Visibility: Detection and Recording of Objects Against a Sky Background

By E. P. MARTZ, Jr.

The term "visibility" is used in reference to *detection* and optical-photographic *recording* of objects of small apparent angular size viewed through the atmosphere and against a day- or night-sky background. The factors influencing such detection and recording are discussed, including the relative luminance of the object by reflected sunlight or by artificial illumination, the attenuation by the intervening atmosphere, the luminance of the sky background due to scattered light, and the sensitivity and recording capabilities of the eye. Other influencing factors include photographic emulsions, other optical detectors and the optical imaging system. This paper undertakes to demonstrate that detection and recording are dependent upon the relative contrast between the object and the sky background and are directly comparable to the astronomical problem of photographing stars against a day- or night-sky background.

TWO DEFINITIONS of the term "visibility" are: (1) the condition, quality or degree of being seen, and (2) the condition of the atmosphere as affecting the distance at which objects can be seen and identified.

Knowles-Middleton (*Vision Through the Atmosphere*) has repeatedly pointed out the critical difference between *detection* and *recognition* of an object viewed through the atmosphere and the necessity for employing a criterion which refers to slant range distance of detectability of an object contrasted against the sky background rather than to any attempt at recognition or identification of the object. Such a criterion might better be referred to as the visual, optical, photographic or electronic *slant range detectability* rather than as the commonly misused term "visibility."

This paper is limited to the discussion of the detection and recording of relatively small objects both within and exterior to the atmosphere and at great distances from the observer. The apparent angular size of such objects, as seen by the observer, will be small and approaching the apparent point source size of stars or very distant lights. Objects which are very large or relatively close to the observer and have large apparent angular sizes, such as the moon or a large aircraft at a distance of a few thousand feet, present no particular problem of detection, recognition and visibility in an atmosphere of any clarity at all. However, when objects of cross sections up to several hundred square feet are to be observed and recorded at distances of tens to hundreds of miles, immediately a multitude of problems appear. Figure 1 shows the primary illumination, attenuation and instrumental factors involved.

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For the purpose of determining flight performance of high-altitude test vehicles, it is clear that there must be a permanent recording of the flight vs. time and not only a detection of the vehicle by visual observers. At the same time, visual or automatic detectors must pick up and home on the vehicle in flight in order to record it by photographic, photoelectric or electronic means. This implies that our detectors, whether human, optical or electronic have sufficient *sensitivity* to sense the object by the light coming from it and sufficient *selectivity* to distinguish it from the background illumination or "noise" of the sky against which it is seen. This immediately implies that detectability and recordability are a function of the relative illumination contrast between the object and its background, whether the object is a bright point (or a dark point) against a bright daylit sky or a bright point against a dark night sky.

Variables Affecting Visibility

Optical theory has been developed to explain the visibility of distant objects in terms of the obscuring characteristics of our atmosphere and the quality of the incident light, but when put to practical use in evaluating different types of light sources, illuminated objects, or other optical beacons, such theory has often been found to be inadequate. This is not because of any failure in our theory, or our optical beacons, but because of the very large number of variables which affect the visibility of any object viewed through the atmosphere under different conditions of solar illumination and the difficulty of measuring, comparing and evaluating these parameters to reach the desired quantitative conclusion. It is very nearly the same environmental problem experienced in electronic instrumentation but complicated, in the visual field, by the factors of the physiology and psychology of the human eye and brain, which are, perhaps, not yet so well understood as photoelectric cells, radar, microwaves and photographic emulsions.

During the day, test vehicles are visible by reflected sunlight, and by light reflected from clouds and from the

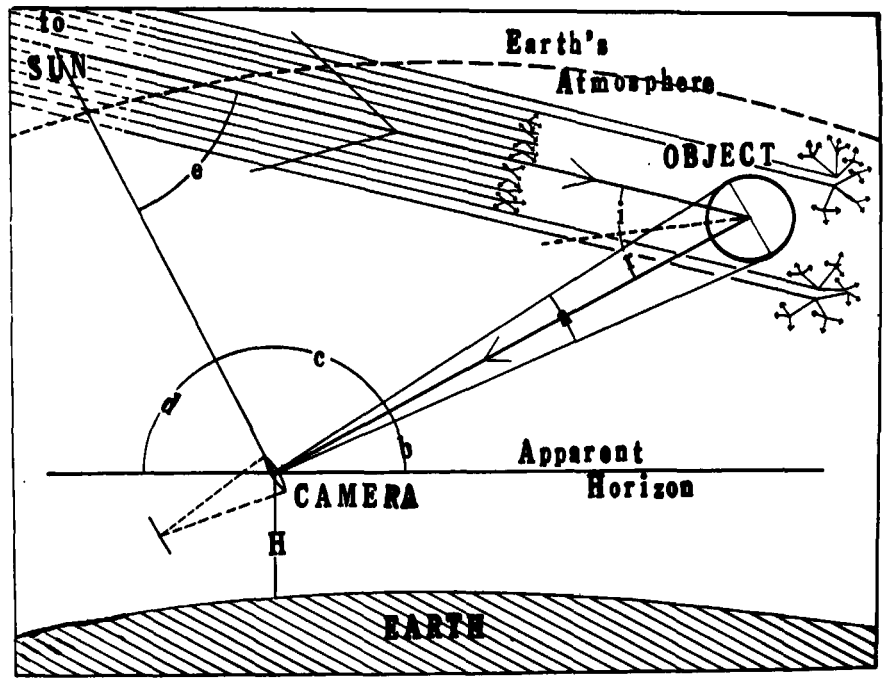

Fig. 1. Primary illumination, attenuation and instrumentation factors.

earth. Normally, these objects can be photographed only when the vehicle is at least 2% brighter, or darker, than the sky background on which they are superimposed. A safer figure is 10% difference in luminance. However, when the vehicle is closer to the observer, or much larger in size, it subtends a larger angular area in the sky and can be detected more easily even if its difference in brightness is less. At very great distances, and with small vehicles, the object usually appears only as a point and *must* have a considerable luminance against the sky to be detected and recorded.

A large vehicle, such as a V-2 rocket or a Moby Dick balloon, will reflect more sunlight to the observer, even when very far away, than will a small aircraft rocket a few feet long and under a foot in diameter. Thus, the larger object will appear brighter against the sky background even when it is a point source. Basically, this becomes the problem of seeing and photographing a point star image against the daylit-sky background.

At night, an artificial light source can be placed on the test vehicle to give the same type of star image. At night the naked eye, if the sky transparency is very good, can just about make out a star of 6th stellar magnitude by its contrast with the dark sky background. However, the night-sky background luminance is only about 22nd magnitude, or about $2\frac{1}{2}$ million times darker than the star.

During full daylight the sky background has a luminance of about 4th magnitude, about 16 million times brighter than the night sky. Therefore, the artificial star must be proportionately much brighter during the day to afford sufficient contrast against the sky background to make it visible. The planet Venus can, of course, be seen during the daytime when the observer knows where to look. At this phase Venus is about minus 4 magnitudes bright, compared to plus 4th magnitude for the sky background — a luminance difference of 1600 times. During the day, 3rd magnitude stars only $2\frac{1}{2}$ times brighter than the sky background are photographed with a medium-sized telescope and infrared film. However, factors of telescope aperture, focal length, and film sensitivity are critical and cannot always be applied to the operational cases experienced in practice.

The immediate concern is with small point source objects which are brighter than the day- or night-sky backgrounds. The use of an object darker than the daylit-sky background has some application to the cases where the object is very large or close to the observer and hence subtends a visible area in the sky. In this case, relative contrast is not the limiting factor. However, when the sky background is bright and the darker object is so small or so far away that it becomes an apparent point, the possibility of detecting or recording it becomes much less than for a point source which is brighter than the sky background. Considerations of optical instrumentation diffraction theory and the attenuating and light scattering characteristics of the earth's atmosphere lead to this conclusion. Exceptions such as telescopically observed transits of the small dark disks of Mercury and Venus across the bright face of the Sun and small black sunspots, are explainable on the basis of the parallelism of the background light of the solar disk.

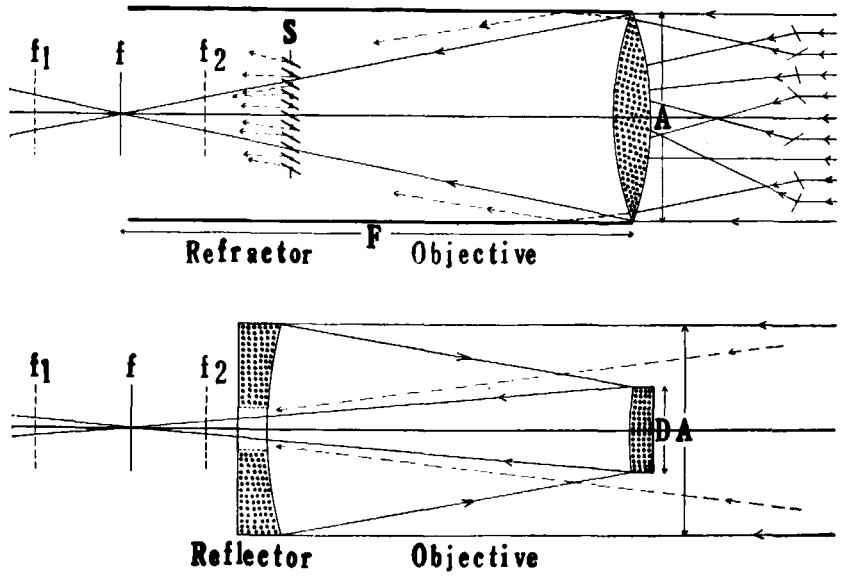

Fig. 2. Instrumental influence on image contrast.

Four Main Factors Influencing Contrast

Basic factors influencing the required contrast to detect and record a distant object are: (a) the relative luminance (or "brightness") of the object, (b) the relative luminance of the sky background during the day or the night, (c) the contrast rendition characteristics of the optical imaging system, and (d) the contrast rendition characteristics of the optical "sensor" or recording element.

Following is a detailed discussion of each of these four factors.

The relative luminance of an object *illuminated by sunlight*, as visible to the observer or recorder, is determined by:

(1) Intensity of the incident sunlight and skylight, allowing for loss due to atmospheric attenuation of the incident light.

(2) The size of the cross-sectional area of the object which is reflecting light and is visible to the observer as a "point source."

(3) The angles of incidence and reflection of sunlight on the visible surface of the object and including the effect of the shape of the object on these angles as influencing the appropriate reflection laws.

(4) Reflectivity and color of the surface of the object and whether it is a diffuse matte reflector or a specular reflecting mirror surface.

(5) Loss of reflected light due to atmospheric attenuation between the object and the observer.

For an object visible by an *artificial light source* carried with it (optical beacon) the relative luminance is determined by:

(1) Light output of the artificial light source.

(2) Directional emission of light from the artificial source with respect to the observer or recorder.

The luminance of the sky background *in daylight* is influenced by:

(1) The amount of gaseous molecular haze and other particles (dust) scattering and absorbing incident light from the Sun.

(2) The apparent angular height of the object above the horizon with respect to the atmospheric path length encountered.

(3) The angular distance of the object from the Sun.

(4) The angular height of the Sun above the horizon.

(5) The altitude of the observing station above the atmospheric haze layers.

Luminance of the *night sky* is influenced by:

(1) The amount of atmospheric haze present to scatter light.

(2) The amount and nature of secondary illumination present due to surrounding lights, aurorae, "light-of-the-night-sky," etc.

Figure 2 illustrates the contrast rendition characteristics of optical imaging systems which are limited by:

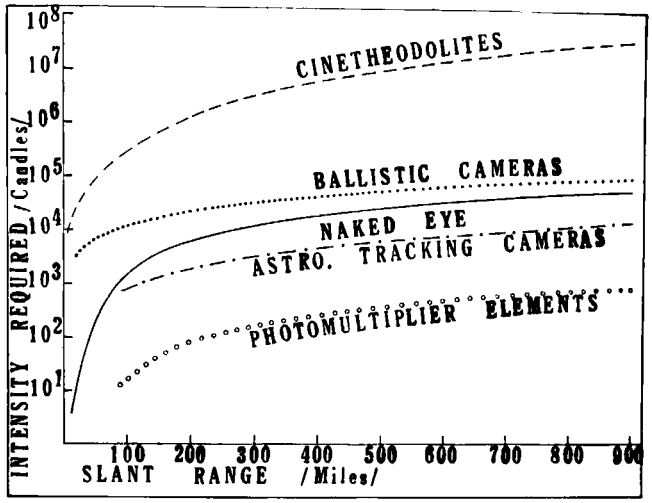

Fig. 3. Optical beacons used on test vehicles.

(1) The aperture of the telescopic-photographic objective.

(2) The focal length of the objective, relative to the aperture.

(3) The character of the optical diffraction image as determined by aperture, focal length, and any obstructions such as secondary central mirrors in reflecting objectives and louvre or "venetian blind" type camera shutters.

(4) Stray and scattered light in the optical system.

(5) Image blurring and "dilution" of the light intensity per unit area on the film plane due to tracking error during the exposure time.

(6) Image blurring and intensity "dilution" due to irregular, small scale atmospheric refraction during exposure and including such effects due to internal air turbulence within the optical system as well as refraction exterior to the camera. ("Astronomical Seeing"—the term applied by astronomers to this small-scale atmospheric refraction blurring the image.)

(7) Image blurring and intensity "dilution" arising from poor focus due to error, thermal effects on optical element mountings, change of object distance, "supplementary lensing" by atmospheric refraction, etc.

(8) Image "dilution" due to poor correction of the optical system for chromatic, spherical and other aberrations.

Optical sensors and detectors include the human eye, photographic emulsions and photoelectric and infrared sensing elements and image tubes.

The *human eye* is limited by:

(1) The sensitivity of the rods and cones of the retina.

(2) Dependence upon dark or light adapted state of the eye.

(3) Dependence upon angular size and shape of stimulus on retina.

(4) Dependence upon sharpness of boundary of the stimulus.

(5) Dependence upon color sensitivity of the eye and color of light from the object (light adapted, 5550 A.; dark adapted, 5150 A).

(6) Dependence upon the presence of disturbing stimuli in the field.

(7) Dependence upon the time duration of flash stimuli.

(8) Turbidity of the eye medium.

Limitations of *photographic emulsions* include:

(1) Dependence upon sensitivity, or "inertia," or "threshold" values.

(2) Limited by the slope of the characteristic curve (gamma).

(3) Limited by graininess and granularity and by the size of the optical image of the object on the film (plus turbidity).

Photoelectric and infrared sensing elements and image tubes are:

(1) Limited in sensitivity by detector threshold and by the electronic amplification possible.

(2) Limited in contrast by degree of "noise" background present with the amplification used.

(3) Limited by size of detector elements or by granularity of image tube screens.

These factors demonstrate clearly the complexity of the problem of detection and recording of distant objects. An additional factor, implied in the listing, is the detrimental effect of the earth's atmosphere in absorbing and scattering light and reducing the amount reaching the eye or camera from the object and hence reducing the contrast between it and the sky background and decreasing the range of detectability. Clearly, this becomes rapidly worse as the vehicle gets farther away, both because of the exponential depletion of light as the atmospheric path length is increased, and because of the fall-off of illumination from the point-source vehicle inversely as the square of the distance.

Fortunately, by use of optical beacons on the test vehicles their brightness as "stars" can be sufficiently increased to make them visible even during daylight; although, admittedly, the problem of optical-photographic detection and recording with such optical beacons is much simpler against the night-sky background (Fig. 3).

Optical Beacons

Such "optical beacons" include anything which makes a larger area for reflection of sunlight, such as chemical smokes or ejected plastic balloons, devices which increase the per-unit-area reflectance of sunlight from the vehicle, such as white and fluorescent paints and corner reflectors, and self-contained light sources such as chemical flares, flash bombs, photoflash bulbs, and electronic gaseous discharge flash tubes. Such optical beacons are directly comparable to electronic radar and other beacons used for the same purposes. As previously noted, if the vehicle and its optical beacon are far enough away from the observer they become point star light sources. A distant white smoke trail can be considered as merely a collection of individual point star images spread out in a line. There is one point in favor of such smoke trails which is that the human eye can detect a thin line seen against a fainter background more easily than it can detect a single point star image of the same luminance. However, for accurate measurement of position on a photographic film, the point image is much preferable.

As previously noted, if the vehicle is either close enough or large enough to present a visible area against the sky to the observer, it does not need to have as much increased luminance and contrast as when it is a single point star source. For example, the surface of the moon is a relatively poor reflector of sunlight (5% to 10%), but it is often visible clearly in full daylight, due to its large apparent area. A section of it small enough to appear as a single point could not be seen at all during the daytime against the bright sky background by the naked eye.

Figure 3 shows schematically the intensity in candlepower required of vehicle-borne optical beacons to be seen as point source stars, and to be recorded at night extrapolated to slant range distances up to 900 miles. The absorption and scattering effects of the earth's atmosphere have been included here, in addition to the inverse square loss of intensity with distance, and the optical detection characteristics of the human eye, the photographic emulsion, and the photoelectric element. The effect of camera shutter exposure times with motion of the vehicle image on the film

during exposure have also been included in terms of the intensity-per-unit-area "dilution" effect. The curves for astronomical-type tracking on the vehicle for long exposure times and for photomultiplier-type detectors have been included only to demonstrate their relative positions. The other curves have been derived from observational data and accepted visibility theory.

This figure is for detection and recording against a night-sky background. During the daytime, all of the curves would have to be raised by a factor of perhaps 10^4 to counteract the "noise" of the daylit-sky background in reducing the relative contrast between the image of the optical beacon and the sky. Narrowband color filters, infrared light, and other techniques will aid greatly in reducing this "noise" without increase in output of the beacon.

Discussion

George T. Keene (Eastman Kodak Co., Rochester, N.Y.): In this case, where you are talking of point sources as opposed to sources of finite area, wouldn't it be desirable to have as large an aperture as possible, since you are seeking only to record a faint object rather than to detect image detail in a small object?

Mr. Martz: The answer is "yes," and the larger the aperture the worse the blurring. This has been well established. We spent a whole day at Peterboro discussing it, if you remember, last summer — and that the larger aperture gives you a more blurred image — therefore you have the light distributed over a larger area on the film, therefore the light per unit area is less on the film and you need a brighter light source, so you have an optimum point in there between gaining light in the optical system with a larger aperture and losing light in the film plane due to the image blurring. Under different atmospheric conditions, the optimum aperture will differ.

Mr. Keene: Probably in this situation, though, the optimum aperture is somewhat larger than when you're actually trying to see detail?

Mr. Martz: Yes, for the purpose of gaining light for a faint, distant point source, you would be able to use a larger aperture to get high sensitivity. You can't draw a line and say it's always 10 in. or 5 in. — or anything else — it depends entirely upon the local atmospheric conditions at the time of observation, and the optical lever arm effect of the focal length.

Atmospheric Limitations on Missile Photography

By SEIBERT Q. DUNTLEY

Optical data taken from an aircraft in flight as well as data secured at ground level have enabled the obscuration of high-flying missiles by the atmosphere to be ascertained and the requirements to be met by telescopic finders and cameras to be specified for several typical weather and lighting conditions.

Missile photography encounters atmospheric limitations whenever the object-to-camera distance is long. This paper is concerned primarily with the long-range case. If missile photography were conducted in the absence of deleterious effects due to the atmosphere, sufficiently large high-quality optics and sufficiently accurate mountings would enable any required level of detail to be resolved in the resulting photographs. The atmosphere, however, sets a fundamental limit on resolution, and this limitation comes about in two ways. First, the atmosphere scatters light in such a manner as to lower the apparent contrast of the distant objects and cause them to merge with their background. Second, the atmosphere contains refractive imperfections which may obscure fine detail in somewhat the same way that ripples on the surface of a pond obscure small stones on the bottom.

Because the atmosphere is usually in motion, the presence of these refractive imperfections, due primarily to small-scale variations in temperature, often exhibit a dynamic manifestation called *shimmer* or *boil;* thus stars are seen to twinkle and extended objects to distort and appear blurred. All who have used telescopes are acquainted with the fact that the effects of atmospheric boil are more pronounced and more serious as magnification is increased. Exactly the same situation occurs in long-lens photography. Atmosphere which exhibits no shimmer effect which can be discerned by the naked eye or by ordinary cameras may cause distant objects to appear as a swirling blur in pictures taken with missile-tracking cameras having focal lengths of several hundred inches. No discussion of the limitations imposed by the atmosphere on missile photography would be complete without consideration of both the effects due to atmospheric scattering and those due to atmospheric boil.

Atmospheric Scattering

In the absence of effects due to atmospheric boil, the apparent luminance of any distant object seen through the atmosphere is the sum of two independent components: (1) residual image-forming light originating at the object and traversing the intermediate space without experiencing scattering or absorption; (2) luminance generated by scattering processes throughout the path of sight, including contributions due to scattered sunlight, sky light, earth shine, etc. The second of these components contains no information concerning the object but serves only to mask it by lowering the contrast available to the camera. At sufficiently low levels of contrast, details cannot be resolved.

A quantitative description of contrast reduction due to scattering within the atmosphere is given by Equation (1).*

$$\frac{B_{missile}}{B_{sky}} = 1 + T\left[\frac{B'_{missile}}{B_{sky}} - \frac{B'_{sky}}{B_{sky}}\right]$$

It states that the apparent contrast-ratio of a missile as photographed from the ground is given by unity plus the transmittance of the atmospheric path between the missile and the camera multiplied by a factor composed of two terms: the first of these is the ratio of the inherent luminance of the missile to the apparent luminance of the sky as seen by the camera; and the second term, which enters by subtraction from the first, is the ratio of the luminance of the sky above the missile in the direction of the path of sight to the apparent luminance of the sky as seen by the camera.

In Eq. (1) the primed luminances are to be thought of as measured by a photometer located close to the missile, whereas luminances without the prime

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*For derivation, see Equation (6) of S. Q. Duntley, A. R. Boileau and R. W. Preisendorfer, "Image transmission by the troposphere," *J. Opt. Soc. Am., 47:* 499–506, 1957.