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PROCEDURES FOR LOCATION OF ASTRONOMICAL OBSERVATORY SITES

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I. — Introduction.

The effectiveness of large telescopes is limited by the terrestrial atmosphere rather than by their optical or mechanical performance. Due to its refractive, absorbing and scattering properties, the atmosphere is one of the important elements that determines the limiting magnitude, resolving power and the wavelength range within which observations are possible. These effects are present even on the clearest nights. In addition, general meteorological conditions such as cloudiness, wind, high humidity, or extremely low temperatures further impair or prevent the operation of astronomical equipment. These effects can be avoided by placing the equipment above most or all of the atmosphere (balloon-borne telescopes, satellite observatory, lunar observatory). For the foreseeable future the cost of placing and operating a telescope outside the atmosphere will be such that it will be restricted to the investigation of problems that cannot be solved with observations made only from the ground. It seems possible, however, to choose sites for terrestrial observatories where the atmospheric effects are minimized. Just where the *optimum* conditions can be found is not yet known, but it is highly probable that none of the existing observatories is located on the World's best site. In fact, it is quite possible that conditions may be found on hitherto unknown sites that could bring a considerable advance in astronomical research before going to space equipment. Whether or not it is practicable to erect and operate an astronomical observatory on the optimum site (or sites) will depend largely on location, because in addition to excellent astronomical observing conditions the site has to be accessible and capable of development for satisfactory working conditions.

In view of the foregoing circumstances, a search for the best sites on earth seems to be justified. Methods for testing the conditions and expressing them in a quantitative way are needed. The purpose of this paper is to discuss some of these methods, and to present results obtained in a specific project of this nature.

II. — Definition of astronomical observing conditions.

The term " astronomical observing conditions " is supposed to comprise all effects by which the terrestrial atmosphere imposes limitations on astronomical observations. Russian authors have proposed the designation " astroclimate ", which may serve the purpose even better. The various contributing effects may be classified into two categories : (1) optical factors, and (2) mechanical factors. Optical factors comprise all those that affect the light beam as it passes from the top of the atmosphere to the signal-detecting device in the telescope. Mechanical factors are those that affect the functioning of the equipment.

1. **Optical factors.** — *a. Seeing or quality of image.* — The first term is widely used by English speaking astronomers, the second has been proposed by Sub-Commission 9 *b* of the I. A. U. This term is supposed to include all random variations in the direction of all or part of the light received by the telescope.

b. Scintillation. — This term describes random variations in the total light flux received by a telescope from a single star.

c. Extinction. — This term describes the loss of light along the path through the atmosphere, due to absorption and scattering.

d. Brightness of sky background. — The brightness of the sky background is of importance when dealing with faint objects. Three terrestrial sources contribute to the background brightness : (i) scattering of light from celestial sources, (ii) scattering of light of artificial origin, and (iii) auroral phenomena. The first two effects may show a correlation with the extinction.

e. Average number of clear night hours per year.

For the proper evaluation of the astronomical observing conditions on a given site, all the optical factors have to be expressed in a quantitative way.

2. **Mechanical factors.** — While it is used for observing, a telescope is exposed to the surrounding air and thus its functioning may be affected by local meteorological conditions. In contrast to the optical factors, some of the effects of mechanical factors can be reduced or eliminated by proper design and engineering of dome, telescope, and auxiliary equipment. Thus it is only those effects that cannot be eliminated by

engineering which contribute to the observing conditions. The factors to be considered are :

a. Wind. — Wind affects observing conditions in two ways. It may cause irregular motions or vibrations of the telescope. Thus, in the presence of wind, all but visual observations cannot profit fully from the optical conditions that may exist. Also, the wind may produce turbulence around and inside the dome with impairment of the optical conditions. Proper design of the dome and ventilation of its interior reduce this effect.

b. Temperature. — It is quite possible that some of the best sites are located at high altitudes where low temperatures are to be expected. This is, at least, a discomfort for the observer; more importantly, his efficiency could be reduced by anoxia.

c. Diurnal temperature range. — Some of the effects that are caused by a large diurnal temperature range can show up in the optical conditions. The most important effect on the equipment itself probably is distortion of the optics. It is also important to have the entire telescope and many of its auxiliary instruments quickly reach an equilibrium temperature close to the surrounding air, in order to reduce mechanical strain and sluggish operation. This condition is difficult to attain with large temperature fluctuations and gradients.

d. Humidity. — Besides its optical properties, the presence of much moisture in the local atmosphere can lead to condensations on optical parts, refrigerated auxiliary equipment, electrical parts, etc.

The optical and mechanical factors just listed essentially describe the astronomical quality of a site. Many more problems exist, however, that concern accessibility, living conditions, etc. These should have no effect on how the equipment will perform and what it can produce, but they may be the determining factors in the cost of developing and operating an observatory.

III. — The importance of factors contributing to the observing conditions.

It is not at all certain that the factors listed in the preceding section will be at an optimum on the same site. It may happen that one factor opposes another. If so, a compromise has to be made, which depends on the weight attributed to the various factors. At first sight, this weighting seems difficult or even impossible for any general purpose observatory. For example, only the number of clear nights counts for a meteor camera; the brightness of the sky background may have a little weight, the seeing none. On the other hand, a lunar observer cares only for seeing. Fine transparency, or brightness of the sky background, are unimportant; the number of clear nights is not all-important. Thus a different optimum site may be found for different purposes. But the situation is different, if one seeks an optimum site for large telescopes. Then the seeing becomes the predominant factor for most purposes, for reasons discussed below. Nevertheless, it may be of interest to discuss the importance of all factors in detail.

1. **Seeing**. — The most obvious effect of seeing is that of a reduction in the resolving power of the telescope. In fact, while the largest telescopes in existence theoretically should resolve a few hundredths of a second of arc, they hardly ever resolve a few tenths because of the seeing. Lunar and planetary work, or double star observations, depend greatly on the actual resolving power. The same is true for work on globular clusters, or on nuclei and brightest stars in galaxies. Many more examples could be mentioned.

Just as important as the resolution of faint stars is the measurement of their magnitudes. The seeing spreads the light of a star over a certain area. There it is superimposed on the sky background, from which it has to be distinguished. The more concentrated the light of a star, the more contrast it has against the background. This condition is important for photographic or photoelectric work. In the case of photoelectric measurements, the effect of seeing on the measurement of faint stars can readily be treated quantitatively, as indicated in foot-note, p. 54

In slit spectroscopy of faint stars one has to make a choice between limiting magnitude and spectral resolution. In order to increase the resolution one has to narrow the slit, while in order to get as much of the starlight as possible one has to widen it. In slitless spectroscopy the resolution is wholly determined by the seeing (with telescopes of short focal length the graininess of the photographic plate may also be of importance).

In photographic photometry seeing can be a troublesome factor. It can greatly affect the calibration curve relating plate photometer readings to magnitudes. Thus photographic transfers of magnitude scales, where two different areas may be photographed on the same plate, can be vitiated because of a change in the seeing conditions, or because the two areas did not have the same zenith distance.

Many more examples of the effect of seeing on astronomical observations could be cited, but those given may suffice to demonstrate its importance.

2. **Scintillation**. — The amplitude of the random fluctuations of the stellar intensity, to which the term scintillation refers, depends on the aperture of the telescope, in the sense of decreasing with increasing aperture. For naked-eye observations they are readily noticeable as twinkling. With apertures of only a few centimetres the scintillation

can no longer be seen visually, but it can be observed readily at relatively high frequencies with photoelectric equipment. With large apertures and long time-constants (1 s or more) they practically disappear. Hence for large telescopes scintillation may be regarded as a relatively unimportant factor. For telescopes up to about 50 cm aperture, however, they may on occasion be of importance.

3. **Extinction.** — The extinction caused by the constituents of the lower and upper atmosphere consists essentially of four components :

a. Dielectric scattering by the molecules of the dry, clean air. The wavelength dependence of this Rayleigh scattering is nearly proportional to the fourth power of the wavenumber. Its dependence on air mass, and on elevation, can be predicted.

b. Ozone absorption in the ultraviolet prevents any radiation with a wavelength shorter than about 2 950 Å from reaching the ground. The ozone layer is so high in the atmosphere that its effect will be the same over large areas.

c. Numerous water-vapor bands partially absorb radiation in the infrared. Parts of these bands may become semi-transparent in dry climates.

d. Impurities in the atmosphere such as smoke or dust produce an absorption of unpredictable nature. If moisture is present these impurities may induce condensation of droplets, which alter the absorbing properties of the atmosphere in an unpredictable way.

The extinction is particularly important in two fields : photometry and spectroscopy. The effect on spectroscopy is to increase exposure times and to limit the usable spectral range. By chosing a site with a high elevation, the useful range can be extended towards the ultraviolet by several hundred angstroms closer to the limit set by the ozone.

For photometric work, it is, of course, desirable to have the extinction as low as possible. However, it is more important that the extinction is constant with time, and that it does not depend on the azimuth. For fundamental photoelectric work, constancy of the extinction is required for practically a whole night. Furthermore, it should be the same in all directions, and the extinction coefficient should be proportional to the air mass. Magnitude standards over the entire sky, free of systematic errors, can be set up only if these conditions are fulfilled. Once such standards are available, the requirements as far as the constancy of the extinction is concerned are no longer so strict. The standards themselves can then be used to check on variations of the extinction, or on its dependence on the azimuth. The necessity for excellent extinction measurements cannot be over-emphasized for precise, reliable photometry.

4. **Brightness of the sky background.** — The importance of the brightness of the sky background on faint star work is shown in foot-note, p. 54. There are a number of components that contribute to the brightness that would be observed from an observatory outside of the solar system, due to scattering of light by interstellar matter and unresolved stars. To this is added the Zodiacal light. Their total effect will be the same over the entire earth. An important contributor originating in the terrestrial atmosphere is the auroral phenomena. Auroral intensities vary greatly with time and are, on the whole, a function of the geomagnetic latitude.

The contributions mentioned above originate outside the atmosphere, or in the upper atmosphere. An important contribution of local origin comes from the light scattered in the lower atmosphere. The scattered light of the interstellar and general star background is of minor importance. Scattered moonlight, however, can greatly increase the brightness of the background. The component due to Rayleigh scattering is dependent on the phase of the Moon, on its position in the sky, and on the elevation of the site. Another contribution comes from scattering of haze, dust, or smoke particles. This contribution may exceed the Rayleigh component. Finally there is the night sky airglow, which consists of emission radiation from many bands due to molecules, and from a smaller number of lines due to atoms.

The component of the sky background intensity originating in the lower terrestrial atmosphere can be expected to be correlated with the extinction, since it is the same particles that produce both effects. In fact, the sky background intensity may be a very good indicator of the composition of the atmosphere, since an increase of one magnitude in the background intensity may mean an increase of only a few hundredths of a magnitude in the extinction. It has been mentioned that a slight increase in the extinction coefficient, due to impurities in the atmosphere, is not of great importance. The increase in the brightness of the sky background during bright Moon phases, due to the same impurities, however, can be of great importance, since it determines the limiting magnitude to which one can work during that time.

IV. — General considerations concerning seeing and scintillation.

1. **Summary of observational facts.** — Although some of the most systematic and intensive studies of seeing and scintillation were undertaken only within the last decade, quite a number of important facts were previously known as the result of visual observations by astronomers. For instance, it is well known that in telescopes of small aperture ($<$ 15 cm) the seeing appears to have two components, one that

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may be described as a blurring of the image, the other consisting of an irregular motion of the image as a whole. The motion is often the more pronounced component. In telescopes of large aperture (> 100 cm), usually only image blur is observed, often of much larger dimensions than the blur observed at the same time through small apertures. All effects increase with zenith distance. At some observatories seeing conditions seem to be correlated with certain weather conditions. Unstable weather or a rapid temperature drop are usually accompanied by poor seeing. Much knowledge has been gained about scintillation by systematic investigations, especially of one particular phenomenon, namely the " twinkling " observed with the naked eye. The dependence of its amplitude and frequency on the zenith distance is often striking. Two effects, which can readily be observed, are of particular interest: (1) planets generally do not twinkle unless very close to the horizon, and (2) the twinkling disappears when observations are made with binoculars, or with larger apertures. In reality, intensity fluctuations are still present, but their amplitude is then too small, or their frequency too high to permit visual detection.

On the basis of these few observational facts, one can readily develop a simple model of the turbulent atmosphere that is capable of explaining them. The theory indicates that the two phenomena, seeing and scintillation, are of a different origin, and hence that they can be treated separately. It is therefore convenient to present the model first, before the two phenomena are discussed in more detail.

2. **Discussion of simple models of the turbulent atmosphere.** — Although elaborate theories are needed to understand fully all turbulence phenomena, a rather simple model can give a good insight into the seeing problem, and it will suffice for the purpose of this paper.

A simple optical consideration will show why the seeing appears to have two components, motion and blur, and why their relative importance depends on the telescope aperture. Let us consider the effect of a spherical cell of air having a density different than its surroundings. For simplicity we assume homogeneous density within the cell. We let this cell pass through a beam of parallel light received by a telescope. If the aperture of the telescope is much smaller than the diameter of the cell, then the effect will primarily be a deviation : the image observed in the telescope will show an undulating motion. A slight defocussing may also be observed at the same time. Expressed in terms of seeing, image motion and, possibly, some blur can be observed. If, on the other hand, the aperture is much larger than the diameter of the cell, then part of the light received by the telescope will be observed as defocussed. In terms of seeing, the effect is that only some blur would be observed. Thus it can be understood why, with small apertures, motion and blur are observed, while with large apertures essentially only blur is seen. The phenomenon means that the largest telescopes have apertures exceeding the diameters of the largest, optically effective, turbulence elements in the air. The conclusion remains correct even if the simplifications mentioned above are dropped. The cell does not have to be spherical, nor need homogeneous density inside. The most important characteristic is its dimension relative to that of the telescope aperture.

On the basis of the simple model described, one can design experiments that should yield information about the sizes of the turbulence elements and about their distance from the telescope. Suppose one has two identical telescopes side by side, with a variable separation. By some optical means the images of both telescopes, pointing at the same object, are brought into the same eyepiece and can be observed simultaneously. Then if the two objectives are very close (ideally superimposed) the images will show synchronized, irregular motions due to seeing. As the separation is increased the motions will become more and more de-synchronized, and they will finally be entirely independent.

This result can be interpreted in the sense that the separation of the objectives has surpassed the dimensions of the largest turbulence elements. Thus one can get some information about their *largest* linear dimensions, and probably also about their *average* linear dimensions. In order to obtain information about their angular dimensions, a device is needed that permits the simultaneous observation of pairs of stars of different angular separation through the same objective. With such a device one would observe that close pairs of stars show synchronized motion, while with increasing angular separation the synchronization vanishes. Thus information about average and maximum *angular* size of the turbulence elements can be obtained. Comparison of these with their *linear* dimensions would also give an estimate of their distance from the telescope.

Another simple consideration leads to the conclusion that seeing and scintillation originate in different layers of the atmosphere. Let us consider the effect of a thin layer of a turbulent air mass at a certain elevation above ground. Parallel light, or a plane wavefront, arrives at the top of the disturbance. After passing it, the light is no longer parallel but shows a certain angular distribution around its original direction. It is readily seen from figure 3 that this angular distribution remains the same anywhere below the turbulent layer. Thus concentration and dispersion of light occurs below the turbulent layer, the converging rays producing a sort of a focussing effect. This effet increases with increasing distance from the turbulent layer, at least until the rays begin to cross each other. Thus non-uniform illumination of the ground is produced. The whole pattern of non-uniform illumination can be considered to be in motion with respect to the ground. This motion leads to variations in the intensity of a star observed from a fixed point, or to scintillation. Two deductions can readily be made on the basis of this result, and they are verified by observation :

a. Turbulence close to the ground is rather ineffective as a source for scintillation. In fact, there is observational proof that most of the scintillation is produced in layers several kilometres above the ground.

b. Due to integration of the illumination pattern moving over the ground, the amplitude of the scintillation should decrease with increasing aperture.

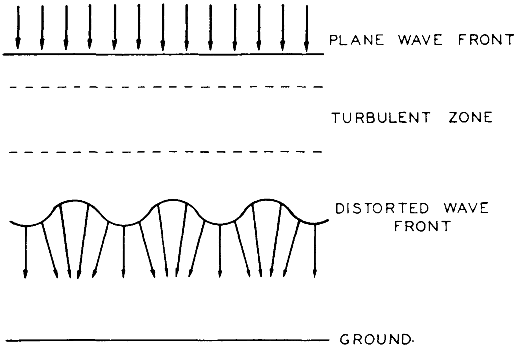

Fig. 3. — Effect of a turbulent zone on a wave-front.

From the above, it is reasonable to assume that scintillation originates in the higher atmosphere where its density is low, and hence the angular deflections of light small. On the other hand, the lower atmosphere with its higher density can produce larger angular deflections, which lead to large seeing effects, but only to small scintillation effects. If this is true then seeing and scintillation may be treated separately.

V. — The study of seeing phenomena.

1. **General remarks.** — As already mentioned, the kind of seeing observed depends on the aperture of the telescope used. In small apertures the atmospheric turbulence will affect the image structure as well as its position. For given seeing conditions, the relative sizes of the two components vary with the aperture, in the sense that with increasing aperture the size of the image grows at the expense of its motion.

There are many different techniques for making seeing observations. They employ visual, photographic, and photoelectric means. Which method to apply depends on practicality, and on the purpose of the investigation. The aim here is to describe methods by which seeing conditions at existing observatories, or at new sites, can be determined and expressed quantitatively, in order to make possible comparison of seeing quality at various places. Consequently, only those techniques are considered that may serve this purpose. Even with regard to these, no claim for completeness is made.

If smaller telescopes are considered, the comparison of the seeing quality at different sites is not so simple as it may appear at first sight. The two components of the seeing may have different importance for different types of astronomical observations. Thus for double star or planetary observations the image motion is of little consequence, while for meridian circle observations the motion is the more important component. For photographic or photoelectric observations both components are equally important. Thus one site may be superior for one purpose, and inferior for another. The most general case suitable for an intercomparison seems to be the *resolving power* obtainable with telescopes of large aperture. We shall show how this quantity can be calculated from observations made with certain small telescopes. In the following paragraphs we shall describe suitable equipment, and observing and reduction procedures for observations that permit the determination of the resolving power, as limited by the seeing, which can be obtained with large-aperture telescopes.

The discussion will be made in two sections, (*a*) the quantitative measurement of seeing with telescopes of large aperture, and (*b*) quantitative measurements with stationary or portable equipment of small aperture. With these methods, comparisons between large and small telescopes can be made, so that data obtained only with small telescopes can be used to calculate what would be observed with large telescopes.

2. **Seeing observations with large apertures.** — Large apertures with respect to seeing are those exceeding about 60 inches. With such apertures, nearly always only an increase in the image size, caused by the seeing, is observed. Motion of the entire image is rare, and always is considerably smaller than the diameter of the image. Actually, the lower limit of the aperture could in most cases be smaller, perhaps down to 30 inches, but it seems safer to use the higher value. Since only image structure effects are expected with large apertures, only consistent methods for expressing the " blur " in a quantitative way are needed.

Except in rare cases, the image structure observed is determined by the seeing rather than by the diffraction pattern corresponding to the aperture. Of course, defects of the image due to malalignment or distortion of the optical components of the telescope may exist. Apart from optical defects the images will, if averaged over sufficient time (a few seconds), show radial symetry. Also, deviations from radial symetry will occur close to the horizon, due to atmospheric dispersion. This effect can be avoided by using suitable color filters. A numerical description of the radial intensity distribution is the quantity (or quantities) needed. A practical way of expressing the image quality would be to quote diameters including perhaps 50, 70 and 90 % of the light of the star. If it is assumed that the images has a Gaussian light distribution, a single diameter is sufficient.

a. Visual observations. — Although the images have fuzzy fringes, the eye usually sees a disk of a certain diameter. The diameter seen, however, depends on the magnitude of the star. Diameters of stellar images can be estimated consistently by experienced observers, but such estimates evidently can be useful only if the magnitude effect is removed. With certain precautions this effect can be greatly reduced. It is important for such observations that a sufficiently high magnification be used, such that even the nucleus of the image has a disk-like appearance. The surface brightness of the central portion of the image must be sufficiently high but not excessive. In practice it would be best to keep the surface brightness of the centers of the different images within a small range, when seeing estimates are made. Meeting this condition may require change in magnification, and in the apparent magnitudes of the stars, according to the existing seeing conditions. This is a safer approach to get a consistent set of estimates than, for example, to have nearly the same apparent magnitudes for all the stars observed.

A better visual method would appear to be to determine the actual resolving power of the telescope by observing double stars of different separations. Pairs of nearly equal magnitude for the two components should be chosen. But this is a time-consuming method, because many double stars may have to be looked at before one can decide at which angular separation the resolution fails. Such observations would have only a small magnitude effect. However, another problem is encountered : with poor seeing the image structure and thus the resolution is highly variable. Even on poor nights one may by chance see good images for a fraction of a second. The extremes in the resolution are of little interest if one is concerned with the general quality of a night or a site. The average resolution over a period of several minutes is, for most purposes, the quantity that is most important. This is to say that one would have to look for a double star that is resolved half of the time. Also, the capability of seeing two individual stars in a more or less merged mass of light is to a great extent a matter of experience of the observer. Therefore, attractive as this method may seem at first sight, it may be too difficult to make it give consistent results.

Visual observations of details of the lunar surface or of planets probably could be developed into a sensitive method, although it would be impractical because such objects are not available at all times.

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Any of the visual methods mentioned will yield a quantity in seconds of arc, which one may call the visual seeing diameter, and it would be of interest to know how much of the light of a star is included within this diameter. This can be done by a photoelectric method, which is discussed later. Also, it would be of interest to know what these diameters mean for certain observing techniques. Thus, for a given visual diameter, what is the minimum separation of a double star that still can be measured, and with what accuracy ? Or, for photoelectric observations, what size of diaphragm has to be chosen to avoid seeing interference ? Or, what is the limiting magnitude obtainable by photographic techniques ? Such questions can be answered by calculation, provided the approximate image profile is known. Otherwise, the answers have to be found by experiment.

b. Photographic observations. — The diameters of photographic images given by telescopes of long focal length are strongly affected by the seeing. The seeing effect is independent of the aperture, provided the latter is not so small that the diffraction pattern contributes to the image structure. Hence estimates of photographic diameters should also yield information about the seeing conditions. Here, however, one encounters a formidable magnitude effect. In fact, for all practical purposes the images grow indefinitely with increasing brightness of the stars. A standardization of the measurements, based on a density in the center of the photographic image that corresponds to the optimum surface brightness in the center for visual images, is not practical, because for images bright enough to make safe visual estimates the density in the center of photographic images is already close to saturation and hence insensitive for standardization purposes. The size of the images at the threshold of the plate may be more suitable for seeing estimates. It should be kept in mind, though, that these threshold images correspond only to the brightest part — the nuclei of the images — and hence have diameters that contain only a small fraction of the light of the stars.

A fully objective method utilizing the slope of a part of a curve relating iris photometer readings to apparent magnitudes has been suggested by the author. The method uses the fact that, for iris photometers which give a reading proportional to the area of the iris diaphragm, the calibration curve (photometer reading versus magnitude) is linear over a large range, with a slope proportional to the square of the image diameter. This method is capable of a very general application, since it should give identical results for telescopes of all apertures, so long as the focal length is sufficiently large and the grain of the plate sufficiently fine, that the image structure is determined only by the seeing. Use of similar plate material, and standardization of the processing of the plates are essential, however, to insure consistent results.

Photographic images of long focus telescopes can also be used to determine the intensity profile of the seeing image. For this purpose the images have to be scanned in a density microphotometer, and the densities then transformed into intensities. A magnitude sequence in the area covered by the plate serves the purpose of establishing the relation between densities and intensities. Photographic profiles, however, may not give the true intensity profiles of the stellar images, because of the intermittency effect acting on the fringes of the images where exposure takes place only at times when the seeing image is particularly large. Within the accuracy desired, this effect, fortunately, is negligible. An intensity profile photographically obtained would be useful in calibrating the visual seeing diameter.

Photographic records of transient image structure can be obtained by very short exposures (1/100 of a second or less). Electronic image intensifying techniques could be very useful for the study of the seeing phenomenon, but they do not readily serve the purpose of determining the average seeing quality of a site.

c. Photoelectric methods. — Two methods of photoelectric seeing determinations have proven to be useful for impersonal study of seeing conditions : image scanning, and measurements through a series of diaphragms. For such investigations most ordinary photoelectric photometers can be used. Usually only a few additions are needed, such as some extra diaphragms, or a slit. Thus these methods can be applied intermittently during regular photoelectric observing programs.

A scan through an image with a diaphragm much smaller than the size of the image gives immediately an intensity profile, but its effective application requires a very large telescope aperture and the brightest stars, in order to keep the signal-to-noise ratio sufficiently high that the scanning can be done with adequate speed. Accurate tracking of the telescope during the scanning is also essential. A more practical method is to scan the image with a slit whose width is much smaller than the diameter of the image. If the slit extends in the direction of right ascension, and the scanning is done in the direction of declination, the recording becomes insensitive to tracking errors, at least to a certain degree. The reduction of the observed profile, obtained by scanning in one coordinate and integrating perpendicular to it, to a radial profile involves the solution of an integral equation. Let x be the distance of the slit from the image center, and $\mathrm{S}(x)$ be the photometer deflection when the slit was at the distance x. Furthermore, let $\mathrm{I}(r)$ be the radial intensity distribution, and r the distance from the image center. Then

$$\mathrm{S}(x) = 2\int_0^\infty \mathrm{I}\left[(y^2 + x^2)^{\frac{1}{2}}\right] dy. \tag{1}$$

The function S (x) is observed, and the function I (r) has to be found from the above equation.

A much simpler approach is to measure the stellar light through a series of diaphragms of different size. The use of a small iris diaphragm would be even better. In this case interpretation of the results in form of a radial intensity distribution involves no mathematical manipulations.

3. **Seeing observations with small telescopes.** — As already mentioned, in small telescopes the seeing is observed to have two components : an irregular motion of the image, and a blurring. The deviations of the position of the image from its average position are of short duration, usually a fraction of a second. At times it has also been mentioned that there exists a slow motion, termed " wandering ", with a time-constant of minutes and amplitudes of the order of 1 second of arc. Evidently its declination component could be best observed, because a sidereal drive of a small telescope can hardly be made accurate enough to allow the detection of motions of such a small amplitude. Even in declination, the requirements of precision for the bearings needed for such a study are difficult to fulfill. Observations of stars very near the celestial pole with a stationary telescope would seem to be a good method to study this " wandering ". This condition puts a latitude limit on such investigations. If the wandering is due to very long waves in the wavefront, it will be the same in telescopes of all apertures, and its effect on almost any type of astronomical observation will be eliminated by even the simplest guiding method. Consequently, the following paragraphs deal only with short-period effects.

a. Image diameter estimates. — The image diameters can be estimated in the same way as with large apertures, which means that the remarks made in Section V (§ 2 *a*) also apply here. However, with small apertures the fact has to be taken into account that the image size is not only determined by the seeing, but also by the optical properties of the telescope objective. With perfect optics, the diffraction pattern is the limiting factor to be considered.

If one estimates the size of the central disk of the diffraction pattern, one gets a diameter d_i that contains two components : the natural size d_n of the diffraction image observed under perfect seeing conditions, and the seeing diameter d. The central disk has a theoretical profile that in a first approximation may be described as Gaussian. If this is the case for the seeing disk also, then the following equation applies :

$$d_i^2 = d_n^2 + d^2. \tag{2}$$

The value of d_n is best determined empirically by observing stellar images under the best seeing conditions. It should be emphasized that a_n is not the diameter of the first dark ring of the diffraction pattern; the latter, of course, can be calculated from the aperture of the telescope. The value of d_n will be smaller for a high quality lens.

A rather sensitive but qualitative method of estimating seeing effects in small telescopes has been proposed by Danjon. It is based on the appearance of the diffraction pattern. Danjon's scale in detail is:

5,0. Perfect images, without perceptible deformation and scarcely agitated.

4,0. Complete diffraction rings, containing moving condensations; slight agitation.

3,0. Broken diffraction rings; central disk has badly defined and wavy edge; moderate agitation.

2,0. Diffraction rings disappearing or absent; lively agitation.

1,0. Star image tending towards planetary appearance.

With an empirically determined curve these values are transformed into " turbulence angles ". Different curves have to be used for different apertures. A detailed discussion of the method has been presented by Dommanget. The turbulence angles determined by this method are, however, of such small value — only a few tenths of a second of arc for poor seeing — that they cannot be reconciled with seeing image diameters obtained with other methods. A recalibration of this method, which in addition to its sensitivity is simple to apply, and uses equipment suitable for field work, is highly desirable.

It seems that for Danjon's method an optimum aperture exists. If it is taken too small, the diffraction pattern will be too large, and hence not sensitive to small seeing effects. If it is too large, the diffraction pattern will never be seen resolved, because even small seeing effects would make it disappear. An aperture of the order of 25 cm seems to be near the optimum.

b. Image motion estimates. — In a telescope equipped with a sidereal drive the image motion appears as an irregular " dancing or jumping " of the image about the intersection of guiding crosshairs. The amplitude of the motion can be expressed quantitatively in a number of ways. The most practical way seems to be to estimate the average deviation of the image from the crosshair. To be more specific, a diameter should be given such that the image stays half the time within a circle of the given diameter. One may also wish to estimate the maximum deflection. Then, however, it would also be necessary to know how often these maximum deflections occur. Furthermore, rapid and large deflections will be seen more readily with bright stars than with faint ones. Thus one may encounter a magnitude effect. This effect is less apt to be present in estimates of the average motion. In fact, tests by the author and by other observers did not indicate any magnitude effect at all in the estimates of the average motion.

If no sidereal drive is available, one can let a star drift along a crosshair and estimate its deviation from a straight line motion. Experience has shown that it is even better to let the star drift between two crosshairs of known separation, and to estimate the width of the path of the star.

Either of the methods mentioned for measuring image motion will be falsified by motions or vibrations of the telescope. A rigid mounting and a dome for wind protection are necessary. In field testing programs,

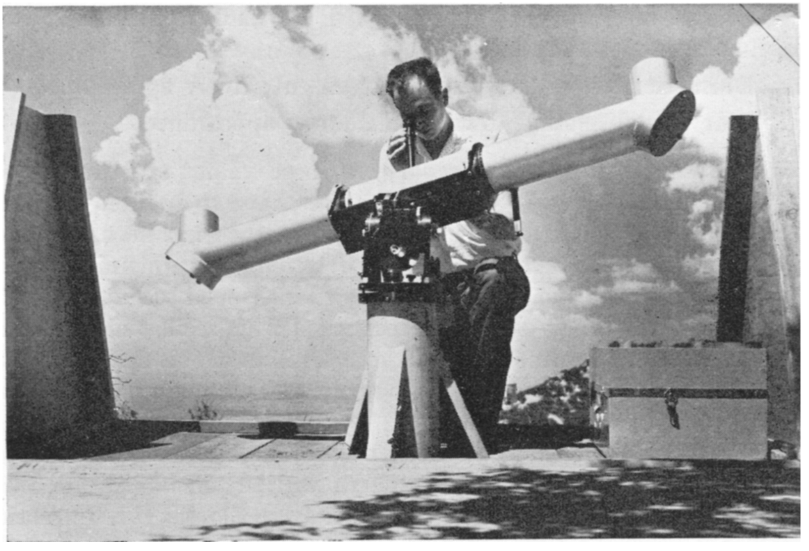

Fig. 4. — A double-beam telescope.

image motion can be measured by these methods only under calm conditions. With a windscreen one may be able to observe up to about 3 miles/h. With a different type of telescope this difficulty can be reduced considerably. In section IV (§ 2) observations through two small apertures of a variable separation have been discussed. It is stated there that, beyond a certain separation between the two apertures, the motions observed through them will be de-synchronized, or independent. The necessary separation for independent motion seems to be about 100 cm. This fact can be utilized in a telescope constructed like a rangefinder, with two objectives. Figure 4 shows such an instrument, and figure 5 shows its optical design. The two objectives O_1 and O_2 form two images in their common focal plane, which are observed simultaneously through a microscope. With a properly adjusted instrument — the normals of all mirrors have to be in the same plane — the separation of the two images of a star is independent of their position in the field of the eyepiece, and therefore the images will not be affected by motions of the telescope tube. Of course, all optical components have to be rigidly mounted within the tube, in particular the two large mirrors R_1 and R_2. With such an instrument image motion can be observed as a relative motion of one image with respect to the other. Since the motions caused by the seeing are independent for the two images, one gains 40 % in relative motion as compared to a single objective instrument. Such instruments have been used successfully in field tests in a 15 miles/h wind without a windscreen.

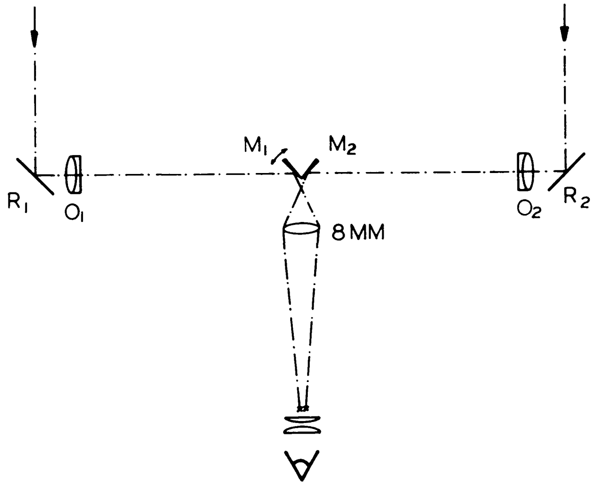

Fig. 5. — Optical sketch of the double-beam telescope.

The methods of observing image motion mentioned so far require visual observations. Photographic methods can be applied if permanent records rather than visual observations are desired. With single or double objective instruments one can place a photographic plate in the focal plane and produce star trails. Guided photographs are not suitable for image motion determinations. While this method seems very attractive, it has one very serious difficulty. The range of density within which irregular deflections of the trails can be measured is not very large. If a star is too bright the trail will become too wide to show the motion perpendicular to the direction of trailing. If the star is too faint the plate will not show rapid and large deflections. The proper magnitude to be used depends on the image diameter which is affected by the blurring. Hence the apparent magnitude to be chosen for trailing is dependent on the seeing conditions themselves. Another difficulty is that not until the plates have been processed will the observer be able to judge the quality of his observations. Combined photographic and visual observations, preferably with the same instrument, seem to be the best solution.

c. The ideal equipment for field work. — Field equipment for remote sites should come in small parts of such low weight that they do not depend on transportation by vehicles. Furthermore, the equipment should not need costly protecting buildings. Also it should be independent of electric power, except for batteries or small motor generators.

The equipment must permit one to observe the entire seeing effect (motion and blur). Since apertures of 100 cm are out of the question, and blur and motion must be separately observed, the same instrument cannot be used. This requirement leads to two types of instruments: (i) a telescope with 40 cm aperture for the observation of blur. It appears that an instrument of this size is near the limit of what can still be considered as field equipment. (ii) A rangefinder type, or double-beam instrument with small apertures, so that all seeing effects appear as image motion. Here, of course, one is limited to stars of bright apparent magnitude. Also, if the diffraction pattern becomes too large, small motions can no longer be detected. Apertures of about 10 cm seem to be the lower practical limit. With such an instrument the blurring effects of turbulence elements much smaller than 10 cm cannot be detected, but this limitation may not be very serious. Turbulence elements of diameters of a few centimeters are readily created close to the ground, or by small obstacles near the telescope. Thus their observation with field equipment near the ground may not represent what a large telescope at the same site, but placed higher in a dome, would show.

4. **Reduction of seeing observations.** — Two steps have to be taken to reduce seeing observations to a common system: (*a*) reduction to unit air mass, and (*b*) reduction to a theoretically infinite aperture. In the case of large apertures only the reduction to the zenith is necessary.

a. Reduction to the zenith. — If atmospheric turbulence elements produce a Gaussian light distribution in an image, then their combined effect should be proportional to the square root of their number. This condition means that the reduction of seeing effects, if expressed in seconds of arc, can be done simply by dividing them by the square root of the secant of the zenith distance. Russian astronomers have conducted an extensive series of tests in order to determine empirically the zenith distance dependence of seeing effects. Although they find considerable variation in this dependence from night to night, their results indicate that, on the average, the above-mentioned relation holds.

b. Reduction to large apertures. — For observations with small apertures the blur and the motion have to be combined in order to give the total seeing effect. If combined properly they should reproduce observations made with large apertures. A list of definitions will facilitate this discussion.

d_i, image diameter observed through a small-aperture objective;

d_n, natural image diameter given by a small-aperture telescope; i.e. perfect seeing image diameter;

d, seeing image diameter computed from equation (2) for small-aperture telescope;

D, seeing image diameter computed for large aperture;

m', image motion observed with a single small-aperture telescope;

m'', relative image motion observed through a double-beam small-aperture telescope.

Furthermore, D_0, d_0, m'_0, and m_0 are the values of D, d, m', and m'' reduced to the zenith.

If in all estimates of diameters, or of image motion, the same fraction of light is included, then one would expect the relation

$$D^2 = d^2 + m'^2 \tag{3}$$

to hold. As already mentioned, this superposition of the two components of the seeing assumes an error-type light distribution in the stellar image. However, it is more likely that, in the various types of estimates, not exactly the same fraction of light is included. A relation of the type

$$D^2 = a^2 d^2 + b^2 m'^2 \tag{4}$$

takes this possibility into account. Here a and b are constants to be determined empirically. Evidently, in case the motion estimates are made with a two-aperture instrument, the constant b will be different. Theoretically, one would expect it to be smaller than in the case of single-aperture observations by a factor of about 0.7.

By taking the reduction to the zenith into account, the final and complete reduction formula for seeing observations becomes

$$D_0^2 = \frac{1}{\sec z}(a^2 d^2 + b^2 m'^2). \tag{5}$$

5. **Statistical analysis of seeing observations.** — It may seem at first glance that the distribution of D_0, or its average value, would fully characterize the quality of a site. However, one can get a more representative description by also taking the number of clear hours or nights into account. An example may illustrate : Suppose that site A has only few clear nights, but all with good seeing, while site B has many

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clear nights with poor seeing, on the average. The average value of D_0 would favor site A, the number of clear nights, site B. In case the distribution of D is as shown in figure 6, then it is obvious that site B

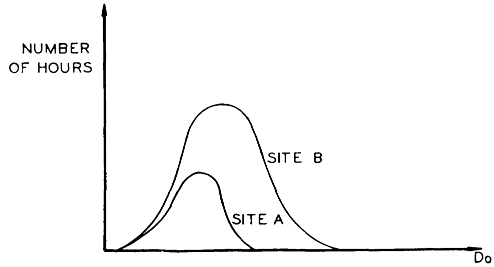

Fig. 6. — Various statistical distributions of image diameter.

is the better one. In case the situation is as shown in figure 7, then one has to attach weights to both seeing and number of clear nights in order to determine which site offers the best observing conditions [1].

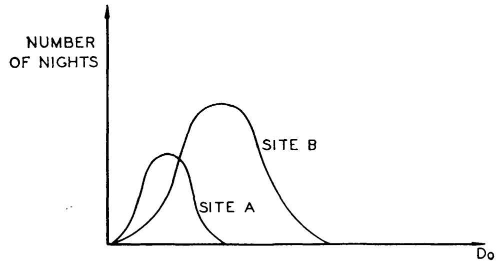

Fig. 7. — Various statistical distributions of image diameter.

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[1] The effect of the seeing on photoelectric work with faint stars can readily be calculated. Suppose that in order to accommodate the entire seeing disk a diaphragm of a radius ρ has to be used. Furthermore, let the emission of the sky background be s quanta per time of observation per square second of arc, while at the same time the star contributes N quanta. Then for the reading D^* on the star we have

$$D^* = N + \pi\rho^2 s,$$

while for the sky background D^s we have

$$D^s = \pi\rho^2 s.$$

These quantities have statistical errors μ^* and μ^s, respectively, which can be calculated from

$$\mu^* = \sqrt{D^*} \qquad \text{and} \qquad \mu^s = \sqrt{D^s}.$$

The observer has to calculate the observed value of N by forming the difference between the observed values of D^* and D^s. Thus for μ^N, the statistical error of the calculated value of N, the value

$$\mu^N = \sqrt{\mu^{*2} + \mu^{s2}} = \sqrt{2\pi\rho^2 s + N}$$

VI. — The study of scintillation phenomena.

1. **General remarks.** — In Section III it was stated that the scintillation phenomenon is a relatively minor factor for most types of astronomical research. Since this conclusion is especially true for large apertures, a short treatment of the subject will suffice for the purpose of this paper.

In Section IV (§ 2) it was indicated that most of the scintillation can be expected to originate in high layers of the atmosphere. This condition means that, in contrast to the seeing, the topography of the terrain is unimportant. One can expect that the scintillation is equal for large areas. Consequently, if a relatively inaccessible site is to be studied, the scintillation studies can be made from a nearby site with better access possibilities, and it becomes possible to use conventional rather than field equipment.

2. **Equipment for scintillation studies.** — It has been mentioned before that the amplitude of the scintillation depends on the frequency as well as on the aperture. The dependence on the aperture can be determined either by using a series of diaphragms on a telescope of relatively large aperture, or by a two-aperture arrangement with variable separation. The filtering of various frequencies, of course, is done by the electronic equipment. Actually, only the low-frequency scintillations of about 1 c/s are of interest. Higher frequency scintillations do not interfere with any of the current techniques of astronomical observations.

In all cases, the detection of the scintillation has to be done by one or two photoelectric cells. The noise of the output of the cell contains the information about the scintillation. This noise can be displayed or measured in a number of ways. The most straightforward arrangement is a recording galvanometer or potentiometer of high speed,

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is found. Of more significance is the statistical error of N expressed as a percentage of N itself. Its value μ can be computed from

$$\mu = 100 \frac{\sqrt{2\pi\rho^2 s + \mathrm{N}}}{\mathrm{N}}.$$

For very faint stars the approximation

$$\mu = 100 \frac{\rho}{\mathrm{N}} \sqrt{2\pi s}$$

may be used. The last equation shows clearly the importance of the seeing for the determination of magnitudes of faint stars. In fact, the last equation shows that the accuracy with which such magnitudes can be determined is proportional to the radius of the diaphragm, which in turn is proportional to the radius of the seeing disk.

coupled to the photocell with a suitable amplifier. The amplifier has to be noise-free, has to select the desired frequency band, but does not have to be free of drift.

In most photoelectric photometers the optical design is such that an image of the primary mirror (or objective) is projected on the photocathode. Thus seeing effects and small errors in the sidereal drive do not affect the result. However, for scintillation studies it has to be kept in mind that the light distribution as found on the primary mirror will be repeated on the photocathode. Practically all cathodes have a non-uniform sensitivity over their surfaces. The non-uniform light distribution, which is essentially the phenomenon to be studied, is superimposed on the sensitivity distribution of the cathode and thus enhanced. The safest way to avoid this effect is to select uniform cathodes.

3. **The shadow bands.** — In Section IV (§ 2) it was stated that a non-uniform light distribution on the ground may be expected. The motion of this light pattern with respect to the ground results in the scintillation phenomenon. The light distribution on the ground can also be demonstrated in another way. Anywhere in the lightbeam, except near the focus, a cross-section will show practically the same light distribution as it is received by the primary aperture of the telescope. If a stellar image is observed far out of focus, a moving pattern of bright and dark parts is seen. They are referred to as shadow bands, or flying shadows. Visual observations of the shadow bands give a rough idea of the scintillation amplitudes at low frequencies.

VII. — The study of the atmospheric extinction.

1. **Equipment.** — At sites with good transparency, particularly at high altitudes, the extinction in the visual region is so small that visual observations are not precise enough to determine its value or its variations. Photoelectric equipment is needed for its study. The extinction can be determined with the help of the brighter stars. Hence a relatively insensitive photometer attached to a small telescope is suitable. A telescope with an aperture of about 10 cm, a photomultiplier tube, and an accurate D. C. amplifier, with all currents from batteries, can fulfill the purpose quite well.

For field tests at various sites over a long period of time, it would be convenient to have the color characteristics of the equipment (expressed by a curve relating the sensitivity of the equipment to the wavelength) remain constant. From this point of view a refractor is to be preferred to a reflector, because the reflection coefficient of the reflecting surfaces of the latter is bound to change with time.

The requirements for the electronic equipment are those of ordinary photometers. The meter, or better the recorder, should allow one to read off the deflections with an accuracy of one half percent of the total scale, or better. Calibration of the sensitivity steps of the amplifier must be done with great care, since the photometer may have to work over a large range in temperature. A drift in the overall sensitivity of the photometer with the temperature, or due to aging of its components, may exist. This possibility can be checked by using an artificial light source employing as a standard a fluorescent material activated by a radioactive substance. However, the constancy of the brightness of this type of standard has to be checked. It is little known, apparently, that a number of these substances have a surface brightness dependent on the temperature. It is, of course, not the radioactive material but the condition of the fluorescent substance that is responsible for this change.

2. **Observations.** — The observations necessary for the determination of the extinction can be divided into two groups : (*a*) fundamental observations, and (*b*) check observations. The meaning of this grouping will be explained at the end of this paragraph.

All the extinction determinations are based on the assumption that the magnitude, m_o, free of extinction effects (in other words, the magnitude the equipment would measure if placed above the atmosphere) can be deduced from the observed magnitude, m, by

$$m = m_0 + k_m \sec z, \tag{6}$$

where k_m is the extinction coefficient at the zenith, and z the zenith distance. This assumption neglects the curvature of the earth's atmosphere. It is certainly a satisfactory approximation for zenith distances smaller than 70°. A similar expression applies to the colors, namely,

$$c = c_0 + k_c \sec z, \tag{7}$$

where c_o is the color that would be measured above the atmosphere, and c is the observed color. The remaining constant k_c, is the color extinction coefficient.

Actually, equations (6) and (7) apply strictly only to monochromatic magnitudes or colors. In practice the forms

$$m = m_0 + k_m(c_0) \sec z, \tag{8}$$

or

$$c = c_0 + k_c(c_0) \sec z, \tag{9}$$

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are more adequate. Often one finds the expressions

$$m = m_0 + (k'_m + k''_m c_0) \sec z, \tag{10}$$

and

$$c = c_0 + (k'_c + k''_c c_0) \sec z, \tag{11}$$

more satisfactory. The coefficients k''_m and k''_c are dimensionless and are usually found to be of the order of 0.000 to 0.040.

It should be noted that all coefficients, for example in equations (8) and (9), do not only depend on the extinction but also on the spectral response of the equipment, and, therefore, they may differ significantly from one kind of equipment to another, even if the same type of photocell and filters are used. It should also be noted that in all equations it is assumed that the extinction is a function of the zenith distance only, and not of the azimuth.

Fundamental observations have to be made when nothing is known about the colors or the magnitudes of the stars to be used for the determination of the extinction. In this case stars (or pairs of stars) have to be followed during the night over a sufficiently large range in zenith distance. The variation of their observed colors and magnitudes with the zenith distance allows the determination of their c_o and m_o values, as well as of the extinction coefficients k_c and k_m. Here the assumption has to be made that the extinction remains constant during the night. Observations of this type during a number of nights (or, better, many nights) are necessary to determine accurate values for m_o and c_o for each star. Subsequently, accurate values of k_c and k_m can be obtained for each observation.

Once the values of c_o and m_o are known for a sufficient number of stars, only check observations are necessary to obtain the values of k_c and k_m. A comparison of c_o and m_o with c and m for a given star can then directly yield the extinction coefficients. Under certain circumstances it may be necessary to observe pairs of stars to obtain k_m.

3 *a*. **Fundamental observations of colors.** — The procedure for fundamental color observations is evident from equation (7). The variables in this equation are c and $\sec z$. Since one is a linear function of the other, two observations of the same star at different zenith distances allow the determination of the two constants in equation (2). It is evident that the extinction must be the same during both observations. In case there is a time-dependent change in the extinction, one can still get an approximation to its average value by observing two stars: one rising, and one setting, at nearly the same time. Both stars should also change in $\sec z$ at about the same rate.

The most important data to be derived from fundamental observations are the values of c_o for a number of selected stars. It will be discussed later which types of stars should be selected. The c_o-value of a given star (naturally not a variable star) can be assumed to be constant for at least a certain period of time. In fact, so long as reflection and transmission coefficients of all optical parts, and the spectral sensitivity of the cathode, remain constant, the c_o-values remain constant also. Variations with time are to be expected from reflecting surfaces (except where total reflection is used). Therefore the use of refractor optics is of advantage. In case a reflector is used, one can at least assume that its color characteristics remain constant for a few months (except for the first couple of months after aluminizing). The c_o-values obtained on a number of nights have to be averaged to give their final values. How many nights are needed depends entirely on the agreement between the results of different nights; it should certainly be more than two. One should attempt to get the c_o-values with an accuracy of 0.004 magnitude, or better.

From equation (7) it appears as if the precision of the data will increase with increasing range in $\sec z$. This conclusion, however, is true only up to a certain point. It has to be considered that the accuracy of the measurements diminishes with increasing zenith distance, due to seeing and scintillation. Considerations concerning the non-monochromatic nature of ordinary color photometry, or of the curvature of the atmosphere, also limit the range within which equation (7) can be applied. Theoretical considerations, as well as practice, indicate that one should not go beyond $\sec z = 2.5$.

The sensitivity of most photoelectric equipment cannot be assumed to be constant over long periods, not even over several hours. However, a slow drift in the overall sensitivity of the photometer has little effect on color measurements, because these are essentially measurements of a ratio. Only rapid drifts would have an effect. These have to be eliminated by repeating the observations two or more times in succession.

3 *b*. **Fundamental observations of magnitudes.** — The purpose of fundamental observations for magnitudes is to obtain a consistent set of m_o-values. They will all have an arbitrary zero point, which, however, is common to all stars. All considerations discussed in paragraph 3 *a* apply here also, except for one: drift in the overall sensitivity will affect fully the measurement of an individual star. It can be eliminated by observing the change in the magnitude difference between two stars, one rising, the other setting. This change, together with the change in the difference of $\sec z$ between the two stars, gives the value of k_m. Effects due to a time-dependent variation in the extinction are more difficult to handle. They can be determined if one can check

the drift with a constant standard light source. Again, averaging the results of several nights is necessary in order to obtain the final m_o-values.

4 *a*. **Check observations for color extinction.** — With a known value of c_o, each observation of a color yields immediately the extinction coefficient, k_c [*see* equation (7)]. In case c_o-values for a large number of stars are available, the azimuth dependence of the extinction can be determined. Its variation with time can be checked by observing one star frequently.

The variations in the extinction from night to night can be studied by a simple method. From observations of the same star every night at the same hour angle, one gets the deviations of its observed color from the mean color. These deviations divided by sec z then give the variations in the extinction coefficient.

4 *b*. **Check observations for magnitude extinction.** — A quick and accurate check on k_m can be made in two ways, if m_o-values are available. In case the photometer sensitivity can be checked by a standard light source, the difference between m and m_o, divided by sec z, then gives the value of k_m. Otherwise, the magnitude difference between two stars at different zenith distances has to be used. The procedure is evident if one applies equation (6) for two stars, and forms the difference between the two equations.

5. **Selection of stars suitable for extinction determinations.** — In case the ultimate purpose of the observations is to give information about the extinction at various sites, there is no need to take into account the dependence of the extinction coefficient on the colors of the stars. One can confine such a program to stars of nearly the same color. Those most suitable seem to be early-type stars of unreddened or slightly reddened color. These stars have a smooth continuum in their spectra without any strong absorption features.

VIII. — The brightness of the sky background.

1. **General Remarks.** — In Section III (§ 4) and foot-note p. 54 it has been shown how important it is to have the sky background as dark as possible. Also the various sources contributing to the background brightness have been mentioned :

a. The sidereal background formed by large numbers of unresolved stars, galaxies and nebulae, as it would be observed from outside the solar system.

b. The Zodiacal light, as observed from outside the terrestrial atmosphere.

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c. Aurorae and airglow.

d. Light of extraterrestrial sources scattered in the terrestrial atmosphere.

e. Artificial light scattered in the atmosphere.

The first two components are always present, but fortunately their effects are small and stable. Aurorae and airglow are produced in the upper atmosphere. Their frequency of occurrence and their intensity do not depend on local topography. They are a function of the geographic position. Low geographic (or rather geomagnetic) latitudes are least affected by these phenomena. It has been suggested that the Van Allen radiation belts may be slightly luminous, but this possibility needs verification. In case this suggestion turns out to be correct, there may be only narrow belts on the earth with the darkest possible sky. At any rate, aurorae and airglow emit light only in certain spectral bands and lines. By choosing the proper spectral regions, their influence can be greatly reduced or avoided altogether. In the following paragraphs it will be assumed that this selection has been made. Components (*d*) and (*e*) depend on local conditions and have to be investigated on the sites.

2. **The sidereal sky background.** — The brightness of the darkest parts of the sidereal sky background is expected to be of the order of 21 or 22 magnitudes per square second of arc. This brightness means, for example, that in a photoelectric photometer having a diaphragm of 1 minute of arc in diameter, the sky deflection would equal that of a 13th magnitude star. A star of magnitude 15.5 would increase the deflection by only 10 %; ten stars of magnitude 18 would have the same effect. Thus the areas where the sky background is measured have to be selected very carefully. The diameter of the diaphragm has to be considered with equal care. Furthermore, the equipment must be sensitive enough to detect the sky signal with an accuracy of at least a few percent.

The sidereal sky background cannot be expected to be uniform over the sky, not even outside the Milky Way, the Zodiacal light, etc. Therefore, it would be highly desirable to establish some background standards over the sky. Not only must the positions of these standard areas be known with precision, but the diaphragm size (or sizes) must also be standardized. Only with such standards can an intercomparison of the sky background intensity at various sites be made.

3. **Measurements of scattered moonlight.** — The brightness of the sky when the Moon is present is a very sensitive indicator for the existence of scattering particles in the air other than the molecules of the air itself. In fact, the increase in background brightness produced

by haze can easily be an order of magnitude larger than its effect on the transparency. Small and simple equipment (the same as suggested for extinction measurements) is suitable. Only the brighter stars will interfere with such measurements, and they can easily be avoided. There are, however, a number of serious complications :

a. The intensity of the sky background depends on the azimuth and zenith distance of the Moon, as well as on the azimuth and zenith distance of the area where the measurements are being made.

b. The intensity depends on the phase of the Moon.

c. The scattered moonlight is polarized.

Allowance for these factors requires too many complicated reductions in practice, unless some standardization of the observing procedure is done. The following suggestions may serve this purpose :

a. Measurements are made only at the zenith. Thus a telescope with a fixed vertical tube can be used.

b. Use of a refractor and no other optics will avoid polarization problems.

c. Measurements are made only when the moon reaches certain values of the zenith distance, for instance, 30, 40, and 50°.

d. By measuring the sky background on dark nights one can determine at which sidereal time interfering bright celestial objects pass through the zenith.

e. By a simple shadowcasting device, the observer can determine when the Moon has reached the required zenith distance. Hence there is no need to calculate the times in advance.

The reduction of the material can be done by a semi-graphical method. For each zenith distance of the Moon, a plot of the measured intensities versus the phase of the Moon is made. The minimum for each phase, no matter from which site the measurements come, can then be taken as a standard. The minimum values probably will define a curve representing the pure Rayleigh scattering corresponding to the elevation of the site. The data from other sites can then be compared with the standard curve, in order to show the additional scattered light.

4. **The daytime sky.** — The appearance of the daytime sky may give some indication about the conditions at night, for when the daytime sky is free of haze it is often quite likely that the night sky will also be clean. A hazy day-sky, however, does not necessarily mean a hazy night-sky. Thus daytime observations have only a limited application. Nevertheless, they can serve to pre-select sites that have a good chance of having a clean night sky. The darkness or blueness of the daytime sky is a sensitive criterion for the presence of haze. Observations of the halo around the Sun serve equally well.

IX. — The meteorological conditions.

1. **Weather Bureau data.** — Meteorological data covering long periods are available for many parts of the world. They are collected by the meteorological services of all countries, by the air forces, airlines, ships, etc. Their primary purpose is to give the basis for forecasting and for determining conditions of importance for air and sea traffic. In a number of countries a network of secondary meteorological stations with recording equipment exists. The data of these stations, together with those of primary stations, are the material for weather statistics.

The nature of the data collected depends on the importance of the station. First-order stations accumulate data on barometric pressure, temperature, relative humidity, wind speed and direction, and precipitation, with continuously recording equipment. Cloud observations are made visually (in a few cases photographically) at certain times of the day. Second-order stations record temperature and humidity, and at times wind velocity. In addition to the ground observations, radiosonde observations, made from balloons with thermometer, hygrometer, and a radio-transmitter, give information about the vertical structure of the lower atmosphere, and about wind velocities aloft.

These data contain information of interest to astronomers. However, they must be selected and interpreted with care, in order to avoid false conclusions. The cloud observations are probably the most important ones for astronomical purposes. It has to be kept in mind, for example, that cloud observations made at meteorological stations are mostly daytime observations. In certain parts, for instance in the eastern United States and in most of Europe, there is little difference between daytime and nighttime cloudiness, and cloud statistics as published by a weather bureau can be directly applied. In semi-arid or arid countries, or in mountainous regions, this is not the case. The diurnal variation of the cloudiness may be very pronounced, for instance the summer afternoon showers in the southwestern United States are often followed by clear nights. This condition may mean that one has to go back to the original observations, and to use only those falling in nighttime, rather than using the monthly statistical results published by the U. S. Weather Bureau. Another reason may make this precaution necessary. Usually, the cloud occurrence is given as a certain percentage. This percentage may mean that during the entire month this fraction of the sky was covered (in others words, it was partly cloudy all the time), or that for this fraction of the month the sky was entirely overcast, while it was clear for the remaining fraction, or any distribution between these two extremes. It is evident that for astronomical purposes the statistics have to be made in a different way.

Precipitation data can help to locate areas of low cloud occurrence, but this correlation is not necessarily helpful. In certain areas the precipitation shows an even more pronounced dependence on the time of the day than does the cloudiness.

Of great interest are the data about the structure of the atmosphere. They can indicate at which level temperature inversions occur, and these are known to cause poor seeing. Good seeing conditions, therefore, can be expected only above the inversions. The radiosonde experiments also yield information about the jet stream, which also is known to produce poor seeing conditions.

2. **Cloud observations.** — The emphasis on cloud observations must be on those during night time, if one is concerned mainly with the conditions for stellar work at an astronomical observatory. In fact, daytime observations can be omitted, unless one is also interested in the living conditions at the site. Night time cloud observations can be made either visually or photographically. Visual observations are preferable, because the observer can appreciate the conditions of the entire sky, which is difficult to do photographically. Also, in case of a partial overcast, the observer can more readily judge whether the conditions are stiil suitable for some astronomical observations, than can be done on the basis of photographs.

When determining the fraction of the sky covered by clouds, astronomical observing practice should be taken into account. In particular, clouds low on the horizon need not be considered. In fact, it seems justified to neglect all clouds below 20^o altitude.

Concerning the types of clouds to be noted for astronomical purposes, it is sufficient to distinguish only two types, namely, those with sharply-defined edges, which are always dense and non-transparent, like cumulus, and clouds with fuzzy edges. The latter type is usually semi-transparent, like cirrus. In case of sharply-edged clouds, there is a good chance that the space between the clouds is actually clear. In the case of cirrus, however, thinner clouds of the same type, but not seen by the observer, may exist between the " clouds ". When thin clouds are present, one sees more cloud with the Moon up, than on dark nights.

a. Visual cloud observations. — The cloud observations made by the observer should give the fraction (in eights or tenths) of the sky above altitude 20^o that is covered by clouds. Furthermore, at least the simple type distinction mentioned above should be made. Also it should be noted whether the Moon was present or not.

On mountain sites the observer may find himself at times in a confusing situation, namely, when the wind drives pieces of fog over the mountain. At one moment the observer may find himself in the fog and consequently writes " 10 " for cloudiness (if given in tenths). A short time later the mountain may be free of fog for a moment, corresponding to a notation " o ". In this case the fraction of time during which the mountain is in the fog would be the proper notation.

b. Photographic cloud observations. — On a moonless night it is evidently not possible to obtain a photograph of clouds. Nevertheless, a photographic record of the clouds can be obtained by long exposures with a fixed camera. During clear periods the photographs will show uninterrupted star trails of uniform thickness. Interrupted trails, or trails with variable thickness, indicate that it was partly cloudy. Absence of trails, of course, means overcast. A movie camera, which with the aid of an external clock work advances the film by one frame at regular intervals, say every half hour, serves this purpose. The shutter of the camera stays open all the time. The frames exposed during daytime will, of course, be useless. As attractive as this method seems, it usually has the disadvantage of a limited field, 40 by 60° at best, but for statistical purposes such information is sufficient.

c. Cloud statistics. — Just as for the observations, the cloud statistics must take into account astronomical observing practice. The total number of clear hours is not the only figure that counts, because for a number of programs one fully clear night is more valuable than two half nights. Programs of photoelectric photometry are of this nature. Furthermore, a partly cloudy sky can still be useful, provided the cloud coverage is not excessive. Statistical information of the following type for every month, in order to reveal a seasonal trend, may serve most purposes :

(i) Percentage of clear hours;

(ii) Percentage of useful hours defined as those with 40 % or less clouds;

(iii) Percentage of useless hours defined as those with 50 % or more clouds;

(iv) Percentage of photometric nights, defined as those with at least three successive quarters with clear sky. Instead of three quarters of the night, one might require a minimum of six consecutive clear hours.

(v) Useful nights, defined as those which are not photometric, but have at least two quarters of the night in succession with 40 % or less of cloudiness.

(vi) Useless nights defined as the remainder of (iv) and (v).

3. **Temperature and humidity observations.** — The fluctuations of the temperature during a clear night are at least as important as its diurnal range. Hence a continuous recording of the temperature is to be preferred to observations of maxima and minima only.

In flat areas and in moist climate the temperature usually has the tendency to drop through the entire night (we refer only to clear nights). On dry mountain sites the temperature drops rapidly during the late afternoon and levels off a few hours after sunset. The temperature then stays constant through the night. Its value corresponds to the temperature of the free air at the same elevation. On sites not very high above the valley floor, and more so on low peaks above a large flat plane, one can often observe a second rapid drop of the temperature later in the night, with a lower constant temperature. At the same time, the valleys keep cooling off through the night, and they reach temperatures in the morning that may be well below those found at the same time on peaks 1000 or even 2 000 m higher. The drier the air, the more pronounced is this effect.

The effects described last can readily be understood. They are due to the rapid and effective cooling of the surface, and to the lack of moisture in the atmosphere. The surface cools by radiation. When the air is dry and no clouds are present, little of this radiation is absorbed by the air or reflected back to the surface. Without water vapor, the air is not an effective radiator, and it cools off very slowly by radiation. In fact, the temperature of the free atmosphere remains practically constant during the night. However, the air in contact with the higher places cools off rapidly and flows down into the valleys, and it is replaced by air of constant temperature drawn from the free atmosphere. The valleys therefore fill up with cold air during the night. The top of the cold air may easily reach an elevation of 1000 m or more during a night. Above this cold air one finds warmer air with temperatures corresponding closely to those of the free atmosphere. The boundary between the cold air drained from the mountains and the free air above it is often marked by conspicuous temperature inversion. In case some moisture and condensation nuclei are present, haze can form in the cold air. The top of the haze clearly marks the level of the temperature rise. This temperature inversion maintains itself during the day until the lower atmosphere has been warmed up enough to re-establish an adiabatic temperature distribution. If the warming up of the lower atmosphere continues after that, convection through the entire atmosphere begins.

The temperature inversion produced by the mechanism outlined above is a source of very poor seeing. On valley floors, or in large flat planes, one can expect to be below the temperature inversion during the entire night. Sites with insufficient elevation will have good seeing conditions for the first part of the night until the temperature inversion has reached their level. A rapid drop of the temperature, and deterioration of the seeing, mark the moment when the inversion climbed over the elevation of the site. The Boyden Observatory in South

Africa, or the Lick Observatory station on Cerro San Cristóbal in Santiago, Chile, are examples.

The average and the maximum elevation of the temperature inversion level are probably the most important data to be determined before other types of studies are made in a given area. Temperature measurements at various elevations, or even only visual observation of the top of the haze layer in the morning are sufficient. Such observations will indicate the minimum elevation for sites worth further investigation.

The relative humidity can also be a good indicator of the location of a site with respect to a stratification of the atmosphere. Moisture can readily radiate and thus reduce its temperature during the night. Thus moist air can be expected to cool off during the night and to sink down to lower levels. This process can easily be seen from mountain sites. Haze driven up to high elevations during the day can be observed to sink down during the first hours of the night. The relative humidity at low levels will increase during the night and may lead to dew or even fog in the valleys. The cold air draining down from the mountains helps the effect. At high levels the humidity will drop during the night. At an intermediate critical level one can observe an erratic behaviour of the relative humidity, usually stabilizing itself with dry conditions later in the night. For a given area the elevation of the critical level may depend considerably on the season. For good seeing conditions and freedom from haze, one has to choose sites above this critical level.

From the above discussion it is evident that a thermograph and a recording hygrometer are among the most important instruments for a site survey. The instruments should be placed in a wooden shelter (painted white), which protects them from direct sunlight but which lets the air pass through freely. On bare ground it is sufficient to place the instrument 1.5 m above the ground. In areas covered with shrubs or trees one may have to go considerably higher.

4. **Temperature and humidity statistics.** — The detection of effects related to a temperature inversion often cannot be done by statistical means, but only by a direct inspection of the thermograph and hydrograph records. A statistical analysis, however, will determine under what average and extreme conditions the equipment and the astronomers will have to work. Again, one has to consider which items affect the operation of astronomical equipment. In the first place, this means that statistics have to be made for clear periods only. The following data are of interest:

a. The diurnal range of the temperature, defined as the difference between the maximum of one day and the minimum of the following

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night (not the difference between the minimum of one night and the maximum of the following day). This figure is needed when insulation problems of buildings and domes are being considered. The average diurnal range, and its minimum and maximum value per month can be derived.

b. The average minimum temperature at night, and its highest and lowest values per month. These data give the average and the extreme operating conditions.

c. Of great importance is the behavior of the temperature at night. The total range of the temperature during night hours can easily be read off the thermograph records, and analyzed statistically. However, this figure alone is insufficient to indicate the stability of the temperature during the night. Thus, a drop of five degrees during the first two hours of the night with stable temperature thereafter, or a gradual drop by the same amount during the entire night, or a gradual rise, or an erratic variation within the same range during the entire night, would all give the same range. However, the effect on the equipment would be quite different. There is a rather tedious way to get a more significant indication for the stability of the temperature. One can read off the gradient of the temperature (in degrees per hour) at many equidistant points during the night. The average of the absolute values of these gradients gives the desired result. There is, however, a technical difficulty. Most thermographs have the tendency to smooth out the temperature variations, thus reducing the value to be derived. There are two ways to avoid this. One can use entirely different equipment for the temperature recording. The bimetal strips usually found in thermographs are by their nature slow. In addition their deflections are so small that a large amplification is needed. This results in a considerable lag of the writing pen. A sensitive thermocouple with a rapid galvanometer would serve the purpose better. A simpler way, which, however, is rough on the observer, is to read a precision thermometer many times during the night. A compromise solution would be to select a group of thermographs with the same lag in their reaction. This solution is adequate at least for an intercomparison of sites.

d. The highest and the lowest temperatures of the month. This information refers more to the extremes of the living conditions on the site than to the observing conditions.

e. The average and the extreme relative humidity. The most important function of the humidity recordings is to indicate the location of a site with respect to a stratification of the atmosphere. Other than that its value is of little interest, so long as it is not near saturation. For certain types of equipment, such as photometers cooled with dry ice or liquid air, it is preferable to have a very low relative humidity.

5. **Wind observations.** — The mechanical force exerted by the wind on the telescope is the only impediment the observer has to consider. It is frequently said that the " mechanical turbulence " (turbulence created by wind passing over an obstacle on the ground) causes poor seeing. The author possesses sufficient observational material to prove that this is not the case. It is unlikely also from a theoretical point of view. Nearly sonic velocities are needed to produce the necessary pressure or temperature differences. Nevertheless, on certain sites some correlation between wind and seeing is observed. It is, however, more appropriate to say that both wind and poor seeing had the same origin, namely large-scale temperature and pressure gradients, rather than that one caused the other. Otherwise, it would be difficult to explain how at times good seeing can be observed with strong wind. This result means that the calmest site does not necessarily have the best seeing, nor does a windy site necessarily have poor seeing. Calm conditions are necessary, though, for purely technical reasons, to utilize fully excellent seeing conditions. Hence the wind velocity is an important characteristic of a site, and it has to be investigated.

Wind velocity recording equipment can be of a very simple nature. An anemometer driving a miniature generator, and a clock-driven recorder are the entire outfit needed. To record the wind direction also automatically requires a more complicated instrument, and usually also electric power. However, the direction of the wind is not of great importance, and there is no need to record it.

The installation of anemometers requires a certain standardization concerning its elevation above ground. On flat areas the standard used by meteorological offices, 9 or 10 m above ground, is adequate. On mountain sites, however, a considerable problem arises; for example if an airstream passes over a ridge, striking it vertically to its extension, a maximum velocity is found at a certain elevation above the top. This elevation depends on wind direction and on the shape of the ridge. A standardization is evidently difficult. It has been the author's practice to install anemometers 3 m above the highest peak of the mountain. Furthermore, in case there are several peaks of equal height and there exists a preferential wind direction, the peak most into the wind was chosen. For mesa-shaped mountains no satisfactory solution has been found yet.

Most anemometers are calibrated at sea level. It may seem that for their use at high elevation a recalibration is necessary. However, one is actually interested in the mechanical force of the wind rather than in its velocity, and it is the mechanical force the anemometers respond to. Hence no recalibration is necessary.

6. **Haze observations.** — As used here, the term " haze " includes all non-gaseous impurities of the air such as droplets, smoke particles,

or dust. In its extreme forme it will be called fog. Usually, the term haze refers to condensations of water vapor only. However, in certain cases the observer may not be able to determine the nature of the scattering particles he observes in the air. Hence a term comprising all impurities is convenient. In the absence of a more suitable expression the above term may serve the purpose.

Haze affects astronomical observations in two ways: first, it increases the atmospheric extinction, and second, with a bright light source present (Sun, Moon, nearby city) it increases the brightness of the sky background. In both cases haze at any level above the observer contributes to the effect. Its total effect can be determined by extinction measurements, or by sky brightness measurement.

There is a way to determine on moonless nights the presence of haze in the local atmosphere. The beam of a strong light source, such as a search light or strong flashlight, shows the scattering particles in the air. Estimates of the brightness of the beam of a standardized light source, estimated on a arbitrary scale, can give at least some rough information about the local haze condition of a site. In arid areas, one has to expect dust in the air, at least on windy nights. Such simple tests as just mentioned may serve to eliminate dusty sites.

As already mentioned above in paragraph 3, a well defined top of a haze layer indicates the existence of a temperature inversion. The top of a haze layer is easily visible from above, but hardly noticeable or invisible from below. The appearance of a haze layer with a sharp top below his site, gives the observer the assurance that he is avoiding at least one temperature inversion. Observations of the elevation of the haze at night can be of great value. They will indicate the minimum elevation needed for a good site.

X. — The evaluation of the quality of a site.

In the preceding Sections it has been shown how a statistical analysis of the individual characteristics of a site can be made. The quality of a site, however, has to be derived by means that take all characteristics into account. In the case of seeing and cloudiness it has also been shown how the two can be combined. When all characteristics are to be combined, it is necessary to give weights to each one of them. It would be a difficult and tedious task to derive, adequately, the weights for each characteristic. The experience of many astronomers will have to be taken into account in order to arrive at a weighting scheme that fits our present equipment and observing techniques. This paper is not concerned with this problem, but a rough indication may be given as to the kind of considerations one might use in arriving at a weighting scheme for each feature.

1. **Evaluation on the basis of the mean values.** — The simplest approach is to use the mean values of all characteristics. A practical way could be to make a scheme by which each mean value is converted into a quality factor, such that with increasing quality the factor increases also. The product of all factors would then give the overall quality of the site. One possible scheme might be the following:

a. Seeing. — The quality factor could be chosen as the reciprocal of the average seeing diameter.

b. Extinction. — The quality factor could be chosen as the reciprocal of the extinction coefficient in the ultraviolet. It should be increased somewhat in case the extinction is found particularly consistent from one night to another.

c. Sky background brightness. — Without actual material at hand, it is difficult to make any proposal. Also one has the problem that the results for the dark and the bright lunar phases may be different. The more important result is that of the dark phase, because it determines the practical limiting magnitude for faint-star work. Once the optimum is known, one may decrease the quality factor by, say, a factor of two for every three tenths of a magnitude increase in background brightness.

d. Scintillation. — Probably need not be taken into account.

e. Haze. — Part of its effect is included in the extinction measurements. The increase of the background brightness over a standard value during bright lunar phases may also be taken into account.

f. Cloudiness. — The quality factor could simply be taken as the total number of clear hours per year. This procedure, however, does not quite fit the needs for two reasons: first, 182 completely clear nights and 183 completely cloudy nights per year are worth more than 365 nights, with each one clear only for the first half of the night; second, there may be an uneven distribution of the cloudiness with respect to the seasons.

g. Wind. — For wind speeds up to about 5 miles/h the same maximum factor should be given. Then it should gradually drop, reaching about half its maximum at 20 miles/h.

2. **The night-by-night evaluation.** — An evaluation on the basis of the average values of the various characteristics may be misleading. A difficulty concerning the proper evaluation of the cloudiness has already been pointed out. More problems may exist, as can be demonstrated by a highly hypothetical example: Suppose that on one site good seeing always comes with a strong wind, and bad seeing during calm periods. Another site with the same average wind and seeing may have just the opposite conditions. Both sites come out alike when

only the averages are considered. This result can be avoided by deriving a quality factor for every night, using a scheme similar to the one described above in paragraph 1. In this system the cloudiness can also be properly treated. The factor corresponding to the cloudiness should not simply be proportional to the number of clear hours, but should also take into account whether they came in succession or not. For instance, one clear hour might have weight one, while ten successive clear hours might have weight twenty. In such a scheme, one can even put in a preference for certain parts of the sky, by assigning higher factors to clear nights during the corresponding season. The sum of all factors of all nights, added up over an entire year, would give the overall evaluation of the site. By forming the totals by the month, rather than by the year, one could detect seasonal trends.