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Initial operation plan for use of the atmospheric haze recorder

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INITIAL OPERATION PLAN
FOR USE OF THE
ATMOSPHERIC HAZE RECORDER

By

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FOREWORD

The author is indebted to Mr. R. L. Dussault, Mr. H. K. Howell and Mr. D. B. Merrill of the Boston University Optical Research Laboratory for their invaluable advice and assistance throughout the preparation of this paper.

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I. INTRODUCTION

A. Statement of Problem

The reduction of apparent object contrast by haze light (atmospheric flare) has long been recognized as one of the limiting factors in the performance of aerial photography; however, only limited aerial measurements of atmospheric haze effects have been made and no measurements are presently reported at the altitudes used by modern military aircraft. A program of atmospheric haze study is now being undertaken by the Boston University Physical Research Laboratory under USAF Contract. An airborne telephotometric device is being constructed to provide the data necessary for this study. The device is now partially completed, and the first airborne tests should occur about the time this thesis is submitted.

The purpose of this thesis is to briefly describe this equipment and to present a proposed program for collection and analysis of data collected during the initial flights of this instrument.

It is expected that this present study will give a quantitative description of the principal atmospheric haze conditions found in modern aerial reconnaissance. Specifically, it is anticipated that the results will show the existence of correlations between haze conditions and other parameters, thereby permitting the optimum scheduling of photographic missions and indicating the best photographic orientation for a given set of conditions.

B. Atmospheric Haze

The earth's atmosphere is composed of loosely-packed gas molecules, water vapor, water droplets and dust. Atmospheric haze light results from the interference of these atmospheric components with the propagation of light waves. The following table lists the approximate sizes of particles found in the atmosphere.

Orders of Size of Atmospheric Particles[1]

Gas molecules		10^{-4} micron
Combustion nuclei	(dry)	10^{-2} micron
Sea-salt nuclei	(dry)	10^{-1} micron
Sea-salt nuclei	(humid)	1 micron
Fog, cloud		1 to 100 microns
Dust		1 micron
Wave length of green light		0.5 microns

The measurable result of atmospheric interference on passage of light can be considered without investigating the physical phenomena causing the interference. To do this, it is convenient to first consider one narrow light beam passing through an atmosphere uncontaminated by other light sources. The intensity of this beam will always decrease as the light penetrates farther into the atmosphere. This loss of intensity is to some extent due to absorption of light by atmospheric particles but primarily results from the fact that some light is scattered to one side by the atmospheric particles. If there are many beams of light in the immediate vicinity of the first beam, some of the light deflected from extraneous light beams will by chance be propagated along the path of the original light beam and will add to its intensity. Thus

1 Brock, G.C., PHYSICAL ASPECTS OF AERIAL PHOTOGRAPHY, Longmans, Green & Co., Page 197

there will be, first, a subtractive effect caused by the atmosphere absorbing and scattering light from the light beam and, second, the additive effect of some of the light scattered from the extraneous light beams. In actual aerial reconnaissance, there are an infinite number of extraneous light beams and an extremely long path length from object to receptor.

"True absorption represents the actual disappearance of light, the energy of which is converted into heat motion of the molecules of the absorbing material. This will occur to only a small extent (in an atmosphere of finely divided particles)."[2] The absorption coefficient in Lambert's equation ($I=I_o e^{-\alpha d}$) includes loss of light due to absorption and scattering. It is in this sense that the term absorption is used in this paper.

"Haze light" or "scattered light", as used in this paper, will connote that light which appears to originate at the atmospheric particles. Attempts have been made to calculate mathematical expressions for primary and secondary scattering of sunlight and approximate formulas developed. References for such studies of scattered and rescattered light are given in the bibliography.

When viewed from an aircraft, the light scattered upward by the atmosphere is added evenly to the light reflected from ground objects, reducing the luminous differences by which these objects are recognized. Since all experimental data indicate that the total amount of

2 Jenkins and White, FUNDAMENTALS OF PHYSICAL OPTICS, McGraw-Hill Book Co., Page 271

up-welling light will increase with increased altitude and since image-forming light attenuation must increase with increased altitude, any increase in up-welling light (for a fixed orientation) must indicate an even greater increase in scattered or haze light. Therefore, the evaluation of up-welling light can be used as a measure of atmospheric haze conditions.

C. Resume of Atmospheric Haze Studies

Early in the 18th century Newton studied the scattering of light by the atmosphere and theorized that this scattering was the cause of the blue color of the sky. In the middle of the 19th century, Clausius derived the equation $I=I_0e^{-Kd/\lambda}$ for the reduction of light intensity as it is passed through an atmosphere. In this equation I is the transmitted intensity, I_0 is the initial intensity, d is the length of the atmospheric path, λ is the wave length of light transmitted, and k is an attenuation constant. Toward the end of the 19th century, J. W. Rayleigh studied atmospheric optics and proposed his theory for scattering of light. His mathematical investigation gave a general law for scattered light intensity, for particles the linear dimensions of which are considerably smaller than wave length of incident light and whose index of refraction is different from that of the surrounding medium. The scattered light intensity, under these circumstances, is found to be proportional to the incident light intensity, to the square of the volume of the scattering particle, and inversely proportional to the fourth power of the incident light wave length.[3]

3 Jenkins and White, FUNDAMENTALS OF PHYSICAL OPTICS, McGraw-Hill Book Co., Page 281

In the lower atmosphere, particles much larger than the average upper-atmosphere particle are constantly being dispersed by dust storms, fires, volcanos, industrial plants and evaporation processes. The extent of this atmospheric contamination varies continually from place to place and from time to time. Thus the atmospheric scattering function is continually varying, and scattered light intensity is found to be proportional to something less than the fourth power of the incident light wave length.

The beginning of weather forecasting after the Crimean War increased general interest in the atmospheric phenomena. The invention of the aircraft gave added impetus to the study of the atmosphere. The importance of aerial photography now requires a greater understanding of the atmospheric phenomena, particularly an understanding of atmospheric haze.

Considerable attention has been given by the Navy and the Weather Bureau to the attenuation of light along horizontal paths and to the deterioration of apparent object contrast along such paths. A photoelectric device for measuring atmospheric attenuation of brightness contrast along a horizontal path is described in a paper from the Optical Research Laboratory of the University of Texas.[4] For this study, seven black and white targets were situated from 300 yards to 15,267 yards from the telephotometer and were graduated so as to each subtend the same angle at the meter. The purpose of this study was to determine the meteorological factors which influence visibility and to determine the prac-

4 Coleman, H.S., Morris, F.J., Rosenberger, H.E., A PHOTOELECTRIC METHOD OF MEASURING THE ATMOSPHERIC ATTENUATION OF BRIGHTNESS CONTRAST ALONG A HORIZONTAL PATH FOR THE VISIBLE REGION OF THE SPECTRUM, J.O.S.A. VOL. 39, (1949) Page 515

tical applicability of Koschmieder's law for theoretical attenuation. In terms of contrast this law can be expressed as $C_R = C_o e^{-\beta R}$ where R is range, β is attenuation coefficient, C_o is the inherent object brightness contrast, and C_R is the apparent brightness contrast. Koschmieder's law was found to be applicable for far more cases of interest than the simplifying assumptions used in its derivation would be expected to permit. In their paper, Coleman, Morris and Rosenberger establish no correlation between meteorological data and contrast attenuation. Presently, studies along horizontal paths are being made at the Wesleyan University, ORDWES facility at Bradley Field, Connecticut. Reports of work accomplished by this school bear a military classification and cannot be described here.

In 1923 Eastman Kodak Co. made aerial photographic measurements of haze factors at low altitudes,[5] and in 1929 I. F. Hand made photometric measurements over various landscapes at altitudes up to 9,000 feet. During 1942 and 1943 D. B. Merrill made several aerial haze investigations for the Army Air Forces.[6] The first flight (from 2,000 to 20,000 feet) measured up-welling light intensity through three filters using G. E. Exposure meters. Only one flight was completed using this equipment in 1942, the results of which showed neutral scattering up to 5,000 feet. Above this altitude, blue light intensity increased most rapidly while red light intensity increased most slowly. In 1943

5 Research Laboratory, Eastman Kodak Co., D. Van Nostrand Co., Inc.(1923) AERIAL HAZE AND ITS EFFECT ON PHOTOGRAPHY FROM THE AIR

6 Photographic Laboratory, Wright-Patterson AFB, Serial Nos. Exp-M-59-677-22-2, Eng-59-667-22-4, Eng-59-667-22-5

an automatic recording device using calibrated exposure meters pointed vertically downward was flown ten times, the highest altitude achieved being 30,000 feet. From this series of flights the average ratio of image-forming light to total up-welling light at 30,000 feet in three spectral ranges was found to be blue 1-5, green 3-10, red 4-10. A final report in this series describes a method for reproducing haze effects in a laboratory by placing lightly painted glass plates between object and camera. These plates were to be used for testing the effects of haze on color photography.

The Royal Aircraft Establishment of England published in 1950 a report by R. Hall describing observations made at altitudes up to 16,500 feet.[7] The theoretical section of this publication defines haze factor as per cent of light intensity added by the atmosphere divided by the ground brightness as seen through the atmosphere of a horizontal, white diffuse reflector on the ground. The conclusion of this report was that haze does not scatter light evenly in all directions, the greatest scattering effect occurring at the image of that point on the ground which is intercepted by the solar ray through the aircraft. The recommendation was that vertical photographs should not be taken when the solar rays will make, with the zenith, angles less than the semi-field angle of the lens.

S. Q. Duntley, in a summary of war-time studies made by Section 16.3 National Defense Research Committee, has given a clear mathematical description of atmospheric scattering and attenuation effects

7. British Technical Note, PH 429, EFFECT OF HAZE IN AERIAL PHOTOGRAPHY

along slant paths.[8] His final equation for apparent object luminance as seen from a distance R is: $B_R = \frac{\sigma_o q}{\beta_o}\left(1 - e^{-\beta_o \bar{R}}\right) + B_o e^{-\beta_o \bar{R}}$

where B_R - apparent luminance

B_o - inherent object luminance

β_o - attenuation coefficient at ground level

q - luminous density of the atmosphere

σ_o - fraction of q scattered toward viewer at ground level

$\bar{R}$ - the optical slant range, the path length within a homogenous atmosphere along which light would encounter the same number of particles actually encountered along the slant path R within a standard atmosphere

This equation is then employed in the development of an expression for contrast reduction. Apparent contrast in this report was defined as object brightness minus background brightness divided by background brightness. The principal limitation of this approach is the employment of an idealized standard atmosphere which seldom exists in nature. The effect of this inherent discrepancy is partially reduced by graphical representations which allow the observer to compensate for sharply defined haze layers at which the atmospheric composition changes abruptly. The altitudes between such layers are then assumed to vary as would a standard atmosphere.

The latest airborne telephotometer tests I have found reported were made by P. D. Carman and R. A. F. Carruthers in 1950.[9] The purpose

8 S. Q. Duntley, THE REDUCTION OF APPARENT CONTRAST BY THE ATMOSPHERE, J.O.S.A. Vol. 38 (1948) Page 179

9 P. D. Carman and R. A. F. Carruthers, BRIGHTNESS OF FINE DETAIL IN AIR PHOTOGRAPHY, J.O.S.A. Vol. 41 (1951) Page 305

of their survey was to determine the frequency of occurrence of the various brightness values throughout a brightness range. Although determination of atmospheric haze values was not the primary purpose of these flights, it is shown that light added by the atmosphere causes a decrease in brightness differences and that as altitude increases the overall brightness range decreases.

Solar radiation as measured at ground level is directly affected by the particle distribution and content of the atmosphere and therefore can probably be correlated with atmospheric haze measurements. Extensive studies of solar radiation have been made by H. Kimball[10] and I. F. Hand[11]. Today, in over seventy solar radiation laboratories located throughout the forty-eight states, Puerto Rico, Alaska, and Hawaii, constant measurements of solar radiation are being recorded from sun-up until sunset. These measurements are of total illumination between the wave lengths 0.3 and 0.75 and are made using a black and white segmented thermocouple termed a pyrheliometer. Measurements are made for the following orientations:

1. On a horizontal surface
2. On four vertical surfaces facing the cardinal points
3. On a surface normal to the sun's direction with skylight eliminated
4. On a surface normal to the sun's direction with direct sunlight eliminated

10 Kimball, H., SOLAR ENERGY DISTRIBUTION CURVES, Monthly Weather Review Vol. 52 (1924) Page 473

11 Kimball, H., Hand, I.F., INVESTIGATION OF THE DUST CONTENT OF THE ATMOSPHERE, Monthly Weather Review Vol. 52 (1924) Page 133

II. THE TELEPHOTOMETER AND ITS USE

A. Recording Telephotometer

Because of the experimental nature of this program, it was decided to approach the problem of evaluating haze conditions by a study of up-welling light. The haze recorder,* now being constructed at Boston University, is a telephotometric device which will measure the up-welling light along a path 15 degrees wide from horizon through the nadir to the opposite horizon. The light-accepting optics of the haze recorder is mounted in the bottom of the aircraft fuselage so as to extend slightly beneath the aircraft.

The up-welling light is accepted by a right prism which will rotate about an axis perpendicular to the center of one of its faces. (See Appendix, Figure 2) This prism reflects the up-welling light into an adjacent fixed right prism. The fixed prism reflects the light upward through a low-frequency, mechanical chopper into a beam-splitter. Here, it is again reflected and passed through a three-sector (blue, green and red) filter wheel into a photomultiplier tube. Light from a calibrating lamp passes through a high-frequency chopper, and then through the same beam-splitter and filter wheel into the photomultiplier tube. The light-accepting optics, or pick-up head, consists of both prisms, the beam-splitter, the mechanical choppers, the calibrating lamp, the filter wheel and the photomultiplier tube.

The photomultiplier signal is sent to a recording assembly where the superimposed, high-frequency signal is filtered out and used to maintain a feed-back self-calibrating system. The low-frequency, up-welling light signal is rectified and displayed on an oscilloscope as

*See Appendix, Figure 1

Y axis displacement. The X axis sweep of the oscilloscope is synchronized with the angle of the rotating prism as it sweeps from horizon to horizon. Thirty-five millimeter pictures are taken of the oscilloscope face and juxtaposed flight instruments during each sweep of the pick-up head.

Flight instruments surrounding the oscilloscope face include a remote indicating compass, a pressure altimeter, a free air temperature gage, gravitational tip and tilt indicators and a set of lights indicating the sweep-plane bearing of the recorder head relative to the longitudinal axis of the aircraft.

The operating sequence of the haze recorder is automatic and, beginning with the sweep plane of the pick-up head parallel to the longitudinal axis of the aircraft, a separate sweep is made of light intensity through each filter (blue, green, red). The plane of the sweep is next rotated 45 degrees where blue, green and red light intensity measurements are again made. This cycle is repeated at 90°, 135° and 180°. The direction of the sweep plane rotation is then reversed and measurements are repeated at 135°, 90° and 45°. The sweep plane of the pick-up head then rotates to 0°, and the instrument is automatically turned off.

The recorder will be calibrated using a source of known spectral quality and intensity, so that the intensity through each filter will read unity when the optical axis is directed toward the calibration lamp. This calibration lamp will be chosen so as to generally approximate the intensity an average ground scene would produce under daylight illumination at low altitude.

B. Initial Flight Plan

1. Definitions

The following five definitions will serve to convey a general concept of the manner in which the "haze recorder" will be flown.

1. Sweep - rotation of the light-accepting optics so as to measure the light intensity from one horizon through the nadir to the opposite horizon.
2. Set - a series of three consecutive sweeps, each measuring the light intensity through a different color filter; first blue, then green, then red.
3. Run - four consecutive sets, all made at the same altitude, with the aircraft heading into the sun. The first set in each run is made with the plane of the sweep parallel to the longitudinal axis of the aircraft.
4. Flight - starting at some set high altitude, it is intended that each successive run be made at one-half the previous altitude. A flight will consist of all runs made during one descent.
5. Mission- A mission will consist of all flights made between one take-off and landing of the aircraft.

Thus each flight should yield a three-dimensional plot of relative intensity of up-welling light for three spectral ranges.

2. Collection of Data

The data used for the atmospheric haze study will be derived from three primary sources; the haze recorder, an aerial observer and ground station reports. There will be some repetition of data in order to achieve positive identification and as a check for instrument malfunction.

The initial flights will consist of a series of runs over a pre-selected target area, each run being at one-half the altitude of the previous run. Test flights, however, will be carried out in reverse order so that the effect altitude has on the electrical components of the haze recorder may be determined. During each run the aircraft will be maintained straight and level while the haze recorder is turned on and one operating cycle completed.

Twenty-four photographs showing up-welling light intensity as a function of sweep angle will be taken during each operating cycle. However, half of these photographs will be duplicates with respect to orientation. This duplication will afford a means of checking the repeatability of the instrument under flight conditions. Assuming the instrument will faithfully record intensity values during laboratory vibration tests and that aircraft electrical power is maintained within set limits, uneven ground reflectance values should be suspected as a cause of non-repeatability of measurements. If this occurs, it is suggested that (as a check of this suspicion) flights be planned over more uniform terrain.

Initial flights other than equipment test flights should be made during clear weather and over terrain which is not perfectly uniform. These circumstances are well-suited for checking the instrument's repeatability of measurement, for clear weather will exclude the possibility of clouds causing variations in light intensity, and lack of terrain uniformity will test the ability of the 15 degree acceptance angle to integrate ground reflectance values.

In most instances, reasons for collecting the data listed below are obvious. When this is not true, later sections of this thesis will describe the value of such data.

The following is a list of all the data to be recorded on each frame of the 35 millimeter film taken during each flight of the haze recorder:

a. Date; mission number, air base from which mission is flown, and time
b. Oscilloscope trace of up-welling light intensity vs. sweep angle of pick-up head
c. Relative bearing of the longitudinal axis of the aircraft and the plane formed by the sweep of the optical axis of the haze recorder; the term "relative bearing" when used will refer to this angle.
d. Pressure altitude of the aircraft
e. Free air temperature
f. Color of filter through which light is passing
g. Gravitational tip and tilt of the aircraft

The following is a list of the data which should be logged by an observer during each flight:

a. Date, mission number, air base from which mission is flown, time of beginning and ending of each flight
b. Location, latitude and longitude of area over which run is made
c. The observer's visual judgment of the weather conditions and general terrain classification
d. The altitude of the sun at the beginning and end of each flight—this can either be measured using a sextant or be computed using triple

interpolation formula.

e. A record of aircraft altitude, free air temperature, wind direction and velocity for each flight level

f. A written report of any malfunctions encountered

3. Collection of Related Meteorological Data

One of the aims of this study is to determine the extent of correlation between the occurrence of atmospheric conditions suitable for good aerial photography and the preceding weather sequence. It is apparent that a determination of this type of relationship will require extensive observations and that generalizations in this respect cannot be drawn from the initial flights. Even though complete past weather records are maintained by, and are available from, other government agencies, the following list of weather data should be secured from the U.S.A.F. weather stations closest to the flight area when the mission is flown:

a. Approximate wind conditions, cloud coverage and relative humidity or dew point in the immediate area for all flight altitudes

b. A synopsis of general weather conditions for the several days preceding the mission. Pertinent data would include:

1) Precipitation - frequency of occurrence, type and amount

2) Frontal activity - kind and direction of movement

3) Contour lines of equal barometric pressure (isobars)

4) Unusual wind patterns and termperatures

5) Ground visibility

c. A synopsis of national or regional weather conditions. The significant features of this section will include general wind patterns and existance of unusual storms or long periods of precipitation. Daily national weather maps are available by monthly subscription from the Weather Bureau, Washington 25, D.C. Monthly "Climatological Data National Summary" publications are also available from the U.S. Weather Bureau. This publication gives monthly averages of the total solar and sky radiation data, diffuse radiation (of sky) and equatorial sun radiation (measured in a plane normal to sun direction) taken by seventy stations throughout the United States. The local station for these measurements is the Blue Hill Observatory, Milton, Massachusetts.

Upon the completion of each mission, the observer should tabulate in permanent form a report of the ground and aerial observations taken. This report should eventually become a part of the complete mission analysis.

III. ANALYSIS PROCEDURES

A. Reduction of Data

Twenty-four oscilloscope photographs will be taken during each run over the target area, with each flight consisting of seven or more runs. Thereofre, at least 168 oscilloscope photographs will be taken during each flight. After processing, it is intended that the film be projected and examined visually. The person making this visual check should note the presence of excessive tip or tilt and any malfunctions of the instruments. If either exists, the film should be appropriately marked. Also during this visual check, the integrating qualities of the

15 degree light-acceptance angle can be evaluated, for insufficient integration of ground reflectance values will be indicated by sharp fluctuation of intensity for change in sweep angle.

It is suggested that at this point a substantial reduction in the number of graphs can be achieved by projecting and tracing appropriate films to form composite altitude plots for each color and relative bearing. In this form, all the light intensity data can be plotted on twenty-four graphs, and every sweep angle will be registered.

By inspecting the above sets of graphs, the number of sweep angles which must be tabulated in order to avoid loss of interesting fluctuations can be determined. For the present, assume that 10 degree increments from vertical up to 70 degrees will be sufficient for recording all interesting data. Complete tabulation of intensity values for one flight of seven altitudes will then consist of 2,520 readings, of which one-half will be duplicate values. It is planned that this tabulation will be completed manually for the first flights; however, it is apparent that automatic computing and tabulating devices must eventually be employed. Inquiries have disclosed the availability of devices capable of performing this data reduction, ultimately recording the data on tabulation sheets or IBM punch cards. Automatic plotting devices are also available which will transcribe data from IBM cards to graphical form. Weather and mission data may be coded and placed on IBM cards.

B. Data Analysis

The data collected and tabulated should be analyzed for three primary considerations. First, it is expected that, from this haze study, it will be possible to predict the best camera orientation and spectral range under any given set of conditions. Second, this program should determine those ground measurements which, separately or in combination, will indicate to a greater extent than visual judgment the existing haze conditions. Third, it is hoped that weather sequences, which produce haze conditions compatable with good photography, can be systematically discovered and recorded as an aid for scheduling future photographic missions.

In order that the reader will have an understanding of the plots or graphs proposed in this thesis, hypothetical curves suggesting the general shape expected will be included following the mention of such graphs.

The composite plots previously described will give the first indication of best camera orientation and spectral range.

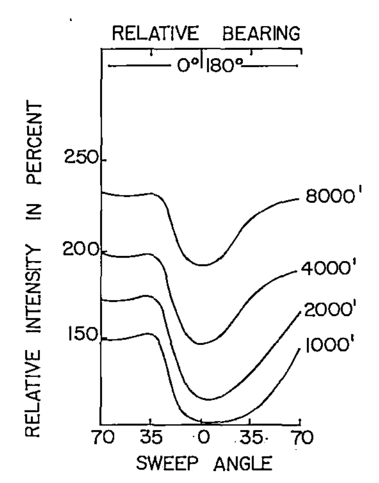


Figure 3. Hypothetical Composite Plot of Appropriate Slope Photographs

When the flights have been made over level and relatively uniform ground areas, depressions in these plots will ordinarily indicate directions of low haze intensity.

This plot will also afford a quick check for synchronization between the scope trace and the sweep of the rotating prism. Unless the sun is directly overhead, the lowest intensity values will generally be noted vertically downward; therefore, when most traces have their lowest values centered on the scope or when the lowest intensity values are scattered evenly about this central point, the synchronization will be satisfactory. Should the lowest intensity values be consistently to one side of center for all relative bearings, then improper synchronization should be suspected. Should the lowest intensity values be consistently to one side of center for only one relative bearing, this will indicate that either the plane was not being flown straight and level or that landscape having a very low reflectance value is located in that direction. When the latter is actually the case, the lowest point on the curve will move toward center and the depression will become narrower as altitude is increased.

Proper operation of the meter indicating the relative bearing of the sweep can be checked by noting picture sequence and the general symmetry of the curves about the vertical axis; generally the 90 degree relative bearing position should prove to be the more symmetrical trace.

Previous investigations have shown that atmospheric haze does not scatter incident light equally in all directions.[12] This is some-

12 Brock, G.C., PHYSICAL ASPECTS OF AIR PHOTOGRAPHY, Page 200

times noticeable from an airplane, when the ground appears clearer in one direction than in others. Polar plots in which r is relative intensity and θ is the relative bearing will be primary tools for determining this direction of minimum haze or best optical axis orientation. Such plots should be made first keeping filter color and sweep angle constant while varying altitude, and then with filter color and altitude constant while varying sweep angle. These graphs will show the effects of directional scattering and specular reflection; while indentations in such plots will indicate low values of scattered light intensity and consequently best orientations for oblique photography. The value of this type plot can be better demonstrated by the following hypothetical polar plots:

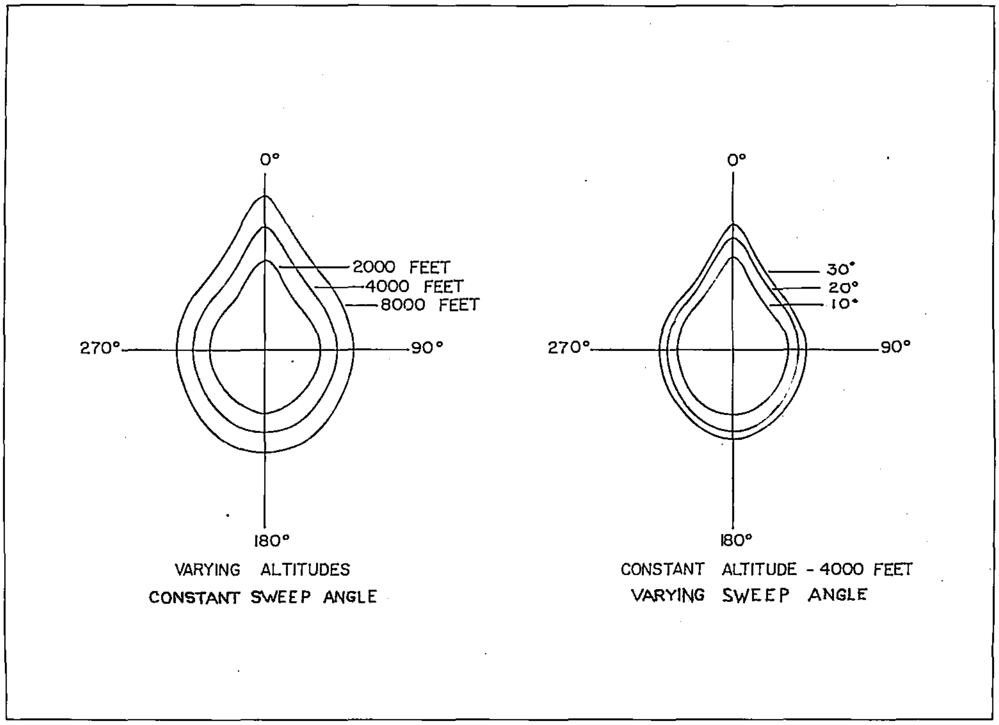


Figure 4.

As the haze recorder is now planned, these curves are to be drawn smoothly through eight points. This is a practical arrangement for simplifying instrument design and construction. It is expected that graphical studies of the data collected on initial flights will disclose the directions in which measurements may be discontinued and will indicate tendencies to be investigated in regions not presently planned for observation. For practical applications, the direction of minimum scatter does not have to be defined exactly. Instead directions should be selected that are removed from regions of intense scattering a distance greater than the semifield angle of any given camera.

It should not be expected that a few such plots will fully describe the directional scattering. Initial plots may show trends, but atmospheric haze effect is a function of a great many variables, and observations should be made for many varied sets of conditions. For instance a sloping haze level, such as is caused by frontal movements, will probably alter the form of the polar scattering plot. Also the location of the low intensity values will undoubtedly be influenced by the sun's altitude. Therefore, a general trend of the direction of minimum haze effect as haze conditions and sun altitude vary may not be discernible from the above plots. In this case, it will be helpful to determine the angle between the sun direction and the line of sight which shows the minimum haze effect. This angle is better defined by the following sketch.

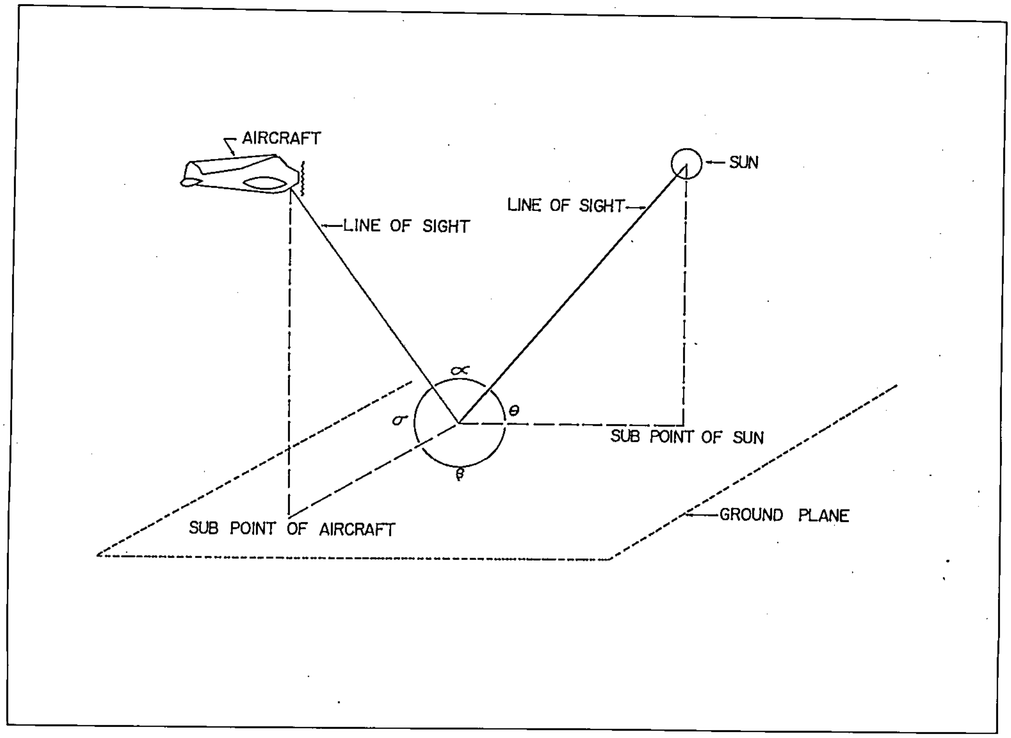


Figure 5.

where: β - relative bearing
σ - dip angle of the recorder head
θ - altitude of the sun (measured at the aircraft)
α - angle between the sun's direction and the observer's line of sight

In this sketch: $\cos\alpha = \cos\beta \cos\sigma \cos\theta + \sin\sigma \sin\theta$

(Development of this equation is given in Figure 6 of the Appendix)

The difference in sun altitude when measured at the aircraft and at point P caused by curvature of the earth does not enter this problem, since with respect to the aircraft all rays from the sun are effectively parallel. Using this equation, a polar plot of intensity against the angle between sun's direction and the observer's line of sight can be constructed. A plot of this type is shown in Figure 7 of the Appendix[13]; the value 0 in this plot equals ($180^\circ - \theta$) as θ is defined for the foregoing equation.

A plot of light intensity through each filter vs. log altitude, similar to those shown in Figure 8 of the Appendix,[14] should be made for vertical measurements and certain other orientations which prove of interest. The general shape such graphs will assume during good photographic weather is established by theory and observations made vertically downward from altitudes up to 20,000 feet. This investigation should extend the observations to the altitudes attainable with modern aircraft, and a series of such plots should be produced showing the variations caused by changes in weather conditions, camera orientations and sun altitude. Such plots will give a clear visual impression of the percentage of scattered light found in each of the three spectral regions. Past investigations and visual observations indicate that the layer of atmosphere just above the ground generally scatters light to the same extent in all wave lengths. This layer of neutral scattering haze is seldom visually apparent from the ground but is usually quite apparent from above. The vertical extent of this layer should be immediately discernible from the relative intensity vs. log altitude plots, for below this altitude the three curves should be coincident.

Future investigations, beyond this initial flight plan, can be made using filters which roughly duplicate the spectral sensitivity

13 British Technical Report, PH 429, Figure 4, Page 15
14 Photographic Laboratory Wright-Patterson AFB, Technical Note Eng-59-667-22-5

range of commonly used film and filter combinations. This type of investigation can then form a partial basis for future selection of film-filter combinations to be used with a given set of conditions. By measuring the light intensity through each filter delivered by the standard calibration lamp used, a ratio of the light intensity to the recorder reading can be established. In this manner an estimate of the light intensity available in each spectral range in any observed orientation can be quickly made without employing elaborate procedures. Some of the factors to be considered in the selection of a film-filter combination are the light intensity available, the ratio of image-forming light to total light, the film speed, the film contrast, and the amount of shadow detail required. Since shadows are illuminated primarily by scattered light and this same scatter light tends to compress object contrast, it is recognized that a compromise must be made in the final selection of film and filter.

Numerous other methods of plotting this data are obvious, and some will probably be employed for later missions. The three plots described above should give an over-all picture of the atmospheric haze light encountered and will indicate those areas in which more extensive observations should be made. The first two proposed plots do not require calculations, and the calculations necessary for the third plot, one completely tabulated, can be used for all missions.

When data from the initial missions has been collected, it is suggested that a study be made of the possibility of devising a workable coefficient of haze or method for classifying the various forms of haze. If a system for classifying the form and extent of haze can be developed, it will aid materially in establishing correlations between haze and the conditions governing haze; however, data now available is inadequate for conjecture as to the probable form of this system.

The aerial photographer long ago discovered that days which visually appear similar in regard to haze often prove to be quite different photographically. In order to better judge atmospheric haze conditions before beginning a photographic mission, these early photographers developed some general "rule of thumb" guides. These included, beyond a cursory examination of general visibility, a visual examination of the darkness of shadows, the hue of the sky, and estimates of the angle subtended by the horizon and the point at which the horizon gray shades off into deep sky blue.[15] To make passable estimates of haze conditions from these qualitative guides requires a great deal of experience and a good visual memory. This present study is the first extensive organized search for physical phenomena which will serve as indicators of haze conditions.

Because of the great number and variety of observations needed for this phase of the study, data collected during the initial flights will be insufficient for drawing positive conclusions. This data will only be valuable when considered in conjunction with the data collected on many future missions. The process of analyzing this data now appears to be a straight-forward job of recording the various phenomena along with the haze classification and then, by studying the various values or by drawing appropriate graphs, determine those values which best define haze. Therefore, this report will only in a general manner consider

15 From conversation with Lt. Col. H. W. Pote

some of the physical phenomena which will possibly be useful in future analysis.

The ground observations found to be most useful by practical aerial photographers will more than likely be found from this study to have an important correlation. The darkness of ground shadows, or more properly the ratio of light intensity reflected by a shadow area to the light intensity reflected from the surrounding area, will roughly indicate the total amount of scattering or total haze value. This ratio can be determined by use of a simple photometer or illuminometer along with some chosen surface, possibly a white matte material. Measurements of this nature are regularly being made throughout the country at solar radiation laboratories previously described.

Observation of the hue of the sky will, to some extent, indicate the thickness of the atmosphere's neutral scattering layer and, to this extent, the quality of the scattered or haze light. A graduated strip of material painted white at one end changing gradually to deep blue at the other and arranged so as to be viewed simultaneously with an area of the sky will allow repeatable values to be assigned to various sky hues.

Other data for consideration will be surface visibility, surface wind direction and velocity, relative humidity, barometric pressure and surface temperature.

The constantly changing conditions of the atmosphere decrease the value of this approach as a separate problem. The larger more complex problem of forecasting atmospheric conditions consistent with good aerial photography should, in importance, overshadow this on-the-spot judgment of haze conditions. This problem is, of course, contingent upon the capabilities of the comparatively young science of meteorological forecasting. Beginning in 1855 with the studies of the French astronomer LeVerrier, the science of weather forecasting has received added impetus from the two World Wars and the expanding civil air services. Today the rapidity with which this science is growing leads one to believe that phenominally accurate forecasting will soon be a reality. Meteorologists today, however, primarily forecast gross weather occurrences. Gross here refers to conditions such as storms, high winds and so forth. Haze can vary a considerable extent under the one condition "clear" as now forecast by meteorological stations. Because of this, it will be necessary to seek out those recorded values which are indicative of the finer weather variations effecting atmospheric haze. The weather values for which the finest variations can be measured and which might possibly be sensitive to slight variations in haze content of the atmosphere are solar radiation, sky color, relative humidity, atmospheric pressure and temperature. Complete treatment of this analysis procedure will require considerable study of weather forecasting theory and technique plus sample observations. Like weather forecasting, final haze forecasting will undoubtedly depend to a great extent on the use of judgment by the forecaster. This will allow consideration to be made of the location of the target area, time of the year and industrial activity.

Interviews with weather officers at the Boston weather office and Bedford Air Force Base has disclosed that all observations taken by such offices are included in the teletype messages sent out every hour and the charts prepared every six hours. The teletype messages include station location, cloud coverage (height and extent), ground visibility, present weather, barometric pressure, temperature, dew point and wind direction and intensity. The charts show wind direction, wind intensity, winds aloft, frontal activity, and contour lines of equal barometric pressure. Such records for the whole country are available at any government weather office.

IV. CONCLUSIONS AND RECOMMENDATIONS

A survey of literature concerning atmospheric haze has shown that, to a great extent, early theories of atmospheric scattering have been substantiated by later observations. However, aerial observations of the effect of atmospheric haze have been limited by service ceilings of available aircraft and sensitivity of measuring devices suitable for use in aircraft. The higher altitudes achieved by modern reconnaissance planes, and the altitudes forecast for future aircraft, increases the importance of haze studies and the development of sensitive electronic measuring equipment makes it possible to collect the extensive data required for this study. As a result of the increased need for this information, this present investigation has been instigated. It is intended that, as a result of this program, the aerial photographer will be able to select conditions which minimize the detrimental effects of atmospheric haze light with more certainty than is possible today.

Using hypothetical values consistent with presently reported data, many methods for graphically presenting haze light intensity data were studied. Those plots finally suggested in this thesis were selected to satisfactorily describe the relationships between haze light intensity and other parameters while requiring a minimum amount of calculation. Visual interpretation of these graphs should indicate the directions and spectral range for which haze light is a minimum. If it is desired to separate the attenuation and scattering which are measured together in this study, it is recommended that (simultaneously with the up-welling light measurements) the sun's intensity be measured. If this is done for the same spectral ranges used for the haze recorder measurements, then between two flight levels approximate values for attenuation and scattering can be determined.

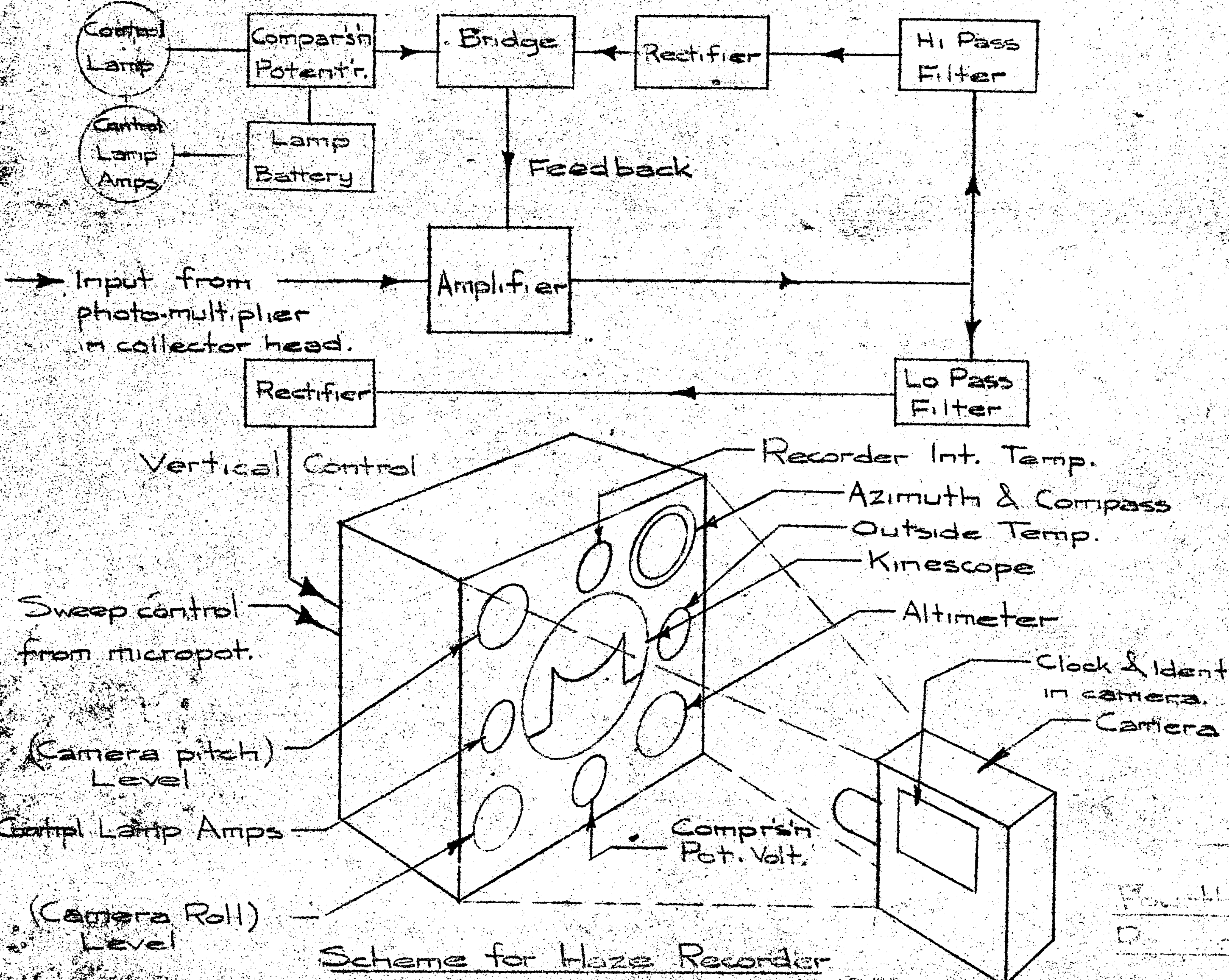
It will be of interest to determine the effect of stratified layers of large particles, and it is suggested that, whenever such layers are encountered during initial flights, the flight plan be altered to include one run just above and one run just below the visible demarkation line. This stratified haze layer often extends from the ground to between 5,000 and 10,000 feet and usually the top of this layer is sharply defined (within 20 feet). The difference between intensity measurements above and below this line will be due primarily to the stratification and only slightly due to the difference in path length.

Discussions with several weather officers indicated that probably no quick and simple method for forecasting atmospheric haze conditions will be developed soon. It is therefore suggested that the techniques developed and used by weather forecasters be employed in this phase of the study. Aerial collection of haze data to the extent required for this type of program is quite impractical. Therefore this study will first seek to establish definite correlations between ground measurements and haze conditions as measured from the air. Many phenomena which can be measured on the ground are a direct result of atmospheric particle size and distribution. It is therefore altogether reasonable to expect the existence of such correlations. Once such correlations have been established, it will be possible to determine atmospheric haze conditions at all times at many ground stations. With this data it may then be possible to develop techniques for forecasting haze conditions with reasonable accuracy.

The spectral quality of the light reflected from the ground is dependent upon type of terrain, vegetation, time of year and many other variables. Whenever aerial photography is being used to acquire information concerning one specific type of object, it would be of value to know the quality of the light reflected by such objects, for then it might be possible to photograph using a narrow spectral band and thus eliminate haze light from other spectral regions. Even for large complex targets, most of the information desired may be retained after eliminating portions of the spectrum. For some photographic requirements, such as camouflage detection, it is necessary to eliminate those wave lengths of light which hide the object. The haze recorder, with its sectored filter wheel, is an ideal tool for determining the relative intensity of up-welling light in several spectral regions for various types of landscape. Upon the successful completion of the initial test flights of the haze recorder, it is suggested that a schedule be arranged for making such observations. This schedule should initially provide for flights over various types of landscape; these flights should then be repeated over similar landscape having different natural situations.

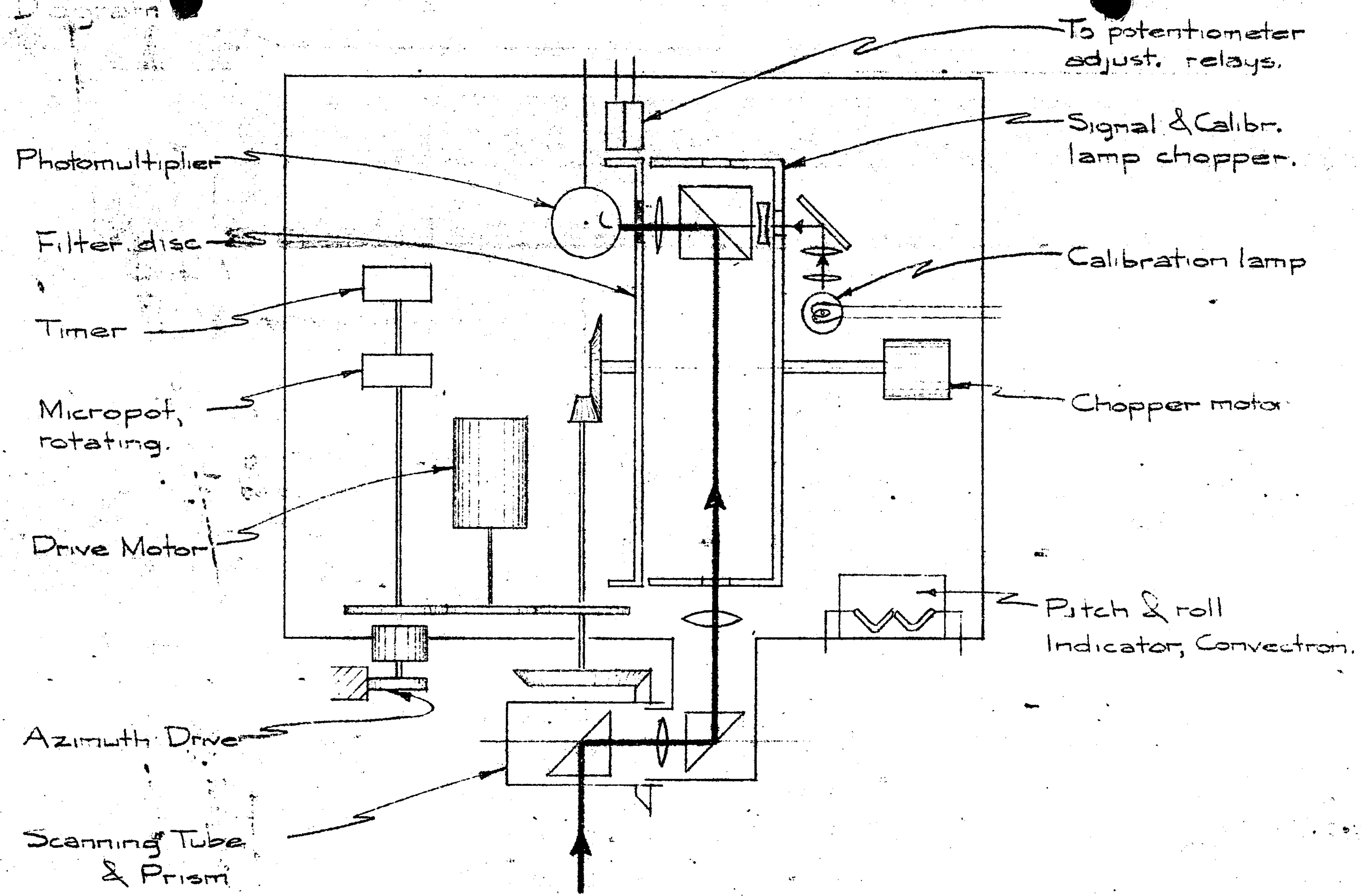
It has been suggested that one or more six-inch metrogon cameras be flown in conjunction with the haze recorder. This would provide a general check on the operation of the haze recorder over uneven terrain, for the position of high reflectance values in the photographs and as measured by the recorder should match. Since for initial flights there will be no attempt to match spectral sensitivity of the filter and photocell with any particular photographic film-filter combination, it will not be possible to quantitatively check the relative intensity increases measured by the haze recorder. However, since the color of large ground areas is generally known, it may be possible to relate the scope traces and the photograph to discover prominent discrepancies. The number of cameras and the type of installation used during the haze recorder flights will be dependent upon the type of aircraft available. It is doubtful that more than one six-inch metrogon camera can be used during test flights in the T-11 attached to the Boston University Physical Research Laboratory.

Automatic Haze Recorder
RECORDING ASSEMBLY



Scheme for Haze Recorder

FIGURE



Schematic - Automatic Haze Recorder
COLLECTING ASSEMBLY

FIGURE II

Determination of angle between the sun direction and line of sight from aircraft to object point P

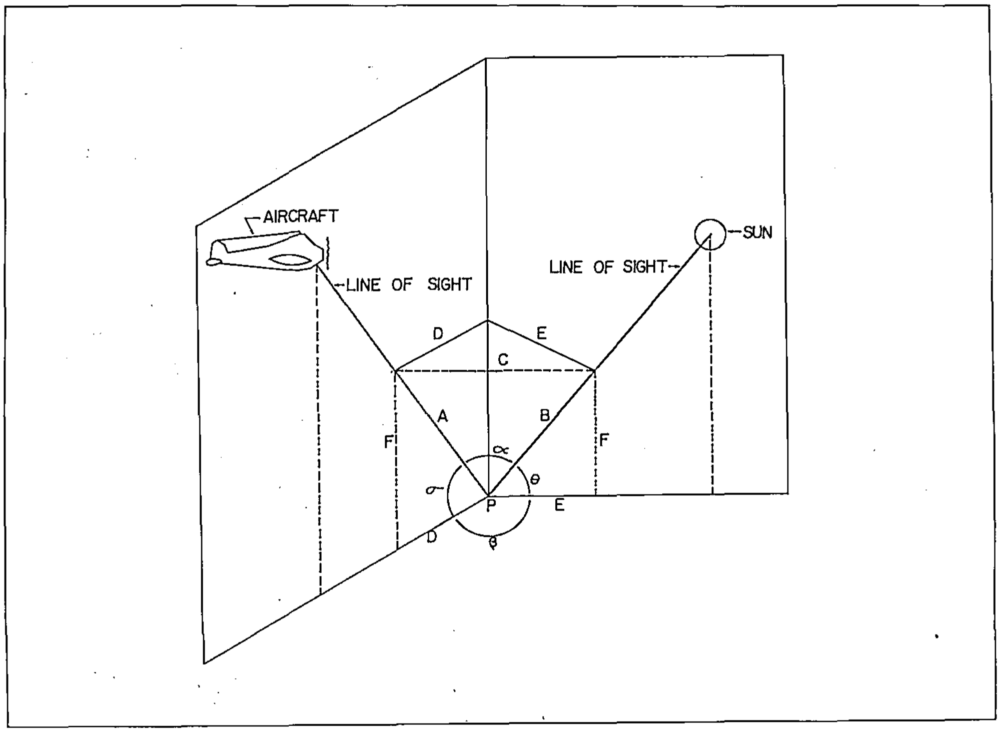


Figure 6.

Using Law of Cosines

$$C^2 = F^2 \csc^2\sigma + F^2 \csc^2\theta - 2F^2 \csc\sigma \csc\theta \cos\alpha$$

and $$C^2 = F^2 \cot^2\sigma + F^2 \cot^2\theta - 2F^2 \cot\sigma \cot\theta \cos\alpha$$

Therefore

$$\csc^2\sigma + \csc^2\theta - 2\csc\sigma\csc\theta\cos\alpha = \cot^2\sigma + \cot^2\theta - 2\cot\sigma\cot\theta\cos\beta$$

or $$\frac{1}{\sin^2\sigma} - \frac{\cos^2\sigma}{\sin^2\sigma} + \frac{1}{\sin^2\theta} - \frac{\cos^2\theta}{\sin^2\theta} - 2\csc\sigma\csc\theta\cos\alpha = -2\cot\sigma\cot\theta\cos\beta$$

$$1 - \csc\sigma\csc\theta\cos\alpha = -\cot\sigma\cot\theta\cos\beta$$

$$\frac{\cos\alpha}{\sin\sigma\sin\theta} = \frac{\cos\sigma\cos\theta\cos\beta}{\sin\sigma\sin\theta} + 1$$

$$\cos\alpha = \cos\sigma\cos\theta\cos\beta + \sin\sigma\sin\theta$$

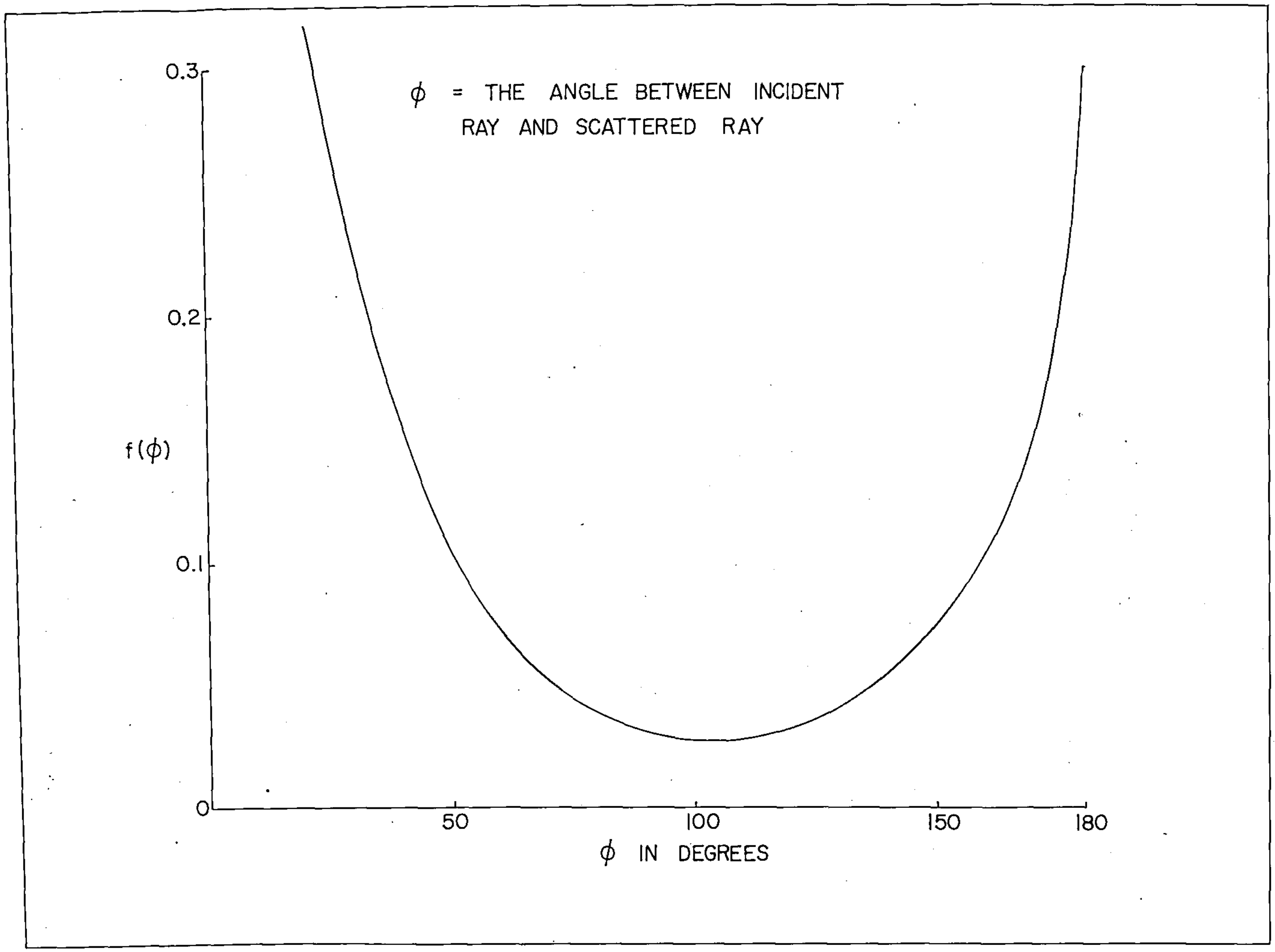


Figure 7. Polar Scatter Function f(ϕ), against ϕ

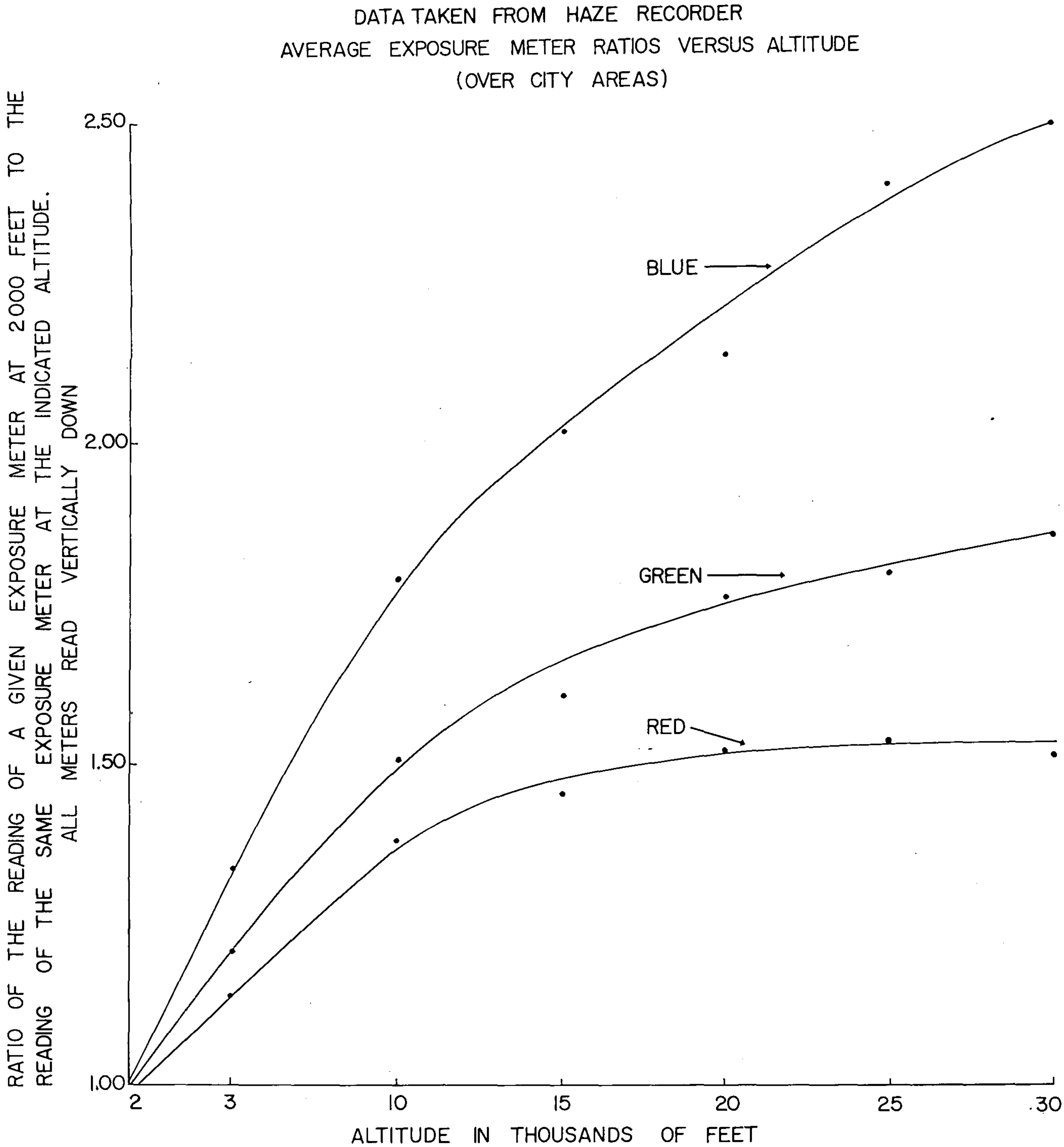


Figure 8. Scattered Light Intensity in Three Spectral Ranges Versus Altitude

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ABSTRACT OF THESIS

An airborne telephotometric device (haze recorder) is now being constructed at the Boston University Physical Research Laboratory to collect the data necessary for a study of atmospheric haze. It is expected that this present study will indicate the existence of correlations between haze light intensity and parameters significant in aerial photography. The purpose of this thesis is to provide an operational plan including data reduction and preliminary analysis for the first exploratory test flights.

The haze recorder is being constructed to measure up-welling light intensity in a narrow path from horizon through nadir to horizon. The plane of this sweep rotates in 45° intervals relative to the longitudinal axis of the aircraft, and a filter wheel synchronized with the sweep from horizon to horizon passes light alternately through blue, green and red filters. Thus a three-dimensional plot of up-welling light is formed for each of three spectral ranges. A photomultiplier tube transforms this intensity into an electrical signal which, after amplification, is displayed on an oscilloscope tube and photographed.

Data for this study will be derived from three primary sources-- the haze recorder, an aerial observer and ground station reports. The camera photographing the oscilloscope face will also record the readings of juxtaposed flight instruments. The instrument panel includes a compass, an altimeter, a temperature gage, tip and tilt indicators and lights which indicate the relative bearing of the instrument. The observer should, in addition, record the sun's altitude, wind direction and vel-

ocity, the general characteristics of the terrain and visual haze conditions. The ground station report should include wind conditions, cloud coverage, ground visibility and a general synopsis of weather for several days preceding the mission.

Twenty-four photographs of up-welling light intensity as a function of sweep angle will be taken during each operating cycle, one-half of which are duplicates. This duplication affords a ready method for checking repeatability of the haze recorder under flight conditions. To insure a check of this property, it is suggested that initial flights be flown over terrain which is not perfectly uniform. This type of terrain will also test the ability of the 15° acceptance angle to effectively integrate ground reflectance values.

The great number of observations made during each flight of the haze recorder make it essential that ultimately automatic computing and tabulating devices be employed. It is suggested, however, that data reduction for initial flights be carried out manually. A substantial reduction in the number of graphs can be achieved by projecting and tracing appropriate films to form composite altitude plots for each color and relative bearing.

This composite plot is well-suited for checking synchronization between the scope trace and the sweep of the rotating prism, for when most traces have their lowest intensity values centered on the scope or evenly scattered about this point, then synchronization will be satisfactory. Should these lowest intensity values be to one side of center for all relative bearings, then improper synchronization is indicated. The centering of the curves can also give an indication of the aircraft altitude during the run.

Polar plots in which r is relative intensity and θ is relative bearing afford good plots for determining best optical axis orientation. Both composite altitude plots and composite sweep angle plots should be made, keeping all other values constant for each graph. Such graphs will indicate the effects of specular reflection and directional scattering. Indentations in such plots will indicate low values of scattered light intensity and consequently best orientations for oblique photography.

A plot of light intensity through each filter vs. log altitude should be made for vertical measurements and some chosen oblique orientations. This graph will show immediately the dependence of scattering on wave length of light.

It is expected that the data collected will be of such a nature that it will be possible to assume that the light intensity values measured at the lowest flight level consist primarily of image-forming light. Intensity measurements made at higher altitudes will then consist of image-forming light plus scattered light. If results using this assumption prove to be unsatisfactory, it is suggested that simultaneous measurements be taken of the sun's intensity at each flight level through identical filters. From such measurements good approximations of attenuation can be made, and combining the measurements from the two sources will give good approximations of relative scattered light values.

Flights beyond the initial flights should be planned to determine those weather conditions which are favorable for aerial photography. From this same data, the most favorable camera orientation should be determined for various sun altitudes. Flights should then be scheduled over many types of landscape and the spectral sensitivity showing the least haze effect over each landscape should be recorded.