18 ATMOSPHERIC OPTICS

18.1 INTRODUCTION

The use of optical instruments, and one may include the eye in this definition for the present purpose, is limited by the transmission of the atmosphere. As will be developed in the following section, the degree to which the usefulness of an instrument is limited by the atmosphere is roughly related to the aperture. Under specialized conditions however, aperture is of no consequence since image information content is reduced to zero by scattering.

Two generalized types of optical systems may be considered with regard to atmospheric effects. First is the information gathering type of system which depends upon image formation for fulfillment of its purpose. Second are photometric devices which have as their purpose only the detection of amount of radiant energy. Except for highly specialized instrumentation, most optical systems in which atmospheric contributions are significant are of the first class. This discussion will deal only with instruments intended for the former purpose.

18.2 EXTINCTION

18.2.1 Types of transparency losses contributing to extinction.

18.2.1.1 The light of the stars, planets and sun is observed to be weakened as it penetrates the earth's atmosphere. The investigation of this effect, termed the Astronomical Extinction, is one method which has been used in investigating the scattering properties of the atmosphere. Further information has been obtained by measuring the distribution of light in the daylight sky. Both of these types of measurement are of course repeated under laboratory conditions with artificial light sources, and are then useful in the study of extinction produced by media such as rain and fog. The extinction in the clear sky has three contributing components:

(1) Absorption by air molecules.

(2) Rayleigh scattering by air molecules.

(3) Scattering by dust and haze.

The scattered component observed from the clear sky is due to factors 2 and 3 only while the first factor includes the continuous Chappuis bands of Ozone that cover a substantial section of the visual spectrum. Also included in the first factor are the molecular absorption bands of Oxygen, Water Vapor, Carbon Dioxide etc. These later bands are of particular interest to those dealing with Infra-Red optical systems. The so-called atmospheric "windows" are merely areas without such absorption. The design of Infra-Red systems is considered a highly specialized application, and further discussion of this type of atmospheric absorption will therefore not be included here. Atmospheric transmission as a function of wavelength is presented in the International Critical Tables.

18.2.1.2 Extinction can be measured by observing the intensity I of a light source as seen through a volume with scattering particles. If I_o is the intensity of the same light source seen through the same volume without scattering particles, the ratio is:

$$I/I_o = e^{-l\kappa} \tag{1}$$

where l is the path length through the particulate medium and κ is the extinction coefficient. Even with a very dilute smoke, for example, a considerable intensity of scattered light I_s may easily be detected at right angles to the direction of transmission. A certain amount of true absorption does of course occur, and this represents the actual disappearance of light -- the energy of which is lost as heat. (The kinetic energy is transformed into heat motion of the molecules of the absorbing material.) The term κ may therefore be considered as consisting of two components, a (absorption) and s (scattering). The lateral scattering of a beam of light as it passes through a cloud or aerosol may be easily demonstrated. This phenomenon is closely associated with both diffraction and reflection. The light scattered at right angles to a primary beam is found to be partially plane polarized. The reason that the scattered component normal to the primary beam is not completely polarized is because of multiple scattering where light is scattered several times and therefore yields a non-constant plane of polarization. The integrated effect is therefore one of partial polarization. The polarization produced in the scattered component has been used as the basis of a compass designed by Pfund. The fact that the maximum polarization is observed perpendicular to the incident sunlight allows the approximate direction of the sun to be measured even though the sun itself be invisible. This information coupled with time data allows direction to be computed in areas where magnetic data are unreliable.

18.2.1.3 The transmissivity of the atmosphere for information-gathering optical systems is an inverse function of the extinction and is limited by particulate scattering such as that caused by haze, clouds and fog, and dusts. The subsequent discussion covers the extinction and, more particularly, scattering by these media.

18.2.2 Particulate scattering.

18.2.2.1 Two of the three factors which contribute to the extinction in the clear sky are concerned only with scattering:

(1) Rayleigh scattering by air molecules.

(2) Scattering by dust and haze.

In the unclear or turbid sky, additional scattering is produced by rain, clouds or fog. If one disregards absorption by air molecules, the extinction may be regarded as a function of the above two listed causes.

18.2.2.2 The first quantitative evaluation of the laws governing the scattering of light by small particles was made by Lord Rayleigh in 1871. His mathematical investigation yielded a general law for the intensity of scattered light. The law derived is generally applicable to particles of any index of refraction different from that of the dispersing medium. The one restriction on the application of the law is that the particle size must be greatly smaller than the wavelength of light.

18.2.2.3 As might be almost intuitively arrived at, the intensity of the scattering is found to be directly proportional to the incident intensity and also directly proportional to the square of the volume of the scattering particle that is typical of the scattering medium so long as the maximum particle dimension is small with respect to a wavelength.

18.2.2.4 A most interesting result of the work of Rayleigh is that the degree of scattering is dependent upon wavelength. Thus, for a given size of particle, long waves are scattered less than short ones, because the particles present obstructions to the light waves which are smaller compared to the longer wavelengths than to the shorter ones. The general expression is given as:

$$I_s = k\lambda^{-4} \tag{2}$$

where k is a constant of proportionality and I_s the intensity of the scattered component. For example, red light at a wavelength of 0.72 microns has a wavelength 1.8 times as great as that of violet light at 0.40 microns. The law predicts:

$$I_{s_v} = (1.8)^4 \quad I_{s_r} = 10 \quad I_{s_r}$$

assuming that the particles doing the scattering are small compared to either wavelength. As was pointed out previously, if the particulate scattering is due to large particles, the wavelength dependence does not follow the law expressed in equation (2). The relative intensity of the scattered component (I_s) as a function of wavelength is shown in Figure 18.1.

18.2.2.5 It is because of this wavelength dependence that so-called "haze" filters are used. The scattered blue light in the sky may be removed by use of a minus-blue filter so that the sky will appear darker in photographs. Indeed, a dark red filter -- corresponding to the wavelength of least scattering -- will show the clear sky as nearly black. Much here of course depends upon the definition of "clear" sky. When the particulate size is such that it is no longer small with respect to the wavelengths involved, white light scattering will occur. This is the result of ordinary diffuse reflection from the surface of the particles. When transparent large particles are considered, more complex results are obtained. In general however, the final result is that white light is scattered as white light and not to a greater extent at the shorter wavelengths.

18.2.2.6 Haze, together with dusts, forms the atmospheric contaminant referred to as the "aerosol". The aerosol consists of airborne particles of microscopic and sub-microscopic size. This aerosol contributes to scattering and therefore to the extinction.

18.2.2.7 The scattering pattern for atmospheric haze cannot be arrived at analytically with the same accuracy as the extinction law given previously. This is due to the fact that secondary scattering occurs. Therefore, the skylight cannot be simply separated into a factor due to molecular scattering and one due to haze.

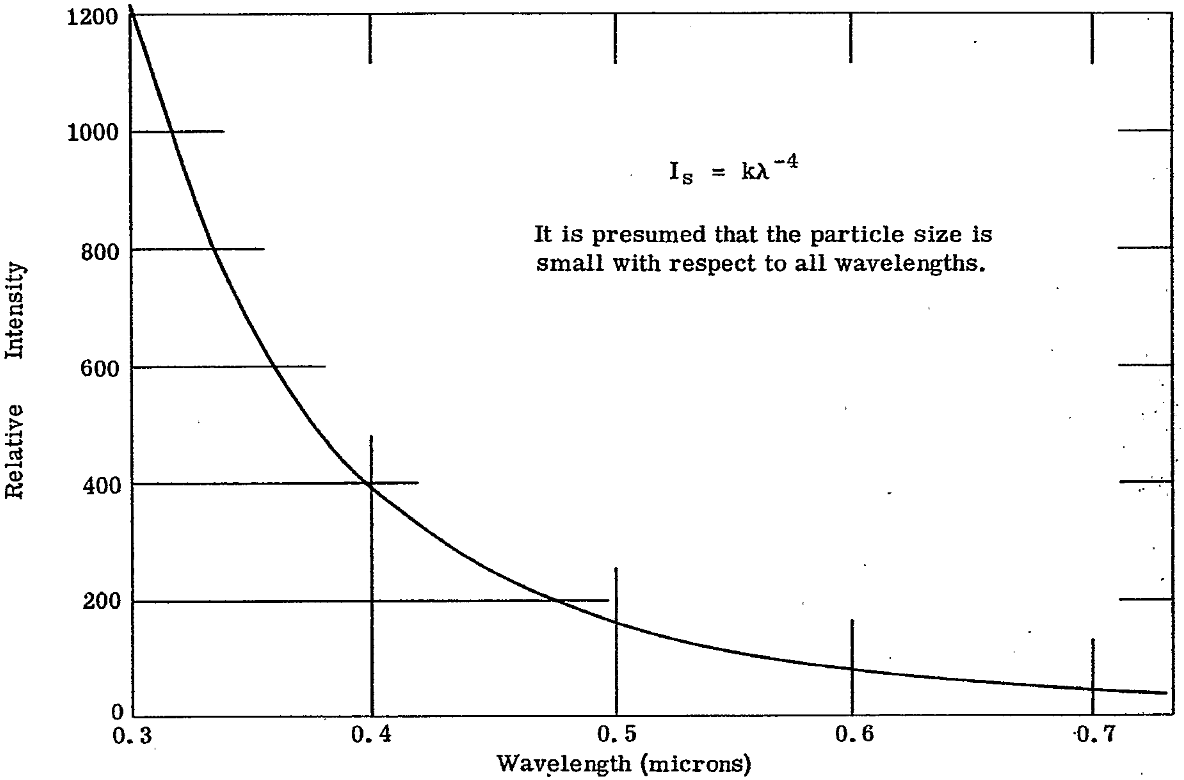

Figure 18.1- Relative intensity vs wavelength.

18.2.2.8 There are two special sources which contribute to the world-wide aerosol. These are volcanic eruptions and forest fires. The eruption of Krakatoa in 1883 was the cause of beautiful sunsets in most parts of the world. A large eruption at Iceland in 1783 caused a particularly red sun to be observed. A more recent eruption of Katmai in 1912 was of special interest since it allowed measurements of particle size to be made. The particles of haze were from 1.0 to 1.2 microns in diameter. Dust particles of the size 0.34 to 0.44 microns diameter were also found and measured.

18.2.2.9 Summer heat haze is a special case. It covers large portions of the earth's surface which are free from dust, fires, or even human habitation. For example, a more or less dense haze hangs over jungle areas in Colombia and the Amazon basin the year around. In the summer months, the heat haze covers most of the continental United States except the desert areas of the Southwest. This haze is of such a density that the open country is almost as hazy as the cities. This heat haze has nothing to do with so-called smog, fog, smoke or even moisture. It is just as dense near the ground, where the relative humidity may be 40 per cent, as near the inversion layer 10,000 feet up, where the humidity may be near 100 per cent. This blue summer haze looks so much like the man-made "Los Angeles" smog that it may almost be considered a "natural" smog. The most usual explanation given for this phenomenon is one based on the production of the "natural" smog by organic emanations from plants. These plants release vast quantities of material into the air. Most of the aromatic substances emitted by plants are hydrocarbons, many of them essential oils. Also, many plants contain terpenes, which after evaporation produce the pungent odors of the deserts and pine forests. Since such summer heat haze is not found over water areas, this explanation is logical.

18.2.2.10 Consider the blue light of a clear sky as seen at sunset. Observing directly overhead, the light scattered will be partially plane-polarized with a maximum perpendicular to the incident sunlight. The reason that completely polarized light is not observed is due to multiple scattering -- scattered light that is scattered a second, third time etc. before reaching the observer. The observation of a red sunset is attributed to the scattering of light by fine dust and smoke particles in the earth's atmosphere near the surface. Since the amount of atmosphere traversed by the sunlight is much greater at sunset due to the low angle, the dust path to the observer is greatly increased with the result that blue and violet have been scattered and the sun appears in the remaining colors. A by-product of the sunset effect is that, due to the low total illumination reaching an observer from the sun and the relatively large amount still present from sky light, the spectral shift in illumination is toward that quality of light yielded by the sky. Under these circumstances, the sky overhead is still blue. The shift is therefore toward the blue end of the spectrum. Due to the so-called "blue myopia" various vision difficulties may be encountered at this time of day even though the total illumination level is quite adequate. The optical instrument designer must consider the use of a spectral balancing filter in visual instruments to be used at dusk. The obvious problem of total light level vs. detectability requires compromise which must be decided upon the merits of each particular application.

18.2.2.11 The drops of rain, clouds, and fog are much larger than the particles that go to make up dusts and haze. A cloud or fog may contain a proportion of very small droplets, but the diameters of the drops that form the largest portion of the cloud or fog are those that dominate the extinction characteristics of the medium. These particle diameters range from 10 to 40 microns.

18.2.2.12 One extremely important fact to be drawn from this, as may be concluded from the mathematical discussion, is that the extinction contribution of clouds, fog and rain where particle sizes are from 10 to 40 microns or larger is virtually constant throughout the ultraviolet, visual, and near infrared regions. Exactly where one may establish the maximum of the extinction curve will fall is difficult to predict. Measurements throughout the 0.4 to 5.5 micron range have been made by many observers. The extinction remains constant within ± 10 per cent. The efficacy of special filters, for example, under these conditions is not real if penetration is considered. A more complex case exists where cloud cover is not complete, and it is desired only to obtain the best contrast condition against this broken cover. In "typical" rain, the droplet size is of course again much larger than in the case of fogs and clouds. Again, the extinction is essentially constant throughout the spectrum. It is for this reason that special color filters are of little or no value in the penetration of clouds, rain or fogs wherein the particle size is of the order of from 10 to 40 microns. A slight gain is obtained by the use of filters in visual instruments which peak the response to fit the response curve of the eye. Likewise, the response of a given photographic material or photo-cathode substance may be matched in order to give some small penetration advantage. Filters are of a definite advantage whenever the particle size is small with respect to the wavelength.

18.3 EXTINCTION AND VISUAL INSTRUMENTS

18.3.1. Imposed limitations on visual instruments.

18.3.1.1 The main limitation produced by extinction exists in two degrees. First, if the transparency is very low (extinction coefficient high) no art exists whereby penetration in the visual spectrum may be achieved. This is the case in dense fogs, clouds and rain. Since it is impossible to design for this case, the best compromise must be made for the second condition, namely; when transparency is reduced by smaller concentrations of aerosol or water droplet dispersions. We will consider instruments of limited aperture and power. Such instruments will not be seriously hampered by poor "seeing" conditions (such as will be discussed subsequently), but will be limited by extinction.

18.3.1.2 Visual optical systems having apertures of up to two inches and magnifications up to 10 diameters are not greatly affected by differences in air density, inhomogeneity, turbulence etc. when used at elevation angles in excess of 15 degrees. Larger systems are more seriously affected, nearly proportional to their aperture.

18.3.2 Filters.

18.3.2.1 The main thing which can be done in visual optical instrument design to optimize performance under less than ideal atmospheric conditions is the addition of a series of suitable filters. The purpose of the instrument will of course govern the choice of filter combinations made available.

18.3.2.2 The color filter which will prove most advantageous depends upon the object being viewed and upon the background. For ground objects, where the background and subject are both subjected to the same scattering effects, filter choice will depend upon the color of the object. For light or dark objects against the sky, the filter choice will depend upon the brightness of the target and the color of the sky.

(1) When the target is white and bright against the clear blue sky, a filter (red or yellow) which will make the sky appear relatively darker with respect to the object is desired.

(2) Observation of dark objects against a blue sky presents a more complex problem. Some observers maintain that if the blue myopia of the observer is compensated, best results are obtained with a blue filter. Others, and the writer is one of them, fail to observe any improvement in visibility of dark objects against the blue sky with any filter, and subsequently suggest that a "clear" condition is best under these circumstances. The same is true of the compromise required in the observation of mixed white and dark objects against the clear blue sky. For visual purposes the "clear" condition is best or nearly so.

(3) While a white target is usually lighter than a clear blue sky background, it may easily be darker than a white sky background. In this instance it is found that color filters are of little or no help. If the target is colored, the choice of filter to obtain the best result is that which darkens the target more than the background.

18.3.2.3 As we have noted, a great proportion of scattered light is partially polarized perpendicular to the incident radiation causing the scattering. The use of polarizing filters may allow an increase in contrast under special conditions where the scattered component may thusly be at least partially eliminated.

18.3.2.4 At the risk of redundancy, it will be pointed out once again that when large particle media are producing scattering, no filter will appreciably increase penetration. In the case of true haze, where the particle size is small, removal of the scattered light is practical by filtration. A minus-blue filter, or even a red filter may be used under these circumstances to improve clarity.

18.3.3 Light gathering power.

18.3.3.1 One chief result of high background illumination is reduced contrast when bright objects are to be viewed. Also, intervening particles cause scattering which further reduces contrast. The later cause of contrast reduction applies to both bright and dark objects viewed against a comparatively bright background. If the visual consequences of this loss of contrast are to be minimized, it is necessary that further contrast loss not be produced by having an exit pupil smaller than the pupil of the eye. It is found to be advantageous, therefore, to accomplish effective aperture reduction by means of neutral density filters rather than by reduction in aperture by means of adjustable or fixed aperture stops. The use of such neutral density filters has a further advantage, not directly connected with atmospheric optics, in that the resolving power of the instrument is not reduced as it might well be if the aperture were reduced by physical limitation of diameter.

18.4 EXTINCTION AND PHOTOGRAPHIC INSTRUMENTS

18.4.1 Effect of instrument orientation. Photographic instruments, for the present purpose, will be placed in two groups -- those used looking up, such as missile tracking cameras, ballistic cameras etc, and those looking down, such as aerial cameras, satellite borne cameras etc. The atmospheric effects due to extinction coefficient variations are quite different in the two cases. Some generalizations can be made which apply to both groups, but the two are better treated separately.

18.4.2 Photographic instruments "looking up".

18.4.2.1 Missile and satellite tracking cameras and telescopes always have the sky as a background. Depending upon the conditions of a particular firing or satellite pass, the sky may be either clear or cloudy, bright or dark. Due to a gain in performance at greater scale, missile tracking and satellite surveillance cameras are usually of great focal length. Satellite acquisition cameras, on the other hand, are of high optical speed and short focal length.

18.4.2.2 As would be expected, the contrast between the target and the sky background is a function of the distance from the camera to the target. Horizontal and vertical components of this distance however, are not of equal importance in the reduction of contrast. For a dark target on a clear day (blue sky background) subject contrast is decreased more by an increase in altitude than by an increase in horizontal range. For a bright target on a clear day the opposite is true.

18.4.2.3 As is the case for visual instruments, the greatest gain in performance is obtained through the use of suitable filters. The type of filter to be used with an optical system "looking up" depends upon the relative contrast of the object and the background.

(1) Filters for photography of white targets against a blue clear sky require effective darkening of the sky background and heightening of the relative brightness of the target. For a spectrally non-selective white target, the use of a red filter (Wratten 25 or 29) ordinarily gives excellent contrast results. A blue filter will give poor results in this situation since this will effectively reduce contrast. A yellow filter will yield satisfactory results under these conditions, but the red filter will be superior provided that the filter factor or effective density is not so great as to reduce the available illumination below operable limits.

(2) Filters for photography of dark targets against a blue clear sky require effective darkening of the target and heightening of the relative brightness of the background. This can be achieved by the use of a blue filter (Wratten 47). The photographic material does not suffer from the blue myopia of the visual observer. Also, photographic contrast in blue is essentially the same as for other colors -- in fact for certain color materials more tone scales are available from the blue sensitive layer than from any other -- so that the contrast rendition can be excellent under these circumstances if a blue filter is used. If the target is in an orientation 180 degrees opposed to the sun, and if the sun is very low on the horizon, a yellow or red filter may actually be better than the blue, due to the blue deficiency of the sunlight which must pass through a greatly extended atmospheric path. In the case of a satellite that is effectively outside the earth's atmosphere however the choice of filters is more complex, since the scattering path length for light reaching the optical system from the target is nearly the same as the scattering path length of the light from the sun (here the atmospheric path length only is considered).

(3) When photography is done on either white or gray objects against a sky background which is whitened by scattering, filters are found to be of little if any assistance. If the target is colored, the choice of filters should be such as to insure the darkening of the target more than the background. For example, a blue filter would be used with yellow or red targets.

18.4.3 Photographic instruments "looking down".

18.4.3.1 It is well known that photographs taken with large and small lenses of similar quality have nearly the same microscopic contrast in the presence of haze, but have ground resolution modules approximately proportional to focal length. There are many other factors to be considered, such as the quality of the lens, the lens mounting, the type and speed of the shutter, the filter used if any, etc. In general however, if all these factors are equal or nearly so, and if the laboratory performance resolution wise (in lines per millimeter) remains independent of focal length as is usually the case with present day aerial lenses, then the focal length is the most important factor in obtaining a given desired ground resolution.

18.4.3.2 The only extinction or scattering phenomenon which can be partially eliminated by means of filters in the case of photographic instruments "looking down" is haze. Minus-blue filters are commonly employed for this purpose. Since most ground objects have extremely low contrast ratios (of the order of log 0.1 and thereabouts) the elimination of haze effects is extremely important. Red filters have a better haze elimination characteristic in the case of true haze, but these have a tendency to cause natural greenery to appear too black for satisfactory interpretation. The usual compromise has been to select a yellow or orange filter for the purpose of haze minification.

18.5 "SEEING"

18.5.1 Atmospheric factors affecting "seeing".

18.5.1.1 "Seeing," as differentiated from transparency, (reciprocal extinction) is concerned with those factors which limit the information content of images by causing a lack of bulk homogeneity in the optical medium preceding the optical system.

18.5.1.2 At least two basic causes for differences in refractive index of air may be demonstrated. First, there is the "suryp" analogy, in which the density -- and thus the refractive index -- is changed by local differences in temperature throughout the air mass. A second method of producing differences in refractive index is by the condensation and rarification of air by sonic means. When a sound wave moves through air, the air mass instantaneously consists of a series of sections of air having in turn increased and decreased densities -- and thus increased and decreased refractive index. These two causes of inhomogeneity in air are the basic causes of "seeing" difficulties.

18.5.1.3 Any observer who has made observations with a medium size or larger telescope is aware that the performance of his instrument is seriously limited by the astronomical "seeing". Images of stars are much larger than is the case if the image diameter were to be limited by the diffraction of the telescope objective alone. Lunar and planetary detail is badly smeared when the seeing is poor. For example, the average seeing disc of the Hale telescope of 200 inch diameter is about 2.5 seconds of arc while theory indicates that the resolution should be on the order of 0.04 seconds of arc. The optical quality of the telescope is not at fault. The difference is due to the quality of the "seeing." And, it must be remembered that the location of the 200 inch telescope was chosen for the good "seeing" conditions existing on Mt. Palomar.

18.5.1.4 The total amount of light received from a bright star by a telescope of moderate size fluctuates in an irregular fashion, and in a manner which can be shown to be due not to any intrinsic fluctuations in brightness of the star, but to the fact that the starlight must pass through the atmosphere of the earth wherein there are regions of density irregularity. A 12 inch aperture telescope, for example, will exhibit variations in intensity of ± 10 per cent of the average value. The frequency of variation may change from several seconds per cycle up to thousands of cycles per second.

18.5.1.5 Two types of effect are attributable to differences in the air mass preceeding the objective. The first consists of oscillation or image motion. This is due to the movement of relatively large air masses at comparatively low velocities. The second is scintillation. Scintillation is the fluctuation in the light of stars known to be caused by motion across the telescope objective of a complex pattern of light and dark bands known as shadow bands or the shadow pattern.

18.5.2 Oscillation.

18.5.2.1 The change in position of an image in the focal plane of an objective system due to atmospheric disturbance is known as oscillation. This image defect does not of necessity destroy visual resolution. There is a good likelyhood that photographic resolution will be seriously curtailed if substantial amounts of oscillation are present however, since the photographic plate is inherently an integrating device and does not by itself compensate for shifts in position of a high quality image.

18.5.2.2 On a simplified basis, oscillation may be thought of as being caused by the passage of various lens shaped or prism shaped "chunks" or modules of atmosphere in front of the objective. If each air module is of a size greater than the diameter of the telescope objective, a comparatively good image will be seen whenever the entire objective diameter is covered by a single homogeneous module. Since such air modules occur in various layers at different altitudes and move with different velocities, it is obvious that seeing becomes a very complex thing that is difficult of analysis.

18.5.2.3 In a real situation, several cross-currents of air may contain air modules of various sizes. When, in accordance with the laws of chance, the optical path through a diameter covering the objective is equal to within the tolerance of one quarter wavelength of light, an excellent image will be found in the focal plane of the telescope.

18.5.2.4 In the case of relatively slow moving air masses which give rise to oscillation, some sort of compensation is practical. Photometric guided tracking instruments have been developed to compensate for oscillation. These instruments detect the angular movement of the image of an astronomical object, and move the photographic plate or the image so that the effective position of the image on the plate is constant, and a good photographic image is produced.

18.5.2.5 The larger the telescope, the less the probability that the air mass over it will be homogeneous within a quarter wavelength path difference at any given time. Thus follows the hard fact that smaller telescopes may frequently give better resolution than larger ones even though their theoretical resolving power is not nearly so great.

18.5.2.6 Even when the air modules passing over the objective are of sufficient size so that theoretical or nearly theoretical resolution may be obtained, the image motion caused by the shifting air masses is such that long period photography may fail to yield anything approaching what may be seen visually. Very short exposure photography has been tried in efforts to circumvent this difficulty. Also, guidance of the photographic plate and/or the image forming beam have been tried to yield better photographic results. Both of these methods have yielded some success. Excellent planetary photographs have been taken recently with the 60 inch aperture reflector on Mount Wilson after the adaptation of a seeing compensator at the photographic focus. This device moves the final image in accordance with the image shift so that a non-moving image on the plate is the result. Short exposures using telescopes of large aperture have also given promising results in planetary photographs.

18.5.3 Scintillation.

18.5.3.1 Those fluctuations in the light of a star that are not due to any inherent change in brightness of the object but instead to the motion across the telescope objective of a complex pattern of lights and darks, known as the shadow bands or shadow pattern are called scintillation. This shadow pattern is caused by the passage of starlight through atmospheric irregularities which must occur at a considerable height. These irregularities diffract the light and cause rarification and reinforcement of the wavefront at various points along the ground. A fairly complete theory of the relationships between the atmospheric irregularities and the pattern of lights and darks produced in the shadow pattern has been developed.

18.5.3.2 It is common knowledge that the theoretical diffraction pattern can only be observed with telescopes of small aperture and under good conditions of "seeing." With instruments of moderate size -- 36 inches and upwards -- such theoretical resolution is rarely if ever achieved. Using the 36 inch aperture example, the theoretical resolution limit would be less than 0.15 seconds of arc. In practice, however, the starlight is usually spread over a disk of from 2.0 to 5.0 seconds of arc in diameter. This is called the "seeing disk." This "seeing disk" is simply the circle of confusion for the rays reaching the focus (physical optics disregarded for the moment), and its diameter is a measure of the lack of parallelism of the rays when they arrive at the objective from the star. We may thus choose to consider the "seeing disk" as the summation of the diffraction patterns formed by each element of the objective and the air column over it. These elementary diffraction patterns are in rapid oscillatory movement both along and at right angles to the optical axis of the telescope. If the aperture of the large telescope is stopped down to the aperture which would yield the theoretical limit of resolution equal to the actual resolution of the large system, the usual diffraction rings will become clearly visible and sharply defined. The amplitude of brightness scintillation will be noted to have increased roughly inversely to the ratio of new to old diameters. This leads to the conclusion that the "seeing disk" formation is a phenomenon largely independent of brightness scintillation. It seems probable that the "seeing disk" arises from refraction of the rays in their passage through our atmosphere, while brightness scintillation is mainly a diffraction effect arising from the presence of much smaller reinforcement and rarification irregularities within the beam.

18.6 THERMAL EFFECTS

18.6.1 Types.

18.6.1.1 Differences in refractive index due to fluctuations in density which are in turn due to thermal effects play a considerable role in the limitation of vision and photography through optical instruments used for ground level observations. This so-called "ground seeing" frequently limits what can be seen even with low power instruments. In some instances these effects seriously reduce the information which can be gathered by such a small aperture optical system as the human eye.

18.6.1.2 Also, thermal effects in and around larger optical systems are frequently the limiting factor in the performance of these systems. Thus, tube currents and dome currents in astronomical and missile tracking telescopes may reduce the performance of the instrument by a factor of two or more if measures are not taken to circumvent the degradation.

18.6.1.3 The "mirage" or atmospheric striae noticed over the desert floor is an example of what may occur when an air mass is heated by radiation and conduction. In desert areas, even low power telescopic systems of small aperture are very limited in use at low elevation angles. A pair of 7 x 50 binoculars will show much image degradation due to this heat shimmer.

18.6.2 Tube currents.

18.6.2.1 Insofar as the final image is concerned, it matters little whether the density discontinuity occurs without or within the tube of the optical instrument itself. Any telescope tube exposed to thermal radiation or temperature differences of any kind will have variations in density of the air within itself. When these differences become large enough, air flow will occur between the dense and rare areas setting up tube currents. Typically, the air just inside the outside covering of the tube is heated or cooled most rapidly, and a laminar convection current forms wherein air circulates from the perifery to the center. If the tube is an open one, the warmed air -- considering that the tube is being heated by the surroundings -- passes out the end of the tube. Provided the tube is sufficiently larger than the free aperture of the optical system, the air which flows out the end will disturb that remaining in the tube but little. This argument has been presented in favor of open tubes. Unfortunately the issue is not nearly so clear cut. The (assumed) warm air flowing out from the opening of a tube will, since it must obey the gas laws, rise after exiting from the tube. Unfortunately, the path in which it must rise is directly in front of the direction of pointing of the instrument, and while the warm air from the top of the tube causes no difficulty in this regard, that from the bottom flows directly past that area which it is desired to protect from any density differences.

18.6.2.2 A solution which answers the objections to both the closed and open tube arrangements is found in the evacuation of the light path volume. The degree of vacuum need not be high in order to accomplish a substantial increase in performance. A striking experiment may be readily performed to illustrate this fact. If a relatively small telescope of three or four inch aperture is set up for knife-edge test by autocollimation, nearly complete degradation of the image forming qualities of the instrument may be produced by heating the tube of the instrument with a small flame. If the tube is then evacuated to a pressure of 1 PSIA the image quality will be restored to near that present before the heat was applied. It is assumed that the objective is sufficiently thick as to withstand the pressure differential without optical deformation or that a thick optical window has been placed near the objective.

18.6.2.3 The minimization of thermal heating of any tube is desirable from a tube deformation and image quality standpoint. It is good design practice to require some air space beyond the actual optical clearance lines in most optical instruments. A layer of insulation inside the tube also tends to even out the thermal effects so that, while heating will still occur, the unevenness of the heating will not augment thermal disturbances.

18.6.2.4 Most of the energy reaching the earth from the sun is contained within the spectral region between 0.36 and 2.0 microns. The use of highly reflective paints is desirable when thermal effects from radiation are to be reduced. The once prevalent idea that solar heating came mostly from the infrared and that therefore only good infrared reflectivity was required of an instrument paint is quite wrong. The total energy (insolation) from the sun may be as high as 0.028 calories per square centimeter per second. Over 90 per cent of this energy is in the wavelength region below two microns, and nearly 80 per cent is in the region below one micron. So, while good infrared reflectivity is desirable in an instrument white, good visual reflectivity is certainly equally required.

18.6.3 Dome currents.

18.6.3.1 As is the case with telescope tubes, observatory and other housing domes have currents associated with their construction and situation. Particularly in the case of domes opened in the daytime for use, currents may be of such magnitude as to render the housed instrument nearly useless.

18.6.3.2 Painting and insulation are commonly resorted to minimize the effects of thermal heating of the dome. Again, a highly reflective white paint with a reflectivity which matches the solar spectrum as well as possible is desired. Insulation produces a thermal lag which, unless coupled with temperature control as noted later, may actually impair performance rather than improve it.

18.6.3.3 Dome currents may be nearly eliminated if the air inside of the dome is maintained at the same temperature as the air outside. This is an isothermal situation not unlike that in the isothermal jacket of an accurate calorimeter. Since, under conditions of solar radiation, the interior of the dome will usually be considerably warmer than the outside air, it is necessary to provide refrigeration if the desired state of isothermal conditions is to be obtained. At times however -- such as sunrise -- the interior temperature will be much below that of the outside, so that heating capability is also required. It is not sufficient to grossly heat or cool the air within the dome. It is essential that the mixing of air be complete and that inhomogeneities do not exist in the air mass within the dome itself.

18.6.3.4 Next to air temperature control, the best practice is to allow the dome air to arrive at some approximation of equilibrium with the outside air before the housed instrument is to be used. Before observations begin, astronomers open the dome for some period of time to allow the dome, telescope and associated equipment to come to a steady thermal state.

18.7 ATMOSPHERIC CONTAMINANTS

18.7.1 Sources and effects.

18.7.1.1 In addition to the natural products which go up to make the aerosol -- water, dust, smoke etc. -- there are man-made atmospheric contaminants which may produce very undesirable effects on seeing and transparency. For example, industrial smog may limit aerial photography. Certainly the sky light from large cities has greatly reduced the effectiveness of the observatories located near them. Here the man-made effect is two fold. Industrial smog scatters the light which is a by-product of the city so that both transparency and contrast are reduced in that area.

18.7.1.2 Atmospheric contamination by radioactive particles and dusts dispersed by explosions can be viewed as a potential source of seeing degradation if the quantity ever reaches sufficient levels to produce light scattering and even perhaps a very low level of direct radiation. As things now stand, astronomers are counting single photons in the course of measurements on some stars. In these circumstances it is obvious that background light must be kept at an absolute minimum.

18.7.1.3 The increasing amount of carbon dioxide in the atmosphere has undoubtedly increased the "greenhouse" effect present in the atmosphere. While this can have no noticeable effect on visible observations, the increase in infrared absorption may cause detectable variations in the performance of infrared systems. Also, if the increase is sufficient, local heating in areas of high carbon dioxide concentration may cause seeing deterioration due to thermal gradients.

18.8 EFFECT OF ATMOSPHERIC OPTICS ON INSTRUMENT DESIGN

(1) A knowledge of atmospheric optics is important to the optical instrument designer so that he may take advantage of suitable filters, paints and housings in the overall instrument design.

(2) The designer who knows that seeing conditions limit the performance of a telescope more than does the theoretical resolving power will not specify aperture on the basis of theoretical resolution without first considering the actual conditions of use of the instrument.

(3) The design of an optical instrument must go beyond the physical boundaries of the device, it must include at least an approximation of the air column which forms just as much a part of the instrument as does the objective lens. When the limitations placed on performance of high quality optical systems by atmospheric optics are considered in the design phase, a more satisfactory instrument cannot help but result.