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RID-O TECHNICAL MEMORANDUM NR. 61-5

EFFECTS OF ATMOSPHERIC TURBULENCE ON OPTICAL INSTRUMENTATION

19 JULY 1961

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SUMMARY

The results of research on optical turbulence at White Sands Missile Range are presented. It has been shown that elevating camera stations 33 feet above ground level can yield nearly a threefold increase in optical resolution during periods of atmospheric turbulence. Early research postulated the existence of thermal-induced air-lenses as the cause of optical turbulence effects. Recent research has shown that air-lenses can account for most of the observed effects. The "prism" concept of turbulence appears to be unnecessary for explaining turbulence-induced image motion.

The dependence of the optical effects of turbulence upon exposure time and aperture size is discussed qualitatively. The source of optical turbulence in the atmosphere and a method of measuring the turbulence-generating potential of various terrain surfaces are described on the basis of micrometeorology.

This research has been limited to an investigation of optical turbulence during the period from sunrise to sunset. However, many of the results apply to the nighttime turbulence encountered by astronomers.

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1. INTRODUCTION

1.1 Efforts to take advantage of the excellent information capacity of optical instrumentation are often frustrated by the presence of optical turbulence in the lower atmosphere. A photographic telescope with a system capability for 40 lines/mm. resolution may yield only one-fifth that resolution in the field, especially during midday operation. Furthermore, turbulence-induced random motions of the optical image dilute the accuracy of pointing data sought from the optical instrument. These motions observed in the focal plane amount to apparent angular displacement of the target in object space. The amplitudes of these apparent displacements, in extreme cases, may run as high as 0.5 minute of arc.

1.2 The optical effects of atmospheric turbulence have been observed as long as Man has noticed the twinkling of stars. Over the centuries astronomers have had to contend dancing and blurred images when the "seeing" was poor. However, serious investigation of optical turbulence in the atmosphere during daylight hours has been conducted only during the past two decades. Nearly all of this recent work has resulted from optical-instrumentation problems associated with missile flight-testing.

2. EARLY RESEARCH AT WHITE SANDS MISSILE RANGE

2.1 It was observed during the early years of long-range missile photography at White Sands Missile Range (WSMR) that sharp images of missiles were seldom obtained at long slant range during daylight hours with the exception of the period shortly after sunrise and shortly before sunset. Although pitch and yaw data on V-2 rockets were obtained photographically at heights up to 100 miles during early morning and late afternoon shoots, the same data were obtained only to heights of 10 to 20 miles during midday operations. The images recorded during midday were generally blurry and of low contrast (see Figure 1). Quite frequently two or three closely spaced images of the missile appeared on the same photograph. These multiple images were at first attributed to vibration in the optical system or camera. However, it was later recognized that they were the result of an out-of-focus condition arising from either the optical defocusing power of optical turbulence in the atmosphere or from the inability to critically focus a telescope when observing a distant target through heavy turbulence.

2.2 Attempts to locate a focal plane under conditions of optical turbulence revealed the presence of good images in planes other than the normal focal plane. These images, called "transient images," were of short duration and manifested some degree of periodicity. G. Neeland and R. Roush[1], under the direction of C. W. Tombaugh, investigated such images under a number of conditions and postulated that optical turbulence might be

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[1] G. Neeland and R. Roush, "Atmospheric Turbulence," Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, Technical Note No. 514; date of publication estimated at June 1951. The work of Neeland and Roush was done at WSMR which, at that time, was operated by Aberdeen Proving Ground.

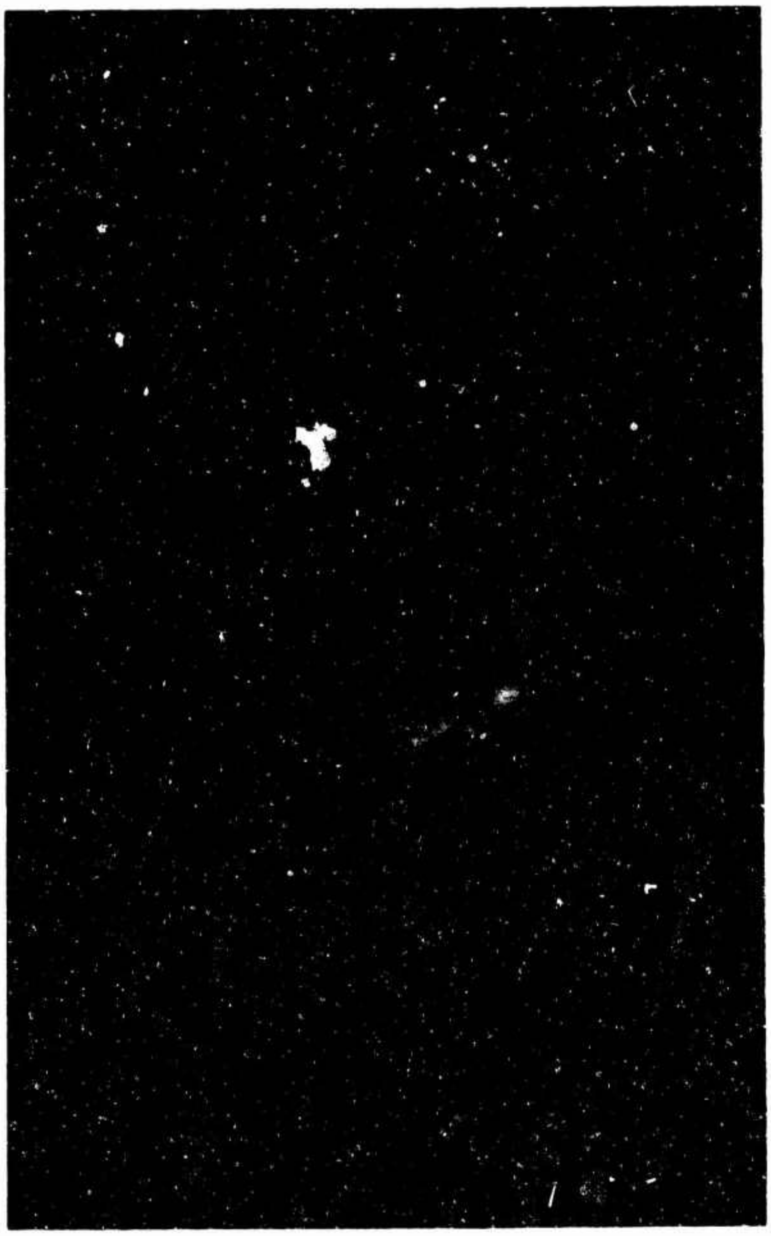

Figure 1 IMAGE OF A MISSILE SHOWS BLURRING EFFECT OF OPTICAL TURBULENCE

explained as "air lenses" of various sizes and optical power passing in front of the telescope objective. They demonstrated that thermal inhomogeneities in the atmosphere, rather than wind currents, are responsible for optical turbulence and that turbulence near the telescope objective reduces image quality more than turbulence more distant from the telescope. They were also aware that the type of effect which turbulence produced on the image was related to the relative sizes of the telescope aperture and the turbulence air-lenses (turbulence cell size). The duration of most of the transient images reported by Neeland and Roush was about 0.2 seconds; few longer than that, some as short as 0.05 seconds. Since they found fewer transient images at large distances from the normal focal plane, they concluded that there are fewer powerful thermal lenses than there are weaker ones in a given period of time.

2.3 At this same time, E. P. Martz, Jr.,[2] studied the image improvement which might be realized by elevating either the camera, the target, or both above the ground during periods of optical turbulence. He found that elevating the camera above ground gave more improvement than elevating the target and that the greatest improvement came when both target and camera were elevated. Martz's tests were conducted from open steel framework observation towers over desert terrain typical of WSMR. He was limited in height to 35 feet above ground level. His data indicates that the resolution capability of an optical system may be increased by approximately three times when elevating the lens from a height of three feet to 33 feet. However, the resolution obtainable from the top of the tower in the presence of turbulence is only, perhaps, half that which might be obtained if there were no turbulence.

2.4 As a result of Martz's work, nearly all camera locations at WSMR are elevated above ground level. Figure 2 is a photograph of a concrete tower station constructed to rigidly support a tracking cinetheodolite camera approximately 25 feet above the surrounding terrain. Dirt mounds and roofs of small instrumentation buildings are also used to elevate cameras above the region of greatest turbulence.

2.5 One might expect that the concrete towers, through the effects of solar heating, would become turbulence generators and defeat the purpose of elevating the cinetheodolite cameras. An investigation was conducted in 1958 by J. A. Roth[3] to determine whether or not the resolution obtainable from the top of the towers was as good as that recorded with a camera supported at the same height by a crane at approximately 25 feet away from the tower. Roth reports "no evidence was found that the concrete towers act as turbulence generators." He also investigated the improvement in

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[2] E. P. Martz, Jr., "Optical Performance in Elevated Camera Structures," Systems Engineering Branch, Flight Determination Laboratory, White Sands Missile Range, New Mexico; Technical Report; 28 November 1951.

[3] J. A. Roth, "Station-Site Turbulence," Range Instrumentation Development Division, Integrated Range Mission, White Sands Missile Range, Final Report on Sub-Task 1-22-4; 30 September 1958.

resolution resulting from the location of a camera at the top of a barren dirt mound 15 feet high (total camera height = 21 feet) as compared with a camera five feet above terrain level near the base of the mound. At midday, the resolution recorded at the top of the mound was nearly twice that recorded at the lower level.

3. PRESENT RESEARCH PROGRAM

3.1 The present research program has a fourfold objective:

(1) to investigate the optical effects of turbulence through experimentation with single turbulons,[4,5]

(2) to obtain comparative data on the turbulence generating ability of various types of terrain found on the Missile Range,[5]

(3) to measure, as a function of telescope aperture, the amplitude and frequency of scintillation and image displacement caused by turbulence under field conditions at WSMR,[6]

(4) to conduct experiments in reducing optical turbulence.[6]

Due caution is exercised in this program to avoid duplicating the work of others in this field.[7]

3.1.1 Optical Effects of Thermal Turbulence in the Atmosphere

3.1.1a In 1947, it was suggested that the optical effects of turbulence might be explained by the concept of hypothetical prisms of constantly changing power, orientation, and size along the line of sight from the telescope to the target.[8] The air-lens, or thermal-lens, concept of Neeland and Roush

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[4] Turbulon--a single elementary parcel of turbulence, an "air-lens."

[5] This work supported in part by the Office of Ordnance Research, Project I-169-P.

[6] Work on these two areas has just commenced and will not be reported in this paper.

[7] It is beyond the scope of this paper to describe all research being done in the field of optical turbulence. A large number of papers have been published since the astronomer A. E. Douglas started modern research on the subject in 1892. For a reprint of Douglas' original paper see "Amateur Telescope Making, Book 2," Scientific American, Inc., New York., N. Y., pp. 585-605; 1949.

[8] L. A. Riggs, C. G. Mueller, C. H. Graham, and F. A. Mote, "Photographic Measurements of Atmospheric Boil," Fournal of the Optical Society of America, vol. 37, pp. 415-420; June 1947.

Figure 2 CONCRETE TOWER STATION

has been previously mentioned. In order to study under controlled conditions the optical effect of single turbulons, an experiment was conducted in which both the physical nature of a turbulon and the effect of the turbulon on an optical image could be recorded simultaneously. The optical schematic for this experiment is shown in Figure 3. A Schlieren-type optical system was used to photograph simultaneously two views of a single turbulon generated in the test area. These two views were oriented at 90 degrees from each other and provided information on the size, shape, and location of the turbulon. At the same time, a target was photographed by a telescope viewing through the turbulon to record its effect on an optical image. The aperture of the telescope was two inches; the image distance, 72 inches; the object distance, 279 inches. The distance from the test area to the telescope objective was 38 inches. Exposure time for the telescope was determined by an electronic flash unit which trans-illuminated the target for approximately 175 microseconds.

3.1.1b Turbulons were generated one at a time by applying six volts a.c. to a small coil of resistance wire located just below the test area. The shape of the turbulon was generally that of a laminar flow,[9] vertically-oriented column approximately one-half inch in diameter. In order to obtain fairly stable turbulons, it was necessary to block off air inlets to the room and to minimize human movement lest interfering air currents be set up. Schlieren photographs of an artificial turbulon are shown in Figure 4.

3.1.1c The target pattern photographed by the telescope served two purposes. Standard bar-type resolution patterns in the four quadrants of the target served to indicate the resolution loss introduced in the image by the turbulon. Four space points on the target, one in the center of each quadrant, were used to measure the image displacement and image distortion (differential displacement) produced by the turbulon. A set of fiducial points on the target were independently illuminated and exposed on the telescope film before each turbulon was generated and the main target pattern photographed. Since the telescope camera shutter was not operated between the fiducial exposure and the target exposure and, further, the camera was not touched during this period, the image of the fiducial points gave a stable frame of reference against which the images of the space points could be measured to determine image displacement and distortion. Also, the measured distance between fiducial point images served to determine the film shrinkage correction factor to be applied to each photograph taken.

3.1.1d The results of the experiment were as follows:

(1) Vertically oriented column-shaped turbulons reduced the horizontal resolution more than the vertical resolution, thereby acting as astigmatic (cylindrical) lenses.

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[9] Laminar flow, since by definition, turbulent flow would not exist <u>within</u> a turbulon.

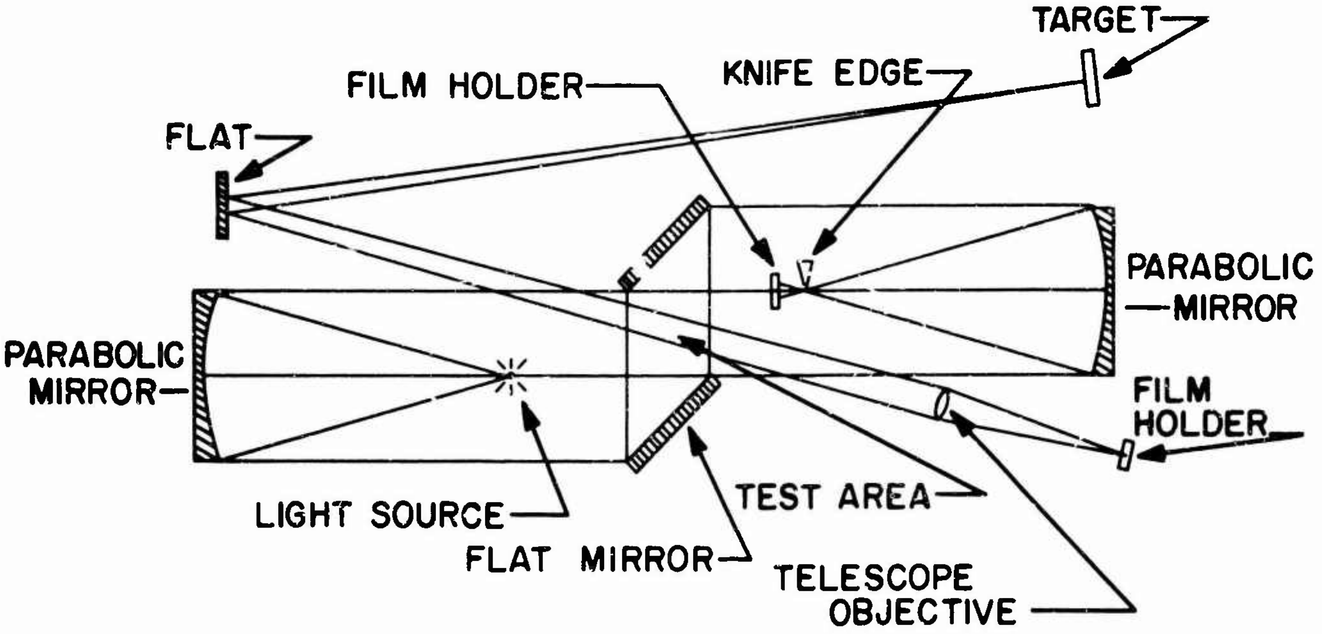

Figure 3 OPTICAL SYSTEM USED TO STUDY THE OPTICAL EFFECT OF SINGLE TURBULONS

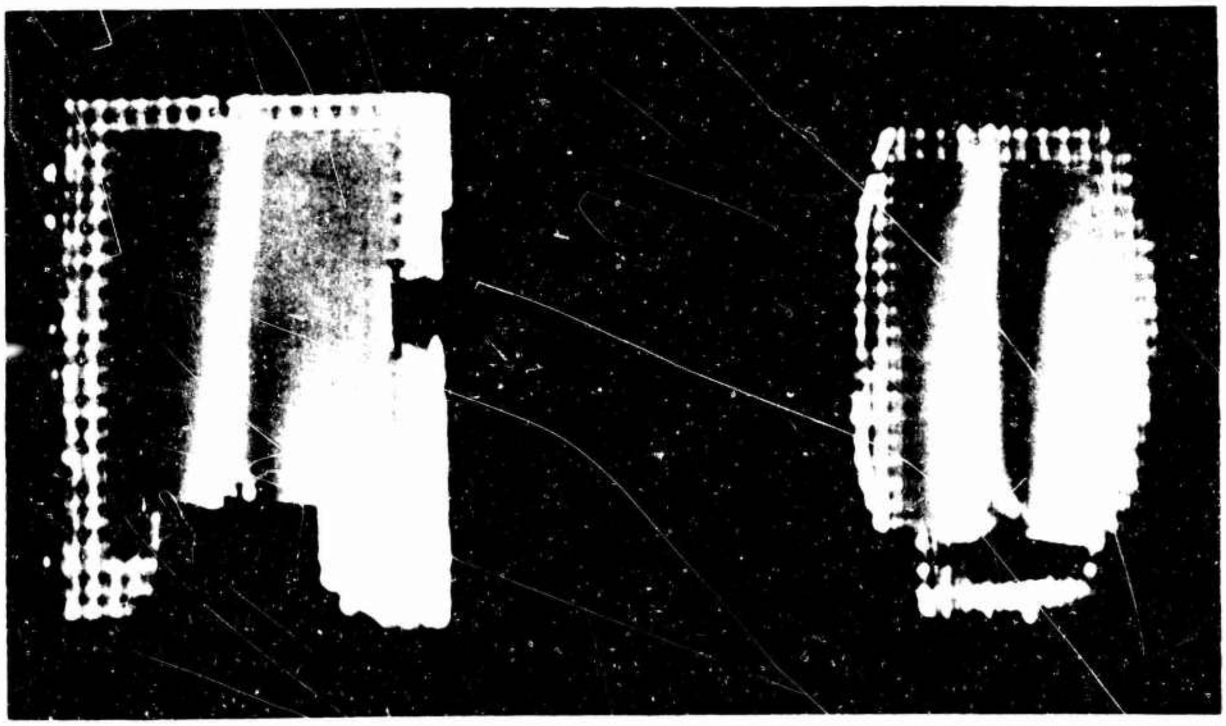

Figure 4 SCHLIEREN PHOTOGRAPHS OF A COLUMN-TYPE WARM-AIR TURBULON

(2) Image points in all quadrants of the image were displaced in the same general direction by any given turbulon. The magnitude of displacements among the quadrants was not constant for a given turbulon. Therefore, both image displacement and image distortion resulted from single turbulons.

(3) The magnitude and the direction of the image displacement appear to be correlated with the magnitude and direction by which the optical center of the turbulon is displaced from the telescope axis.

These results were produced by single turbulons which were smaller than the telescope aperture in the horizontal direction and which extended fully across the aperture vertically. The magnitude of image displacement was generally less than 2.5 seconds of arc.

3.1.1e The third result enumerated above is of special interest. The data unexpectedly revealed that, if the turbulon was located to one side of the telescope axis, the image was displaced toward the opposite side. It can be shown by geometrical optics that, if a negative lens is located in front of a telescope objective and somewhat off axis, there will be a displacement of the image in the opposite off-axis direction (see Appendix). Thus, the first and third results indicate that the column-shaped, warm-air turbulon acted as though it were a negative power, astigmatic lens. This, of course, should be expected from the fact that the density, hence, the refractive index, of warmed air is less than that of air at ambient temperature. But, it further implies that there is no need for a prism model of turbulence--both image motion and loss of resolution can be produced by an air-lens.

3.1.1f Under field conditions, one is not confronted with merely a single turbulon occulting the line of sight but, rather, with a field of turbulence extended both across and along the line of sight. Figure 5 is a Schlieren photograph showing "effective" cell size[10] of turbulons in the open atmosphere. Cell size is not a constant but is dependent upon terrain, insolation, and atmospheric conditions. The slightest breeze can completely change the nature of the cell pattern while it is blowing past the objective of the telescope. If the effective cell size is very much smaller than the telescope aperture, each off-axis cell will displace a portion of the image forming light in a manner similar to that observed in the single turbulon experiment. The net result will be a blurred image which will not manifest any image motion characteristics, but have position stability. On the other

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[10] The "effective" cell size is smaller than the turbulon size since we are looking in depth at turbulons against a background of randomly spaced turbulons. Boundaries of more distant turbulons may appear in the center of closer ones. However, the effective cell size will be, in some respect, proportional to the turbulon size.

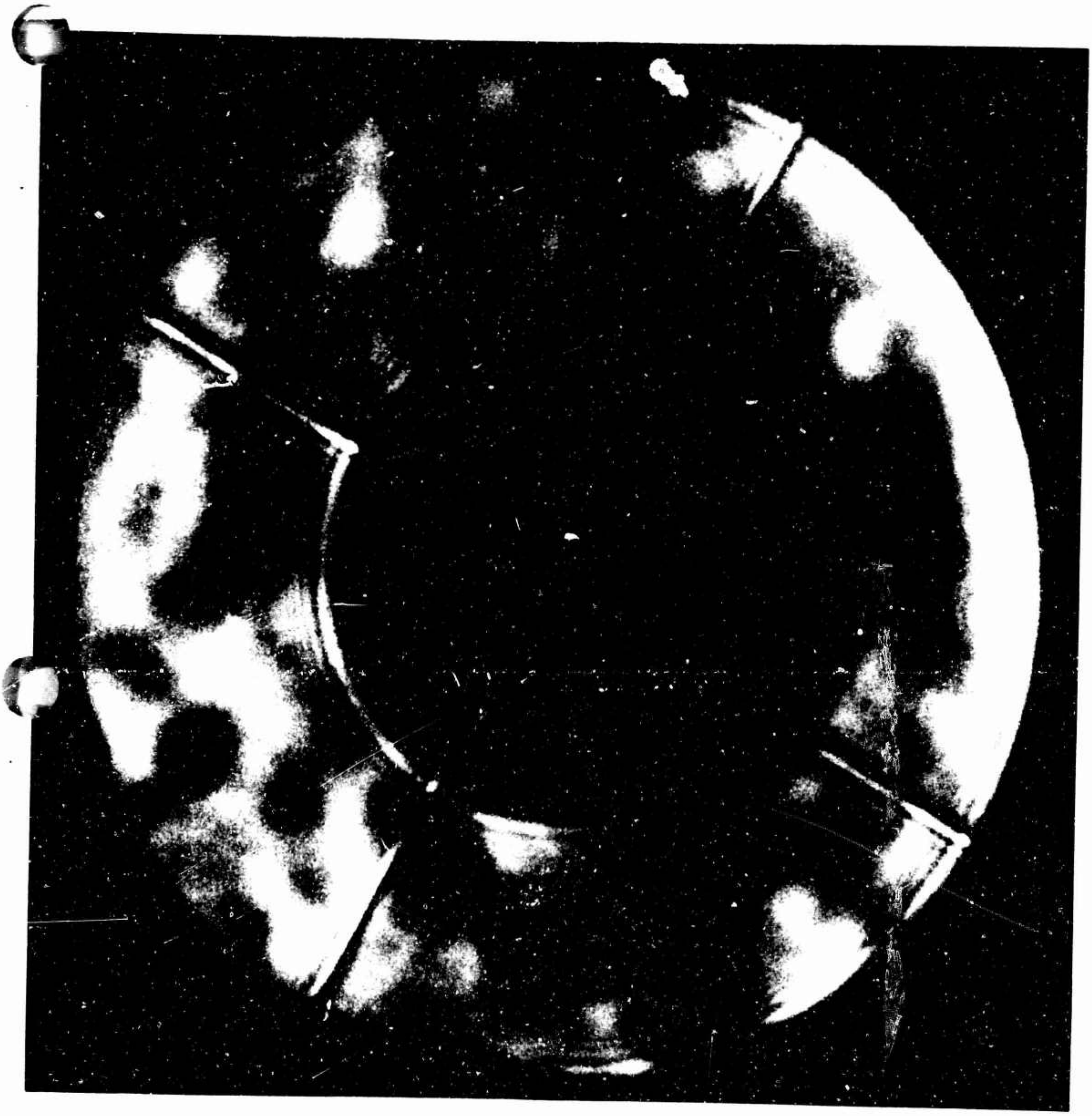

Figure 5 SCHLIEREN PHOTOGRAPH OF TURBULENCE CELLS IN THE OPEN ATMOSPHERE

hand, if the effective cell size is considerably larger so that the effects of many cells are not integrated across the aperture, image motion and distortion will be observed and resolution will be better than that of the blurry image resulting from the many small cells. This suggests that for cinetheodolites, where image stability is of great importance, large optical apertures are required in the presence of optical turbulence. Furthermore, for the large tracking telescopes which provide highly detailed images of missiles at long ranges without great concern over image position stability, small apertures will provide better resolution in the presence of turbulence. The effects of turbulence override the normal aperture-resolution relationship of physical optics. Optimization of aperture size is the subject of future research at WSMR.

3.1.1g There is another type of image blurring resulting from turbulence. When image motion is caused by relatively large cells and the imposure time of the camera is sufficiently long, a blurred image will result from the fact that the image moved during the exposure. In general, an exposure time of 1/100 second or shorter will prevent this type of blurring. However, it is impossible, through the use of short exposures, to prevent the type of blurring which results from a large aperture viewing through a field of small turbulons.

3.1.1h The scintillation effect of atmospheric turbulence is directly related to the size of the receiving aperture; the effect being greatest at very small apertures. Scintillation results from the distant, optically powerful turbulons causing light rays to be partially or totally refracted away from a small receiving aperture. Fortunately, nearly all optical instruments used for missile tracking have sufficiently large apertures to avoid scintillation effects. A star which twinkles when observed with the eye does not twinkle when seen through a medium- or large-size telescope.

3.1.2 The Source of Thermal Turbulence

3.1.2a It was mentioned in the second section of this paper that, during the periods shortly after sunrise and shortly before sunset, good images could be obtained of missiles photographed at long ranges. What makes these periods different from the rest of the daylight hours when turbulence is observed and image quality drops off drastically? If, during the periods near sunrise and sunset, one measures the temperature lapse rate (vertical temperature gradient) of the atmosphere in the first three feet above ground level, one will find the lapse rate to be no greater than adiabatic (-1°C/100 meters) or, possibly, inverted (positive slope). Both of these conditions are indicative of a vertically stable air mass. However, during the rest of the daylight hours, the lapse rate generally becomes super-adiabatic (unstable air) with temperature difference as great as 17°C between ground level and three feet above. As the sun illuminates the ground, some of the solar energy is reflected, some absorbed and conducted to subsurface soil, some absorbed and re-emitted at longer wavelengths (infrared), and some absorbed and given up to the boundary layer of air just above the surface by conduction.[11] This very thin, superheated boundary layer becomes buoyant because of its high temperature and low density and bubbles upward to form turbulons.[12,13] Lapse rate measurements give an indication of the buoyancy, or turbulence potential, of the lower atmosphere.

3.1.2b White Sands Missile Range, encompassing 4000 square miles, has a variety of terrain surfaces and surface covers ranging from white sand dunes to black lava beds, and from sparsely vegetated desert to dense swamp grass. J. A. Roth is conducting a year-long program of measuring lapse rates from heights of 0.5 feet to 24 feet over white sand, sparsely vegetated desert, and swamp grass.[14] As one might expect from a comparison of reflectivities, the lapse rate over white sand shows less instability of the atmosphere than that over desert terrain. Somewhat unexpectedly, the highest lapse rates (greater turbulence potential) were those measured over 10-inch deep dense swamp grass. It has been previously supposed that the lapse rates encountered over such grass would be less than those over the desert. The temperature of the air at the top of the grass was actually higher than that of air at the same height above desert sand. Roth's program has been expanded recently to include man-modified surface covers such as commercial crops and close-cropped lawn grass in an attempt to gain a better understanding of lapse rates over green vegetation. The lapse rate over a large pond is also being studied.

4. CONCLUSIONS

4.1 A systematic research program on optical turbulence has been conducted more or less steadily during the past decade at White Sands Missile Range. The advantages gained by elevating cameras above ground level have been measured and are now being realized through the use of concrete towers, earthen mounds, and other types of structures. However, elevating the camera stations only reduces and does not eliminate the turbulence problem.

4.2 An "air-lens" turbulon theory for the optical effects of atmospheric turbulence has been partially developed and can be used to explain some of the observed effects. On the basis of this theory, scintillation, image motion, image blur, and the relationship of aperture size and exposure time to observed turbulence effects are qualitatively understood. The frequently observed undulating appearance of fairly small line images has yet to be explained.

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[11] R. Geiger, "The Climate Near the Ground," Harvard University Press, Cambridge, Mass., pp. 1-9; 1957.

[12] Ibid. pp. 51-61.

[13] R. S. Scorer and F. H. Ludlam, "Bubble Theory of Penetrative Convection," Quarterly Journal Royal Meteorological Society, vol. 79, pp. 94-103; January 1953.

[14] The full results of this program will be reported later.

4.3 The generation of optical turbulence is understood on the basis of a micro-meteorological bubble theory. The turbulence potential of the air near the ground is indicated by a readily measured quantity, the temperature lapse rate. This potential is being measured over various types of terrain surfaces with the surprising result that dense swamp grass has a higher potential for producing optical turbulence than does sparsely vegetated desert.

4.4 Although this research has all been directed toward the optical effects of atmospheric turublence, the results apply equally well to systems working at radio frequencies. From the general refraction equations, one might expect that humidity inhomogeneities may play an important part in rf turbulence effects if such inhomogeneities are found in the turbulent lower atmosphere. For the optical problem, only thermal-induced density inhomogeneities are considered important.

5. APPENDIX

5.1 The fact that the image displacement produced by a single turbulon is related to the off-axis position of the turbulon was first noticed by L. A. Adams, formerly associated with this program. His explanation for the effect is given below.

5.2 Consider two light rays emitted from a point source and focused by a telescope are shown in Figure 6. Ray 1 passes through the center of the negative lens and, therefore, is not deviated until it strikes the telescope objective. In image space, it will cross the axis at the normal focal plane. Ray 2 is selected as that ray which, in image space, is parallel to the axis. The dashed extension (apparent direction) of this ray in object space will pass through the first focus of the telescope objective and will intersect with Ray 1 defining the apparent location of the point source. Their intersection in image space gives the position of the image of the apparent point source.

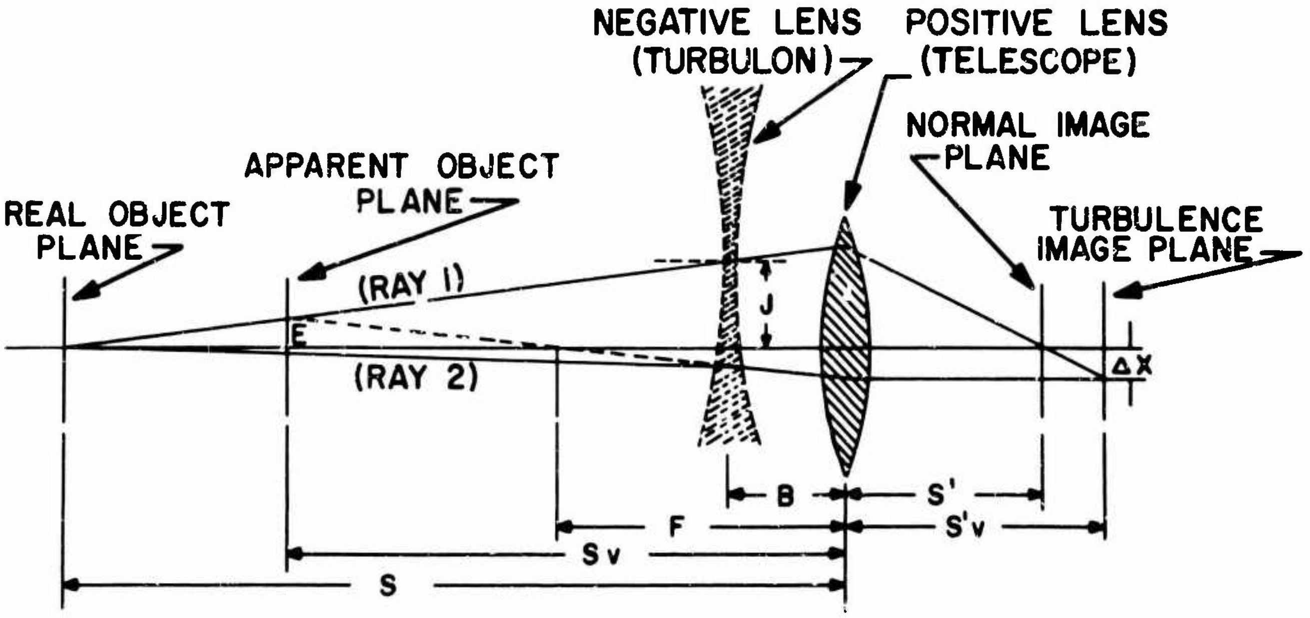

Figure 6 IMAGE DISPLACEMENT CAUSED BY AN OFF-AXIS NEGATIVE LENS

5.3 From similar triangles, we have

$$\frac{E}{S - Sv} = \frac{J}{S - B}$$

and

$$\frac{E}{Sv - F} = \frac{\Delta X}{F}$$

Combining the two equations, we have

$$X = J\left[\frac{F(S - Sv)}{(S - B)(Sv - F)}\right]$$

where J and B depend upon the position of the negative lens and Sv is a function of the optical power of the negative lens.

5.4 When the complete bundle of image-forming rays are considered, it will be found that the centroid of the defocused image observed at the normal image plane will be very nearly $(S'/Sv')\Delta X$ from the telescope axis.