.55 is required to produce a contrast of not less than 0.02 at the camera window. The large values of the required contrast below the corridor of continuous flight are associated with aerodynamic heating rates which cannot be withstood by the glider using presently available cooling methods.

The foregoing results are for a wave-length of 4,000 angstroms. It is known that this wave-length is not of great interest in photography since light of this wave-length is often filtered out, and most film is not sensitive to this wave-length. It was chosen to illustrate the loss of contrast at the lower end of the visible spectrum. By going to longer wave-lengths the loss of contrast is greatly reduced. Calculations were also made for a wave-length of 7,000 angstroms, and it was found that the effect of luminosity was not so great. Hence, a yellow filter is also beneficial in reducing the loss of contrast due to luminosity. The present angle of attack of 20° is not large for a reentry glider and, for higher angles

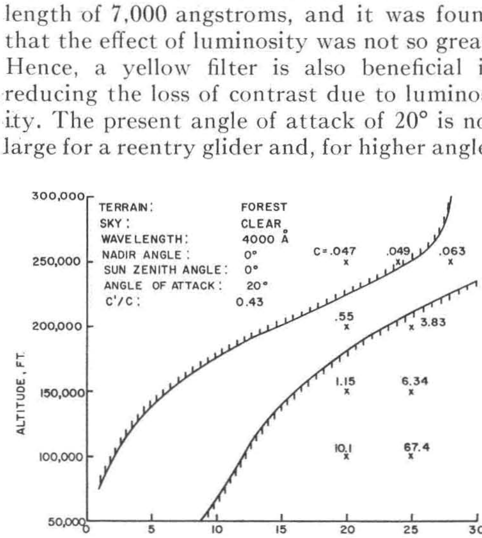

FIG. 16. Required ground contrast, C, to produce a contrast of 0.02 at camera window of blunt swept-wing configuration.

of attack, much greater luminosity can occur.

One assumption made throughout the study is that the air is in thermodynamic equilibrium. It is distinctly possible that non-equilibrium thermodynamic effects can be significant. This point requires further investigation.

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*Geological Significance of Fracture Traces**

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ABSTRACT: *Fracture traces, as now mapped in a variety of landscapes, are parallel or sub-parallel to joints in areas of flat or very gently folded rocks but are not parallel to the dominant joint sets in folded rocks. They apparently extend downward to depths of at least 3,000 feet at Bisbee, Arizona, where ore pods, which are fracture-controlled, are parallel to surface fracture traces. A probable wrench fault in Alaska separates two areas of different fracture-trace orientations, but fracture-trace orientations are identical on both sides of a thrust fault in central Pennsylvania. Extrusive and intrusive igneous rocks in the same area of Alaska show different fracture-trace orientation.*

INTRODUCTION

FRACTURE traces (also known as microfractures and linears) have been defined (Lattman, 1958) as natural linear features that have less than one mile of continuous expression, as viewed on aerial photographs. These features are rarely visible except on aerial photographs, and hence are of particular interest to the photogeologist. Recent investigations have revealed systematic relationships among fracture traces, joints, faults, folds and rock types. It is the purpose of this paper to collate this scattered information, much of it as yet unpublished, so that photogeologists may be made aware of current progress in understanding the geologic significance of fracture traces.

The authors are grateful to Dr. Richard Jahns for his thoughtful critique of this paper.

FRACTURE TRACES

ORIGIN

Nearly all workers in this field (Blanchet, 1957; Mollard, 1957; Lattman, 1958) have considered that fracture traces are the surface expression of joints or zones of joint concentration. No investigator has been able to demonstrate this hypothesis conclusively. In most areas a cross-section of a fracture trace cannot be found, owing chiefly to the absence of bedrock exposures at the critical locality. But in the Powder River Basin of Wyoming, a mapped fracture trace passes across a vertical sandstone cliff. Here a zone of joint concentration can be seen to underlie the fracture trace (Figures 1 and 2). Strong circumstantial evidence, described by the investigators named above, supports the con-

* College of Mineral Industries: Contribution No. 60–94.