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IMAGING OF INCOHERENT OBJECTS BY INTENSITY CORRELATION INTERFEROMETRY

Final Report

Research Grant: AFOSR 72-2155
Oct. 1971 to Sept. 1976

Prof. H. Gamo, Principal Investigator

SCHOOL OF ENGINEERING

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New optical, electronic and information processing techniques for imaging of incoherent objects through fluctuating medium were studied. These techniques are based on the principles of Hanbury Brown-Twiss intensity interferometer and its generalization by the principal investigator. The effect of the fluctuating and scattering medium between an incoherent objects and sensors were investigated by using

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both laboratory simulation and field experiments. The statistics of intensity fluctuation of laser beam transmitted through both simulated and practical atmosphere were analyzed by the real-time data acquisition system, which consists of PDP 15/20, an analog-to-digital convertor, two digital volt meters and two digital-to-analog convertors. Incoherent objects were simulated by a pseudo-thermal source, and the homogeneously turbulent atmosphere was artificially generated for simulation experiments. The strength of temperature fluctuations C_T^2 and refractive index fluctuations C_n^2 of the laboratory generated turbulence were experimentally determined. Statistical parameters of intensity fluctuations of laser beams transmitted through the turbulent atmosphere were determined.

Effects of corner-cube reflector and a flat mirror on the optical transmission through turbulent atmosphere were compared to the direct transmission for both cases of simulation and field experiments. The field experiments were performed using a reflector mirror system and a 10" matching Newtonian telescope and corner-cube reflectors, installed on the nearby hill and a building on the campus.

Various computer programs for statistical signal processing and automatic measurement processes were developed, as well as programs for the computer simulation of wave propagation through the turbulent atmosphere.

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1. INTRODUCTION

The objective of this research was to develop a new electro-optical imaging technique for incoherent light source, which is not seriously disturbed by the atmospheric turbulence.

The basic physical quantity to be processed for imaging of incoherent light sources is the *mutual intensity* as a function of distance between two observation points.[1] The mutual intensity is the cross-correlation of incident complex wave amplitudes transmitted from an incoherent light source. The time delay between these two wave amplitudes are taken to be zero, where the magnitude of cross-correlation is maximum. The mutual intensity of an incoherent light source is generally a complex quantity, specified by both magnitude and phase. When the mutual intensity is determined as a function of the distance between two observation points, the angular intensity distribution of the incoherent object can be obtained from the mutual intensity, based on the Van Cittert-Zernike theorem.[2] In the far field case, the angular intensity distribution is given by the Fourier transform of the mutual intensity.

The usual photographic image of an incoherent source by using a lens system can be interpreted as the results of analog Fourier transform of mutual intensity on the pupil plane.[3]

Under the presence of the atmospheric turbulence, the photographic image of an incoherent object will be seriously degraded by the phase and amplitude fluctuations as well as the fluctuation of angle of incidence. Thus, the method of indirect imaging of an incoherent object through turbulent atmosphere based on the intensity correlation interferometry and image processing becomes an attractive alternative, worth further investigation. Both the intensity correlation interferometer with a coherent background and the triple intensity correlation interferometer proposed by the principal investigator can determine both magnitude and phase of the mutual intensity, without being seriously disturbed by the atmospheric turbulence.[4,5] It should be noted that the original Hanbury Brown-Twiss intensity interferometer is not sufficient for general purpose imaging because the phase of mutual intensity cannot be determined by the interferometer.

The essential feature of the indirect imaging based on the modified intensity correlation interferometer is that the mutual intensity can be determined without being seriously disturbed by the atmospheric turbulence.

This type of imaging system is insensitive to the phase fluctuations. The amplitude fluctuations due to atmospheric turbulence will make the signal-to-noise ratio of detected mutual intensity smaller, and consequently the imaging process requires longer observation time than the usual photographic imaging. After applying the signal averaging procedure to the mutual intensity measured, we should be able to recover the image of an original incoherent source, irrespective of the presence of atmospheric turbulence.

The development of imaging system based on the generalized intensity correlation interferometer is a challenging research topic in the fundamental optics as well as in optical electronics, because it requires new types of opto-electronic detector system and real time digital signal processing.

First, we report the laboratory simulation experiments using a pseudo-thermal source, the laboratory generated, homogeneously turbulent atmosphere and a linear array of photodetectors. Second, the field experiments of optical transmission through the turbulent atmosphere using a reflector on the campus. Third, some results of preparing computer simulation of optical transmission through turbulence are described, with emphasis on the generation of non-gaussian random processes with prescribed moments or cumulants. Brief review of pertinent research works and the interactive experimental control system program based on the FOCAL language for PDP 15/20 are described in the appendix.

2. LABORATORY SIMULATION

A preliminary experiment on intensity correlation interferometry was performed using a pseudo-thermal source as an incoherent object and analog multiplication. The pseudo-thermal source consists of a rotating ground glass with the He-Ne 6328Å gas laser. The statistics of laser radiation scattered by a rotating ground glass were measured by using the experimental system illustrated in Fig. 1, in which an Analog-to-Digital convertor interfaced to the PDP 15/20 digital computer played the important role. The histogram of irradiance fluctuations obtained is very close to the exponential distribution (cf. Fig. 2). This indicated that the statistics of wave amplitude fluctuations are close to gaussian and the pseudo-thermal source can be treated as an incoherent light source. The schematic diagram of an intensity correlation interferometer tested by using an analog multiplier (Intronics 501) is illustrated in Fig. 3, and a typical result is shown in Fig. 4.[6] Since we intended to develop the digital signal processing system for studying various intensity correlation interferometers, the system using intensity correlation by analog multiplication was not elaborated.

Prior to developing the pseudo-thermal source using a rotating ground glass, we also investigated the statistical properties of the light scattered by suspended Brownian particles. Polystyrene latex of known particle diameter such as 0.714 μm (Dow Chemical) were suspended in distilled water. The advantage of this type of source is that it does not require the external driving force such as a motor for rotating a ground glass plate.

Disadvantage is that the coagulation of colloid may change the long range characteristics of the pseudo-thermal source. The dynamic scattering in nematic liquid crystal and an array of light emitting diodes would also be useful as a pseudo-thermal source for representing the incoherent objects.

Statistics of the pseudo-thermal source were thoroughly investigated by measuring moments, central moments and cumulants using our digital instrumentation. The details are described in the Ph.D dissertation by Donald G. Lubnau (June 1976).[6] We also presented a paper on depolarization properties of random rough dielectric surfaces at the Optical Society of America Meeting (October 1972).[7]

In conjunction with this research, the principal investigator has re-examined the derivation of the Van Cittert theory of partially coherent radiation. By establishing the Fokker-Plank equation for joint probability density of partially coherent wave field, the missing link between the Zernike theory and the Van Cittert theory were clarified. This was presented at the Annual Meeting of the Optical Society of America (October 1972).[8]

While performing the measurements of irradiance fluctuations by a photovoltaic detector (Si PN junction) we noticed that the noise level depends on the reverse bias voltage and intensity of incident laser radiation. Thus, we measured the excess noise in silicon photodiode (E G & G, SGD 100) while changing the intensities of the incident He-Ne visible gas laser radiation. This is described in the M.S. dissertation by Rose A. Shuttleworth, (1974).[9]

After several measurements of optical transmission through real turbulent atmosphere, we found it rather difficult to obtain consistent results due to the uncertainty of atmospheric conditions. Therefore, we decided to build a simple laboratory generation of the atmospheric turbulence which will provide the reproductible homogeneous, isotropic turbulence over a reasonably large region. Consequently, we can now conveniently perform optical transmission measurements using the turbulence chamber. This is one of the highlights of our research activities during the five years and its details will be described in Arun K. Majumdar's Ph.D dissertation (May 1977).[10]

The turbulence chamber (100 inch x 31 inch x 9 inch) consists of 10 small electric heater/blowers with provision for heating at 750 watts or operating just fan only without heating (see Figs. 5 and 6). An aluminum foil screen and three screens of 2 mm aluminum wire meshes were placed in front of the heaters, in order to generate the homogeneous, isotropic turbulence. The turbulence within the region (12 inch x 100 inch x 3 inch) at the 4 3/4 inch standard height for optical measurement was found locally homogeneous and isotropic. The average wind velocity and temperature were 0.41 m/sec and 53° C, respectively.

The turbulence chamber was characterized by both thermal and optical methods. The temperature structure function $D_T(r) = <|T(r_1 + r)-T(r_1)|>^2$ were measured in various locations by using the differential micro-thermocouple system (Chromel/Constantan, Type E, Hy-Cal Engineering). (See Fig. 7, 8 A and 8 B). From the measurements of the temperature structure function versus probe distance r, we found that the following Kolmorgov-Obukhov's 2/3 power law holds at probe distance from 2 to 6 cm:

$$D_T(r) = C_T^{\,2}\, r^{2/3}$$

The parameter for the strength of temperature fluctuations $C_T^{\,2}$ was 52.9 $(°K)^2$ meter-2/3.

The power spectra of temperature fluctuations were obtained by applying the Fast Fourier Transform method to the digital temperature fluctuations stored in the data acquisition system. (See Fig. 10). Within the frequency region higher than 5 Hz but lower than 80 Hz, the theoretical frequency dependanace $f^{-5/3}$ of power spectra for the homogeneous isotropic turbulence in sub-inertial range is in close agreement with our experimental results. For an average wind velocity C.41 m/sec we obtain the inner and outer scales of turbulence, ℓ_o = 5 mm and L_o = 8.2 cm, respectively.

The refractive index structure constants C_n were calculated from C_T measured by using the formula

$$C_n = \frac{77.6 \times 10^{-6}}{T^2}\, p \;\left[+ \frac{0.00753}{\lambda^2}\right] C_T \;.$$

The distribution of $C_n^{\,2}$ is illustrated in Fig. 11, where the x and y coordinates are parallel to the optical path and airflow, respectively.

The strength of this laboratory generated turbulence is approximately 10^3 times larger than that of the real atmosphere. This is an important feature of our turbulence chamber to make the simulation of the real atmosphere within the laboratory possible.

Irradiance fluctuations of a collimated single mode He-Ne 6328Å laser beam were measured by transmitting the 1" diameter collimated beam over the 2.5 meter distance of the turbulent atmosphere mentioned above. From the measured moments up to the fourth order of irradiance fluctuations we obtained the variance of log-irradiance fluctuations by using the formula:

$$C_\ell(0) = \frac{1}{4} \langle [\, \ln(I/I_o) - \langle \ln(I/I_o) \rangle]^2 \rangle$$

$$= \frac{1}{4} [\, 6 \langle y^2 \rangle - 4 \langle y^3 \rangle + \frac{11}{12} \langle y^4 \rangle - 6 \langle y \rangle^2$$

$$- \frac{1}{4} \langle y^2 \rangle^2 + 4 \langle y \rangle \langle y^2 \rangle - \frac{2}{3} \langle y \rangle \langle y^3 \rangle]$$

where

$$y = I/I_o$$

This equation is useful for evaluating the variance of log-irradiance fluctuations with arbitrary probability distribution, because the histograms of irradiance fluctuations observed often deviate from the idealized log-normal distribution. The variance of log irradiance fluctuatons for the case in which the Fresnel zone $\sqrt{\lambda L} << \ell_o$, is given by

$$C_\ell(0) = 3.2\, C_n^{\,2}\, L^3\, \ell_o^{-7/3}$$

By inserting the first-four irradiance moments and the $C_n^{\,2} = 2.98 \times 10^{-11}\ m^{-2/3}$ obtained by the temperature fluctuations measurements, we obtained $\ell_o = 2.9$ mm.

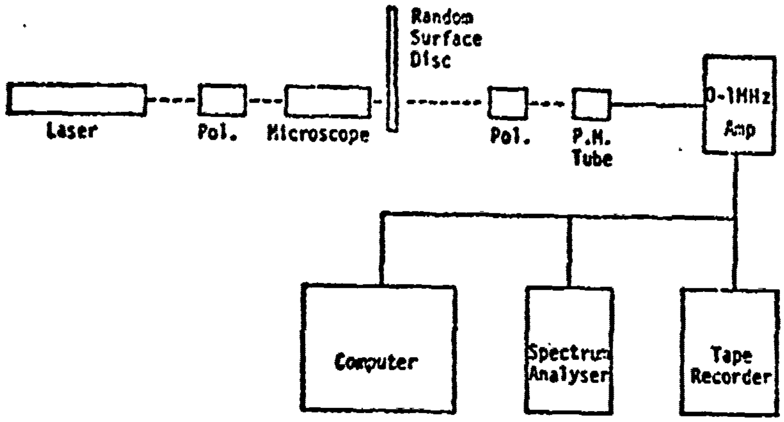
Using the multi-path optical transmission in the turbulence chamber, we have measured the variance of log-irradiance fluctuations and histograms versus optical path length L. The preliminary results indicated clearly the saturation effect over the longer path length. This was presented at the URSI meeting in Massachussets (October 1976).[11] We have also compared the direct transmission measurements of irradiance fluctuations with those using the flat mirror or corner-cube reflector. According to the preliminary results, irradiance fluctuations of collimated He-Ne 6328Å laser beam are smallest in case of the beam reflected by a corner-cube reflector compared to the direct transmission and that reflected by a flat mirror over the same optical path length. The coefficients of variation (γ_0), skewness (γ_1), and excess (γ_2), are summarized as a table:

	corner-cube reflector	direct path	flat mirror
γ_0	0.025	0.054	0.012
γ_1	0.65	0.31	0.79
γ_2	0.40	0.88	0.79

This result may be interpreted as follows: Since during the short transmission time the turbulence can be regarded as "frozen", the beam reflected by a corner-cube will tend to go back following the same path. Consequently, forward and backward transmission would be somewhat correlated. On the other hand, the beam reflected by the flat mirror would propagate in much wider range of directions due to the Snell's law, and thus, the forward and backward transmissions are statistically more independent than the corner-cube reflector case. The preliminary results were presented at the Optical Society of America Meeting (October 1976).[12] We plan to analyze these experimental results more precisely by formulating the theoretical model.

Intensity correlation interferometry using the RETICON, 64 linear array of silicon photodiodes, (RL-64-P) are being developed (cf. Fig. 12) in order to clarify the influence of atmospheric turbulence on the intensity correlation interferometer. Since the size of the diode is comparable to the spacing between photodiodes, the digital signal processing for reducing the directly measured quantities to the discrete sampled intensity correlation is essential. A simple case was analyzed by Mohamed Refaie, a graduate student.

In these experiments, the influence of phase fluctuations due to the atmospheric turbulence is an important subject in intensity correlation interferometry. Thus, we started to prepare the investigation of phase fluctuations.



Experimental System for Histogram and Spectrum Measurements

Figure 1

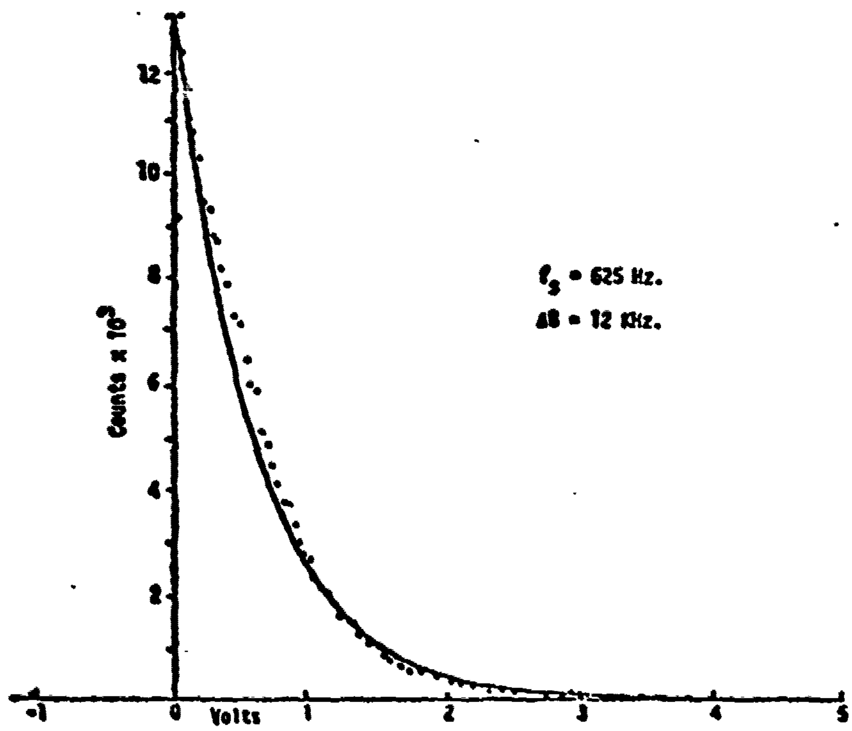


Figure 2

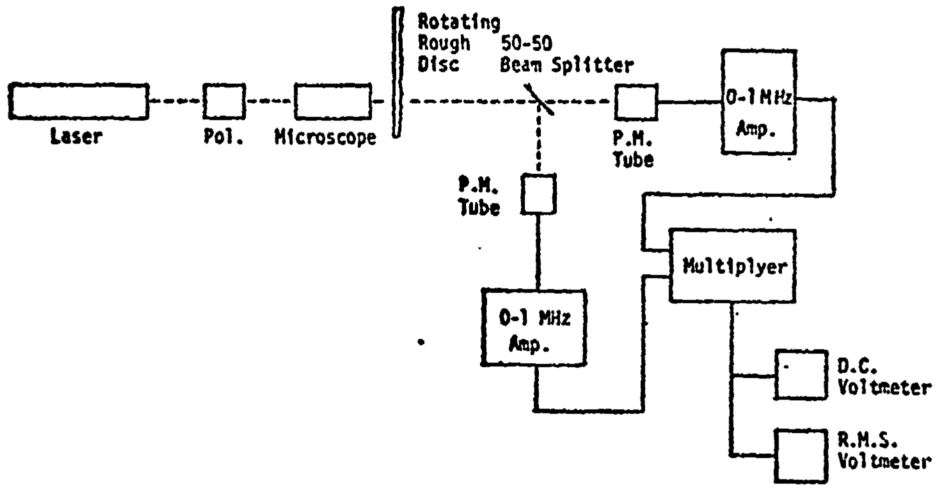


Figure 3

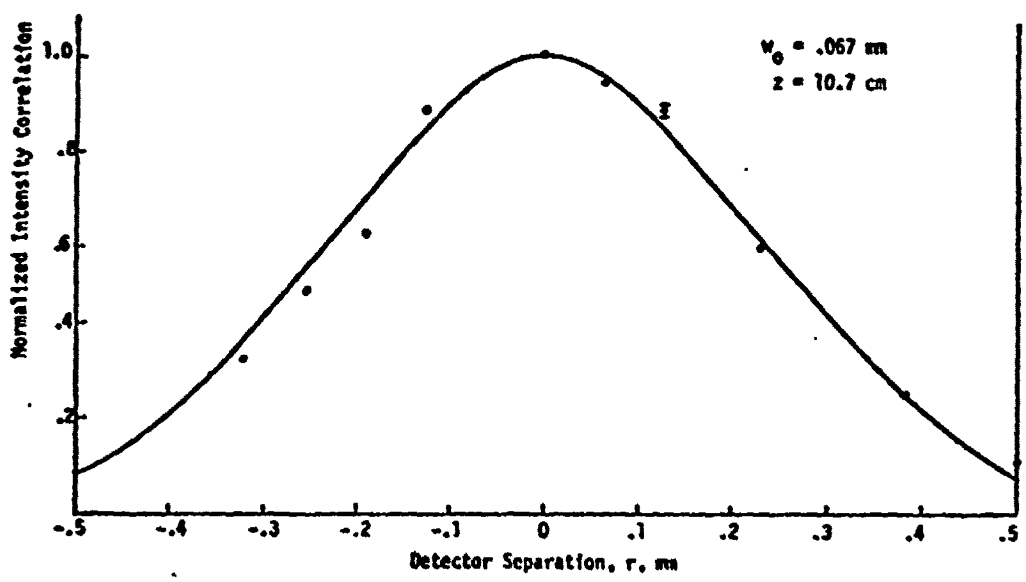


Figure 4

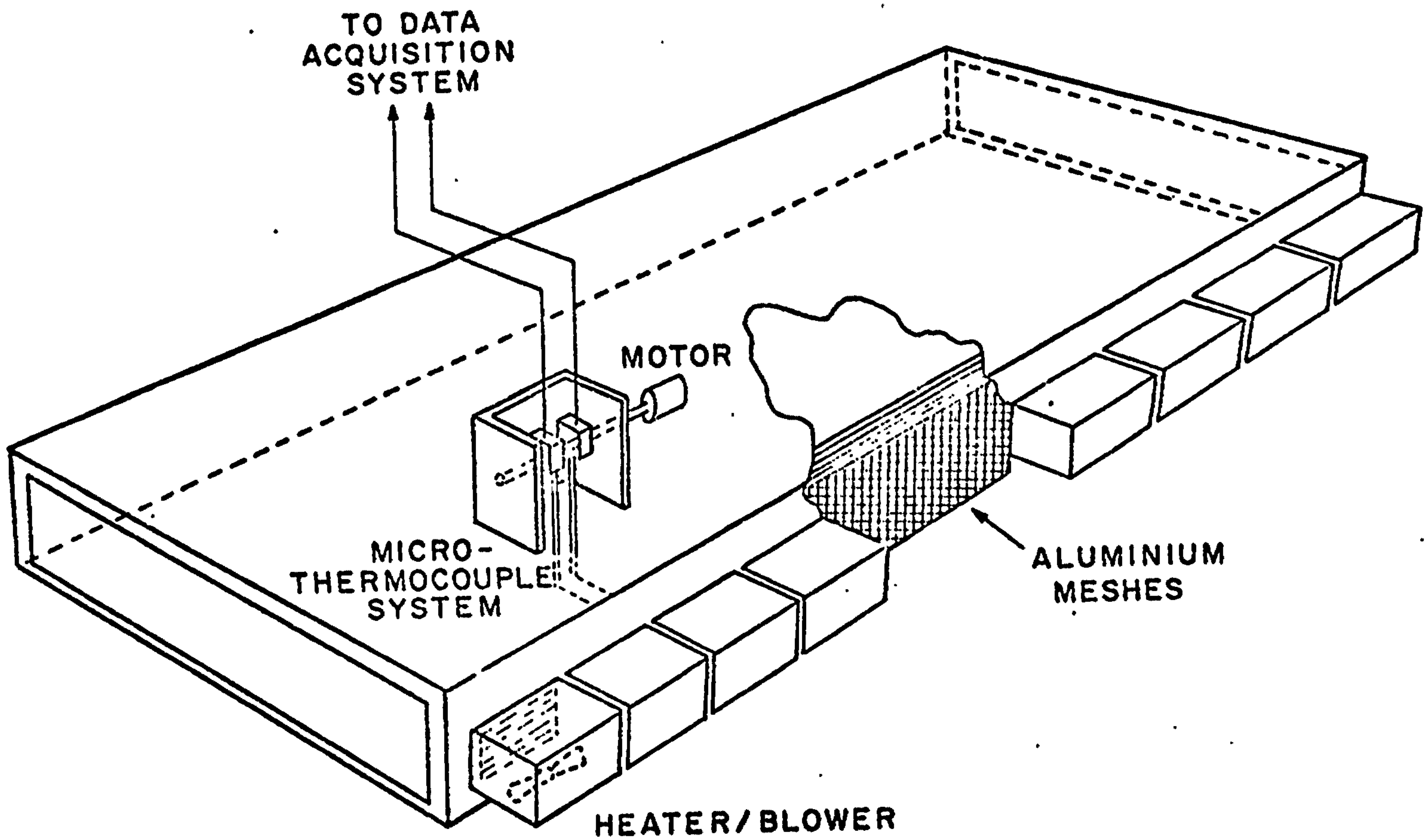

TO DATA ACQUISITION SYSTEM
MOTOR
MICRO-THERMOCOUPLE SYSTEM
ALUMINIUM MESHES
HEATER/BLOWER

FIGURE 5

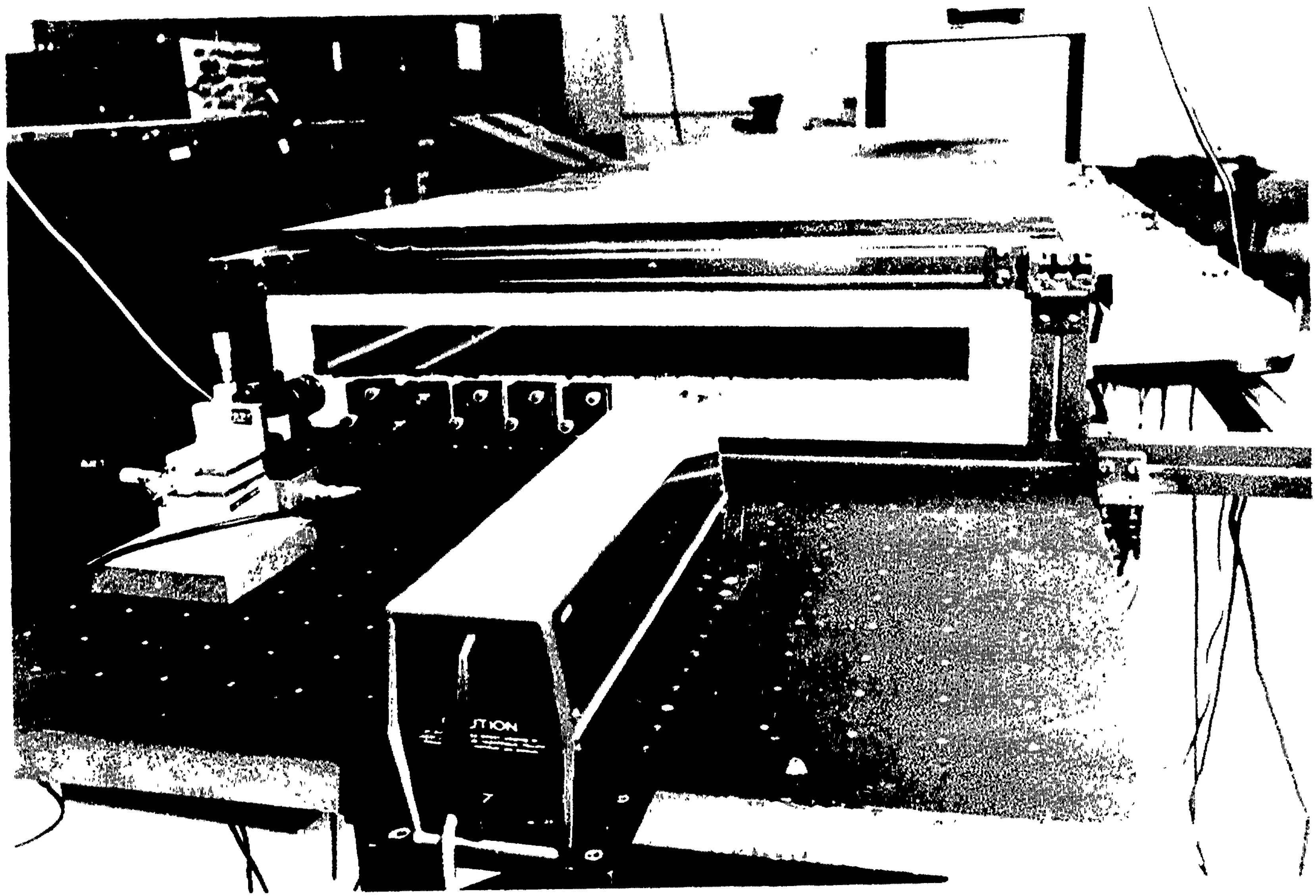


FIGURE 6

ATMOSPHERIC TURBULENCE CHAMBER
AND
MULTIPLE TRANSMISSION EXPERIMENT

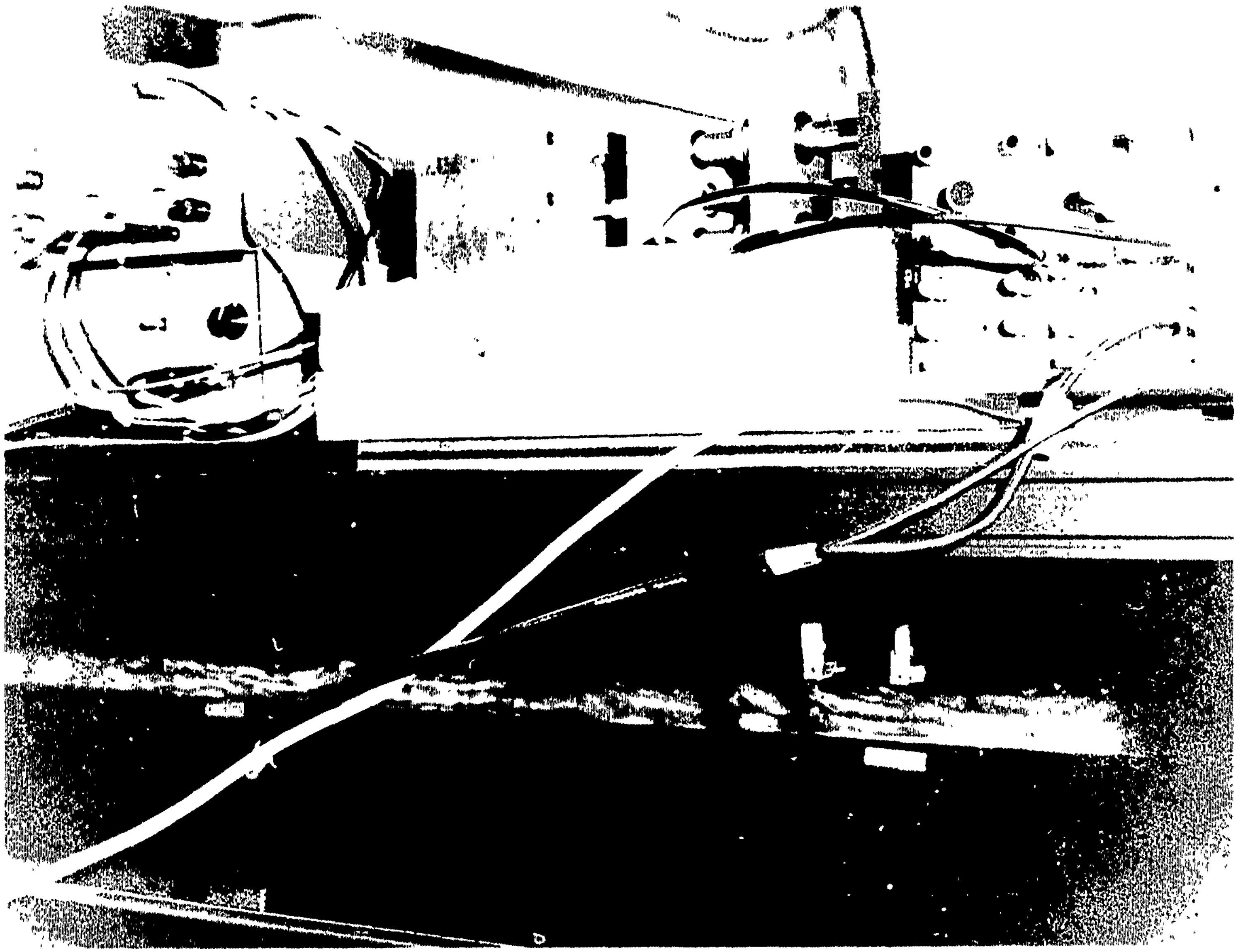


FIGURE 7

MEASUREMENT OF C_T^2 USING A PAIR OF MICROTHERMO-COUPLES

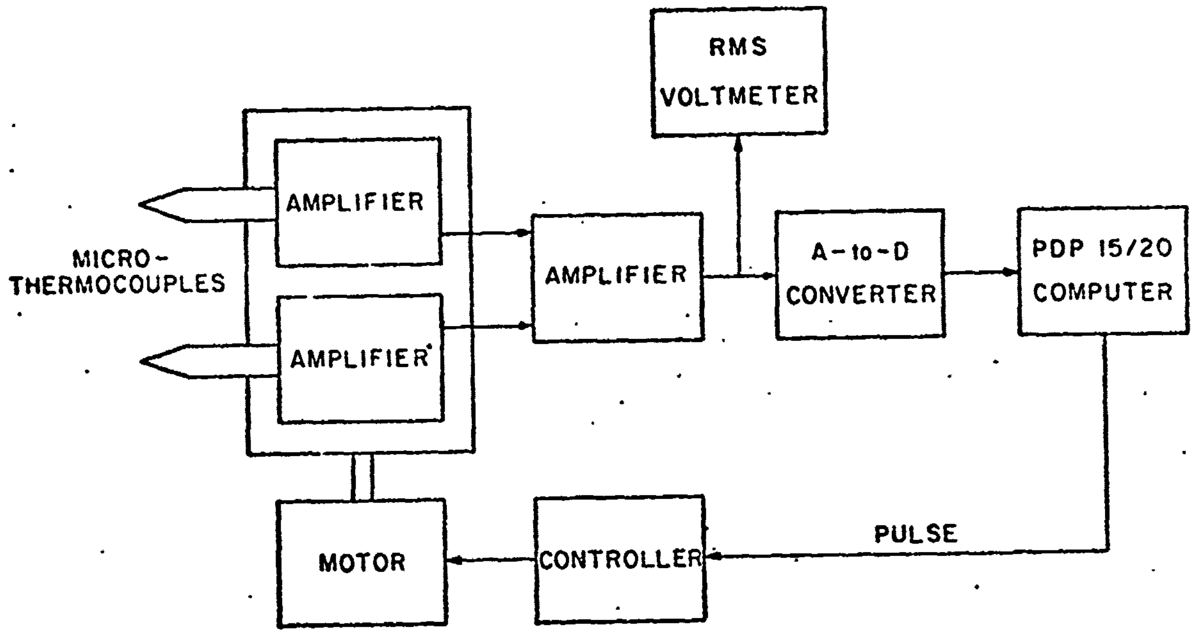


FIGURE 8 A

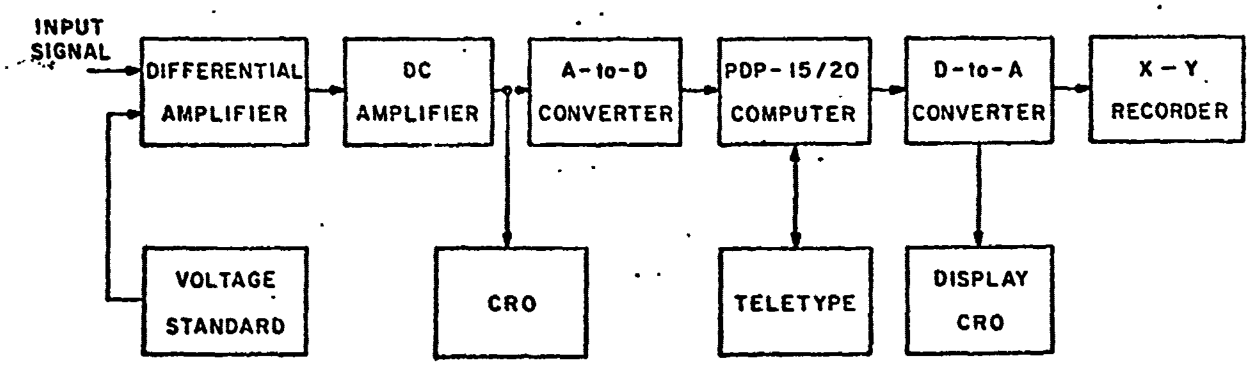


FIGURE 8 B

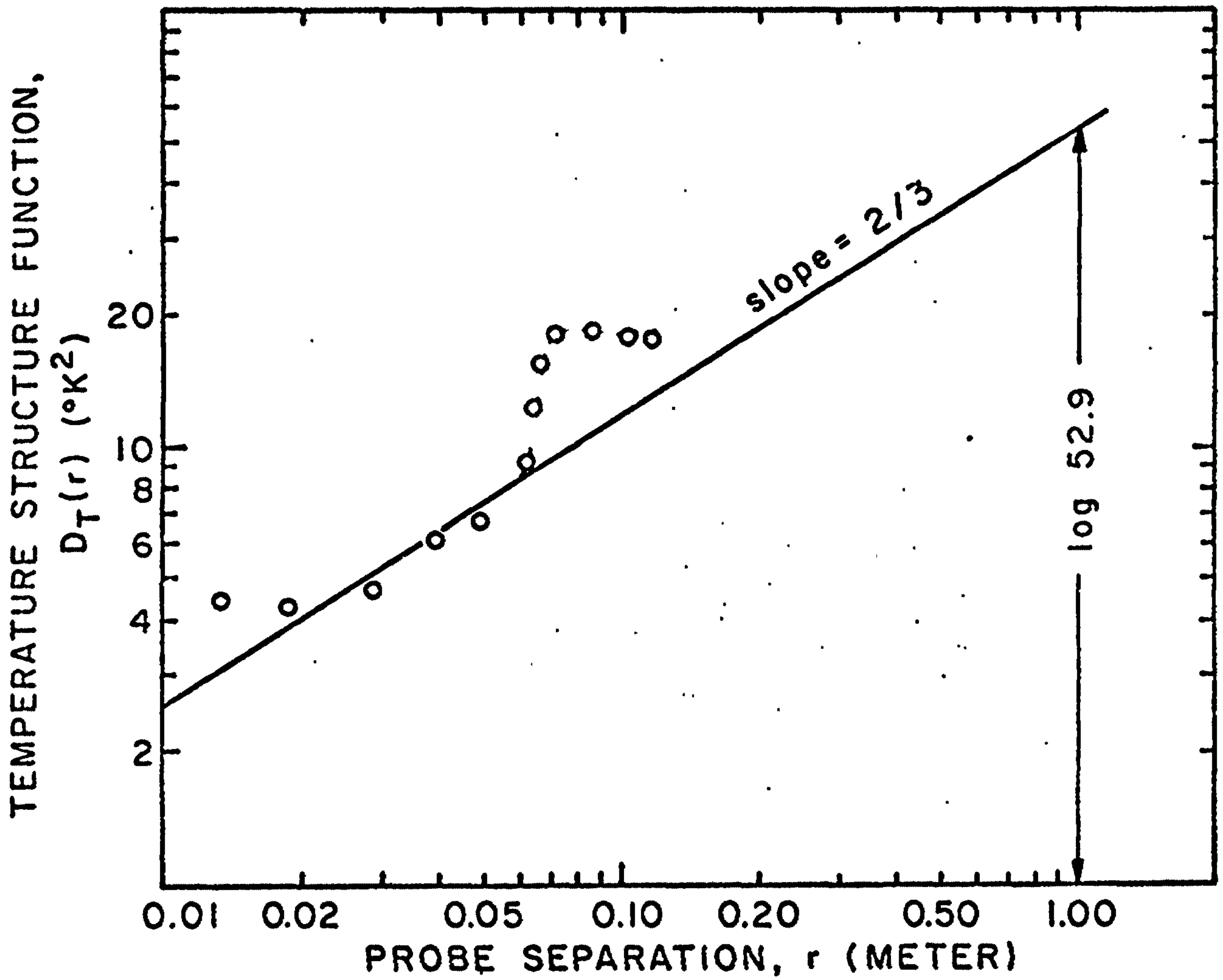


FIG. 9 TEMPERATURE STRUCTURE FUNCTION VERSUS PROBE SEPERATION

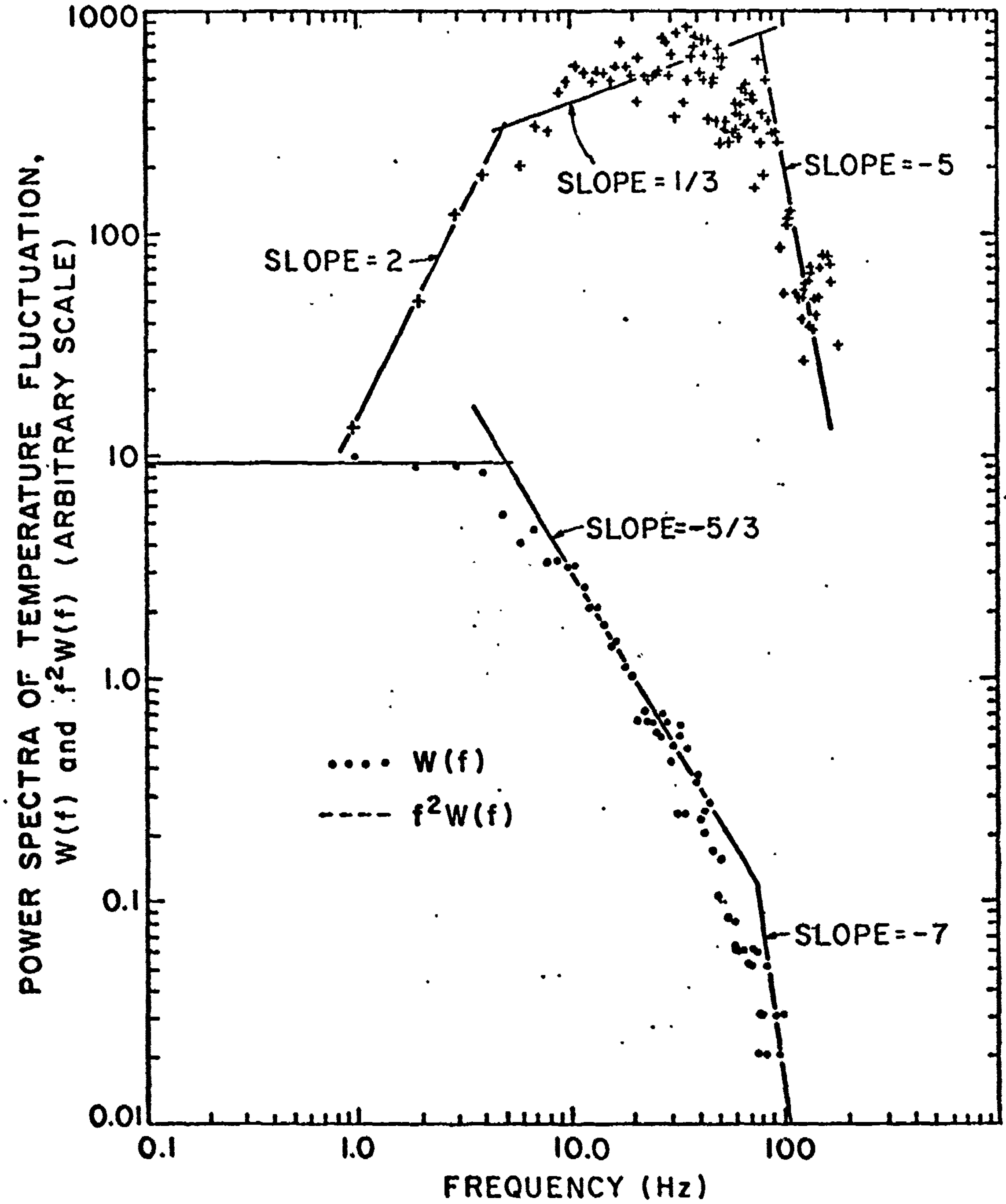


Fig. 10 Power spectra of temperature fluctuations W(f) and f^2 W(f)

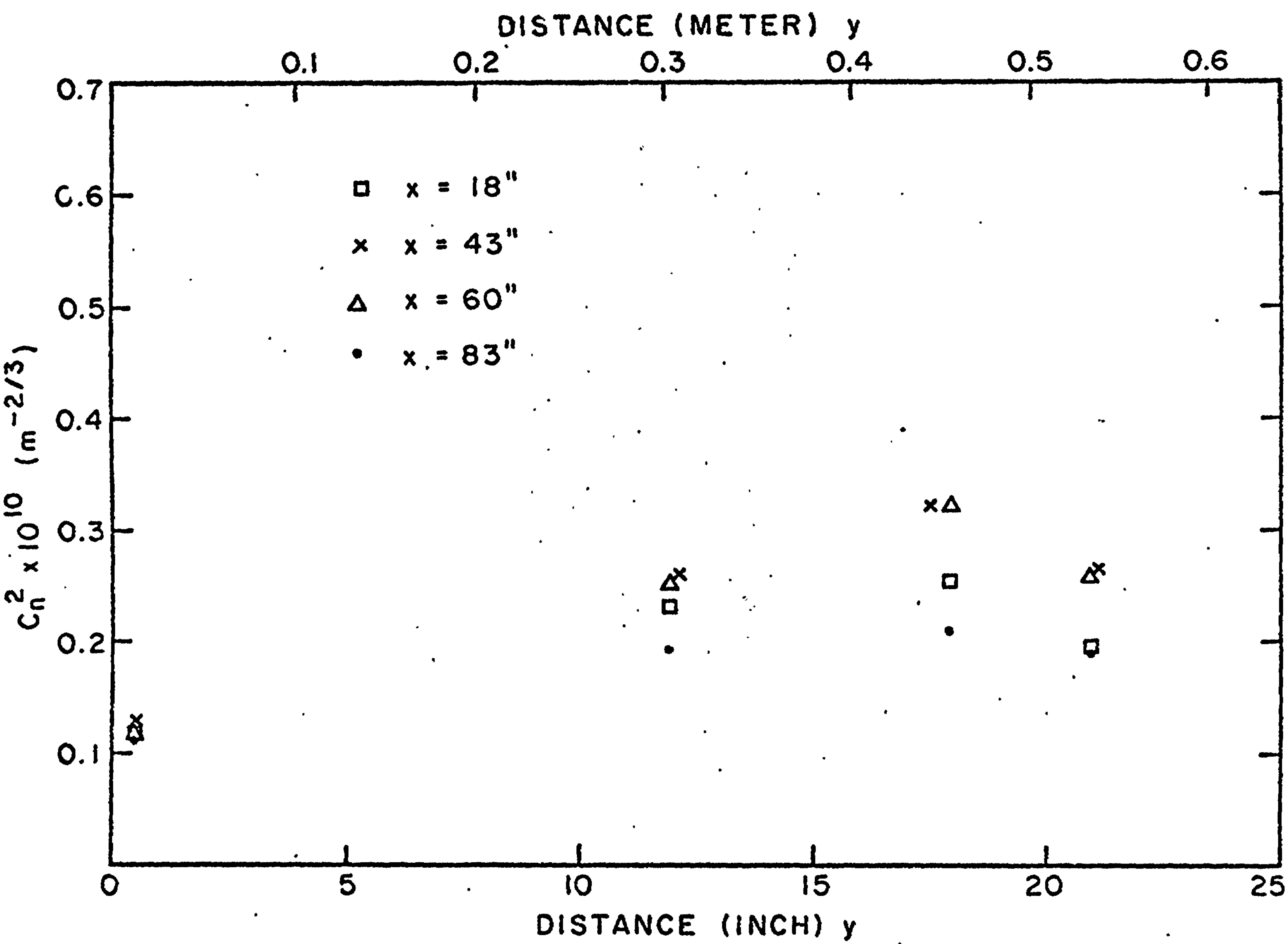
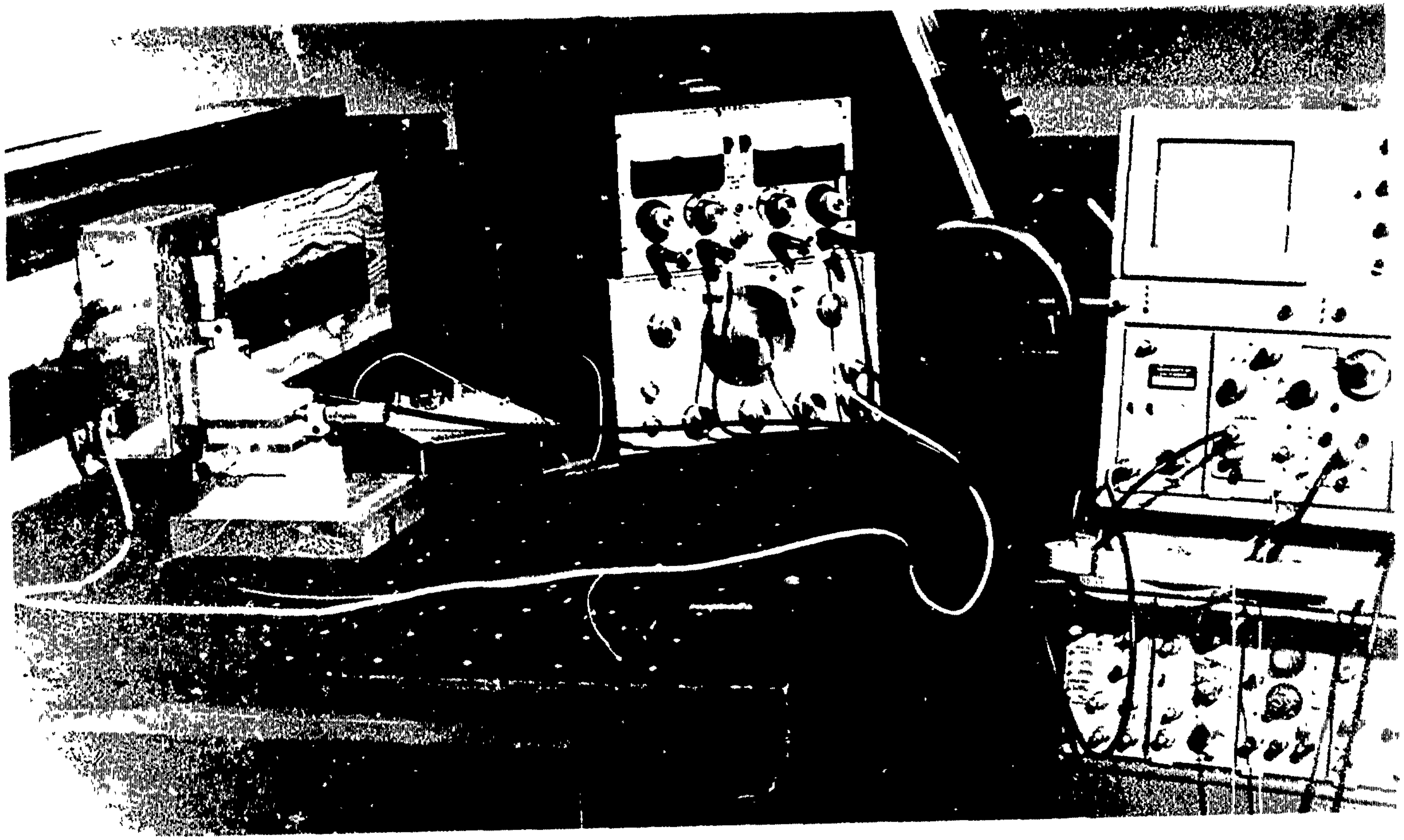


FIG. 11 STRENGTH OF TURBULENCE C_N^2 VERSUS AIR FLOW DISTANCE



INTENSITY CORRELATION EXPERIMENTS USING
RETICON LINEAR IMAGE SENSORS

FIGURE 12

3. FIELD EXPERIMENT

A corner-cube reflector and a flat mirror and the basis for a He-Ne Laser (Spectra Physics 135, 6328Å) were installed on the roof of the Physical Sciences Building (see Fig. 13). The laser beam from Room 952, Engineering Building was transmitted to the reflectors on the Physical Sciences Building over the distance 274 meter. A small receiving telescope (2" diameter, Zoom, Swift) with a photomultiplier tube (IP21) with an interference filter and a pin hole mounted on the micro-positioner is placed next to the He-Ne gas laser in Room 952 (see Fig. 14). The output signal from the photomultiplier tube is amplified by the Tektronix differential amplifier and monitored by a Cathode Ray Oscilloscope on the ninth floor. The output signal from the differential amplifier is transmitted to the Room 436 for digital signal processing by the PDP 15/20 through a 50 Ω coaxial cable. The wind velocity and wind direction are being measured on the roof of the building and their information is being monitored at the digital data acquisition console. The details of digital data acquisition system and programs used are identical to those used for laboratory simulation experiments described in the previous section.

When a collimated beam (diameter 2") of the He-Ne 6328Å was transmitted from the Engineering Building to the Physical Science Building, the following experiments were performed in the evening of 14 Dec., 1976 to the morning of 15 Dec., 1976 from 7:00 pm until 7:00 am. The reason we chose night time was that the atmospheric turbulence is relatively steady compared to the day time.

The results obtained are compared with respect to coefficients of variation (γ_0), skewness (γ_1) and excess (γ_2):

	corner-cube reflector	flat mirror	direct path
γ_0	0.71	0.99	0.3826
γ_1	0.90	0.66	0.1239
γ_2	1.80	0.79	0.2045

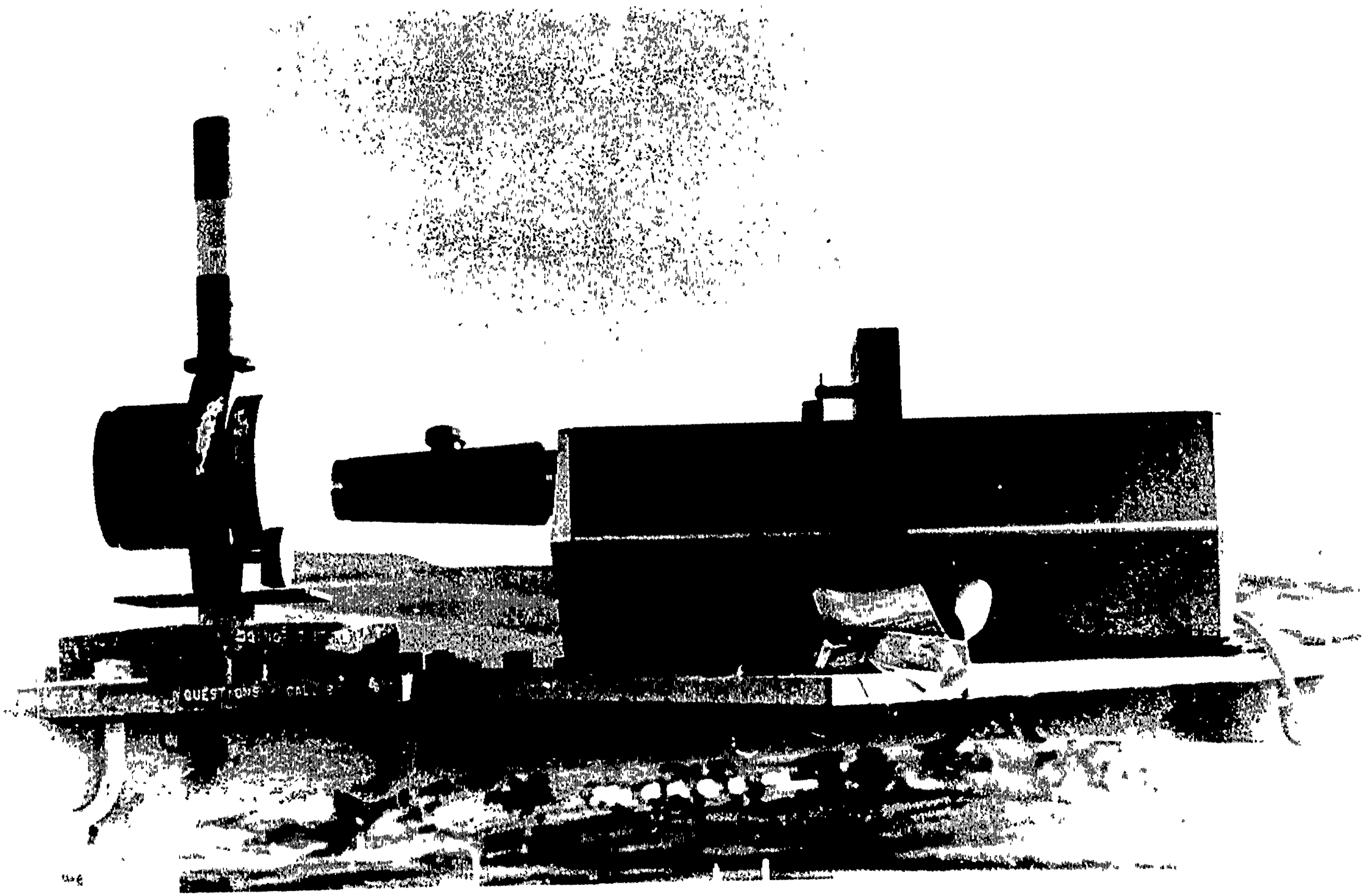
These numbers are typical examples of results obtained. These results were not taken simultaneously, because dedicated, real-time data processing makes simultaneous experiments impossible. During the digital processing, the weather conditions might have changed. The optical path length for the direct path measurement is the half of the total path length of either corner-cube or flat mirror reflector cases.

It is most desirable to use the analog instrumentation tape recorder for storing the analog data of direct, corner-cube and flat mirror cases, simultaneously and analyze these data, later by the PDP 15/20. For this purpose, we plan to utilize the recorder CEC VR 3600, (3 FM Channels, 500 kc, and 3 AM Channels, 1.5 MHz).

We have installed another corner-cube reflector on the top of the campus hill. We can transmit the laser beam from Room 952 Engineering to the reflector over the distance 587.65 meters. We have taken histograms of irradiance fluctuations observed under various weather conditions and also measured coefficients of variation, skewness and excess. Comparing these results with log-normal, Rice-Nakagami distributions, we found many cases deviating from these distributions. The results were discussed at the Optical Society of America Meeting (1974).[12] This location is not convenient for comparing the direct laser transmission because of the lack of electric power supply. Therefore, we may use this reflector after establishing the model of corner-cube reflector in conjunction with optical transmission through the turbulent atmosphere.

During the year of 1974, we installed the corner-cube reflectors (6 units) on the roof of the former Naval Radar site (N - Calif - 1015) at Pleasant Peak in the Cleveland National Forest; altitude, 4,000 ft., approximately 20 miles on the line of site from Room 436, Engineering Building. Unfortunately, before fully utilizing these reflectors, they were stollen. Due to inconvenience and lack of security, we have discontinued the use of this site.

During the year of 1973, we obtained the coelstat consisting of the 16" and 12 1/2" flat mirrors, (Fig. 15). The 16" mirror can be controlled remotely so that we may seek a specific target. We obtained a 10" Newtonian telescope matching the coelstat and installed it in Room 952, Engineering Building (Fig. 16). These mirrors and telescope were manufactured by the Cave Optical Co., Long Beach, CA. After completion of the coelstat telescope system, we transmitted the laser beam through it to the campus hill and analyzed the reflected beam. Then, we detected the effect of the minute mechanical vibration due to the disturbance of wind on the coelstat by analyzing the power spectrum of irradiance fluctuations. A good wind shield such as prefabricated dome is necessary to utilize the system most meaningfully.



A CORNER CUBE AND FLAT MIRROR REFLECTORS AND
A HE-NE LASER FOR DIRECT TRANSMISSION EXPERIMENT

FIGURE 13

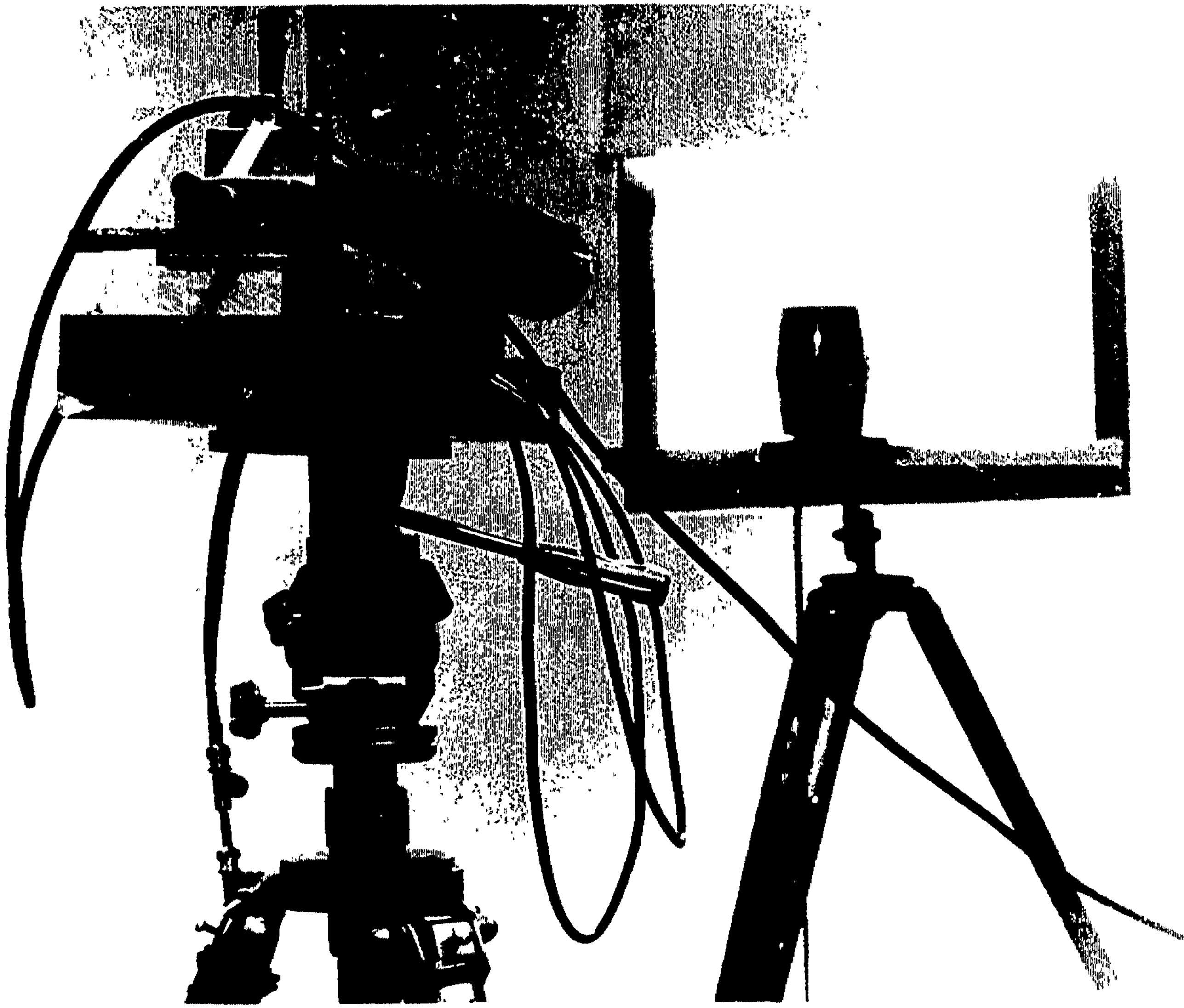
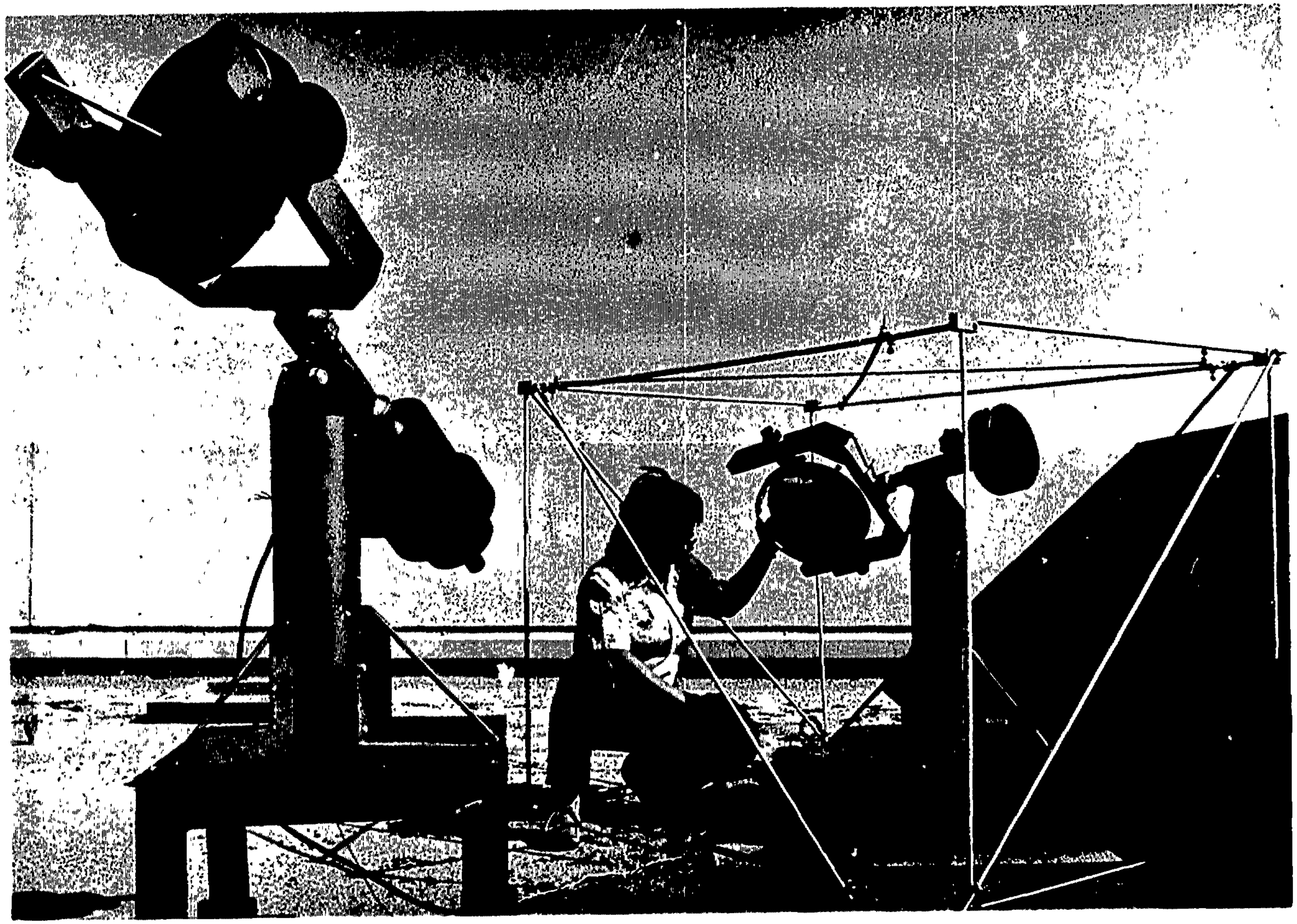
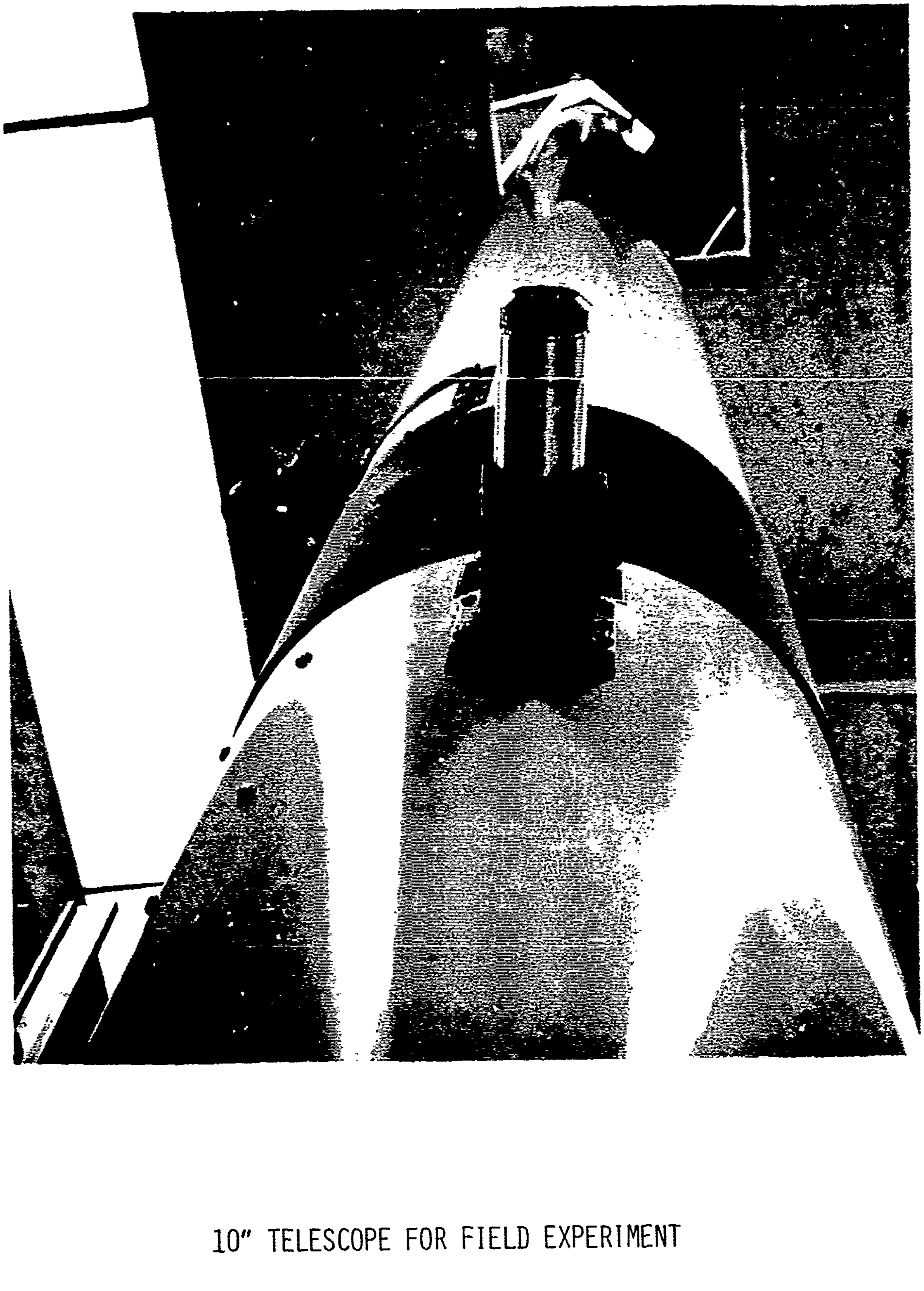


Figure 14 A HE-NE LASER TRANSMITTER AND A RECEIVING TELESCOPE WITH PHOTOMULTIPLIER



COELOSTAT FOR FIELD EXPERIMENT

FIGURE 15



10" TELESCOPE FOR FIELD EXPERIMENT

FIGURE 16

4. COMPUTER SIMULATION

In order to facilitate the computer simulation of optical propagation in the turbulent atmosphere, we have developed the following two basic programs: (1) complex Fourier transform and its inverse transformation and (2) computer generation of gaussian random variables.

The diffraction and scattering of electromagnetic waves in turbulent atmosphere can be treated most conveniently by using the complex wave amplitudes, of which real and imaginary parts are mutually Hilbert transform. This method is well-known in optics as the analytic signal representation. Using the PDP 15/20 with 24 k words core memory, we can now perform compex Fourier transform of 512 words of complex signals. This updated program is included within the IECS described in Appendix A. This program was developed by Wayne Teeter, a honor student in the Senior class, as an engineering aide to this project.

The next step is to define the optical transmission function of turbulent atmosphere and to calculate the diffracted wave produced by a section of the turbulent atmosphere at the observation points. The numerical analysis of diffraction integrals can be handled conveniently by successive use of the complex Fourier transforms.

The optical transmission function of the turbulent atmosphere can be simulated by specifying the refractive indexes of the turbulent air from the ensemble of computer generated random variables. For simplicity, we may assume the gaussian distribution for refractive index at least at the beginning. The fluctuations of the index of refraction should be non-gaussian, because the refractive index is proportional to the temperature of which statistics are clearly non-gaussian. Thus, we have been preparing the computer generation of random variables which can be specified by the central moments or cumulants. Since we measured up to 4th cumulants in the laboratory, computer generation of random variables is emphasized on the first four cumulants.

It would be interesting to note that the complex Fourier transform will also be useful for this random variable generation process. For instance, we first define the characteristic function of the random process using the specified cumulants and then calculate the probability distribution function by applying the complex Fourier transform to the characteristic function. By comparing a computer generated random number x $(0 \leq x \leq 1)$ with the distribution curve, we define a random variable. This is essentially an encoding scheme to generate signals with a non-gaussian statistics from an input pseudo-random number.

The generation of gaussian random variables using the pseudo-random numbers generated by the PDP 15/20 was carried out by Loc Ta, graduate research assistant.

It is an interesting and useful exercise to analyze the case of corner-cube reflector and the plane mirror in the propagation through the turbulent atmosphere. We may establish models for corner-cube and flat mirror cases by comparing the simulation results with experimental results in either a laboratory generated turbulence or in the field.

CONCLUSION

During the past five years, we have studied and established various basic tools for systematic investigation of imaging of incoherent objects through the turbulent atmosphere; pseudo-thermal sources for incoherent objects, the turbulence chamber for laboratory simulation and computer programs for statistical signal processing, automatic measurements and generation of random variables. A general purpose interactive experimental control system program has been developed for PDP 15/20 and has been fully utilized for this research up to the limiting capacity of the computer. These accomplishments will be useful and essential for the next step of the related important research such as establishing the models of the turbulent atmosphere and feasibility study of imaging systems for incoherent objects through the turbulence.

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A GENERAL PURPOSE INTERACTIVE EXPERIMENT CONTROL SYSTEM (IECS)

The IECS is based on the Digital Equipment Corporation PDP-15 computer with 24K words of main memory, two magnetic tape drives (DEC-Tape), a paper tape reader/punch and a Model 35 Teletype. In addition to the standard hardware several "custom" items have been added. They are: an analog-to-digital converter (ADC) with a sample-and-hold front end and a 7 microsecond conversion time, two digital voltmeters (DVM's) with a 5 digit BCD readout and two digital-to-analog (DAC) converters with 10-bit resolution. Fig. 1.1 illustrates this configuration and the interaction between the devices. In support of the hardware attached to the I/O bus there is a graphics pen-plotter and a CRT display oscilloscope attached to the output of the DAC's which provide the graphics output for the IECS.

The control of these add-on peripherals is done in the normal manner through input/output commands sent along the I/O bus. Several machine language utility programs handle the transfer of data to and from the extra peripherals and are described in the following section. All the extra peripherals operate under the interrupt control except the DAC's which do not require interrupt service. The relative conversion speeds of the input peripherals (ADC and DVM's) is such that an overlap in the sampling speeds allows a wide range of signals to be converted. The maximum sampling rate of the ADC is 120KHz while the conversion rate for DVM's is approximately 10 to 200 milliseconds depending upon the magnitude of the voltage being sampled. With the ADC the user may perform most sampling tasks currently in operation in our research group. The sampling speed of the ADC is continuously variable over the range of 0.5Hz to 20KHz (or fixed at 27KHz or 120KHz) to provide for the variety of source signals present in the enviorment.

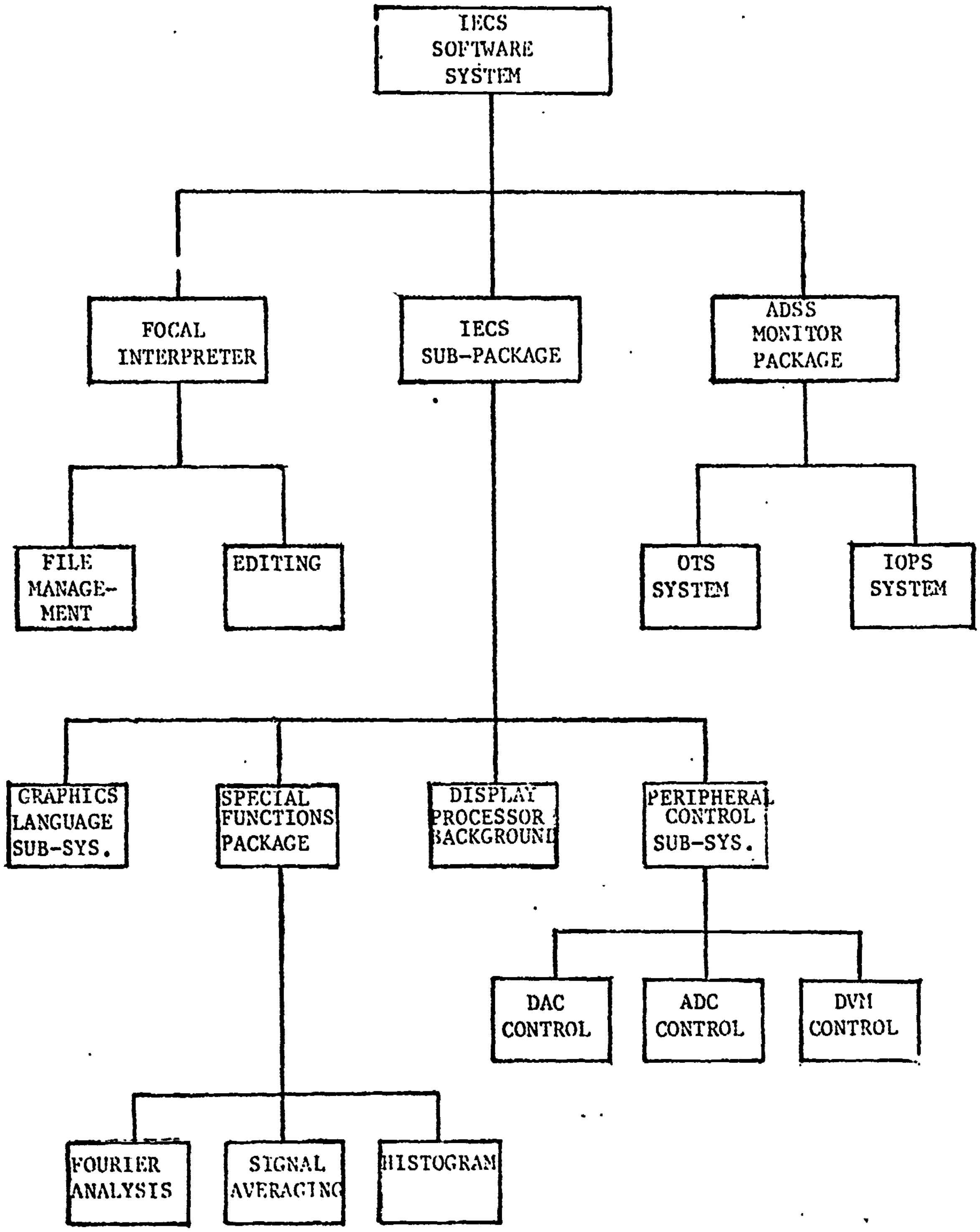
The graphics output devices, pen-plotter and display oscilloscope, are used to display data generated by direct acquisition or indirect computation within the IECS. The graphics pen-plotter and the display ocsilloscope are controlled using the 10-bit DAC's providing a 1024 point resolution for the graphics output data. When the display ocsilloscope is in operation the current image on the screen is refreshed every 30'th of a second to provide a flicker-free trace for viewing. The pen-plotter in turn operates at a much slower rate and is capable of plotting one point every 80 milliseconds.

The standard peripherals, magnetic tape and paper tape are serviced through the normal system utilities and provide a means for mass backup storage of programs and data. The teletype is used chiefly for the processing of language commands and the printing of some data output. A link exists to the PDP-10/70 computer through the magnetic tape where any large printed output may be taken to be listed on the high speed line printer.

Given the best hardware system available a computer still requires software to implement the desired actions. It is through the software that a computer system becomes the powerful computational and control tool that we witness today. The software on which the IECS is based was initially developed by the Digital Equipment Corporation for use on the PDP-8 computer. The programming language FOCAL was designed to be run on the first minicomputer priced in the range affordable by the general public. This computer (the PDP-8I) had a memory of 4K words, a Teletype and a paper tape reader/punch. It was a "bare bones" system to say the least. To be of any use to our application, the FOCAL language had to be extended to include control of the peripheral devices attached to the I/O bus. The original PDP-15 version of the FOCAL interpreter was first extended by several individual groups including the University of Mississippi Medical School and a group of users at the Los Alamos Scientific Laboratory. The current version of FOCAL operating in conjunction with the special utilities package that comprises the IECS is a modified version of the above two enhanced versions. It would be correct to say that the FOCAL processor operating under the IECS is a far cry from the original FOCAL language processor first implemented on the PDP-8 in 1965.

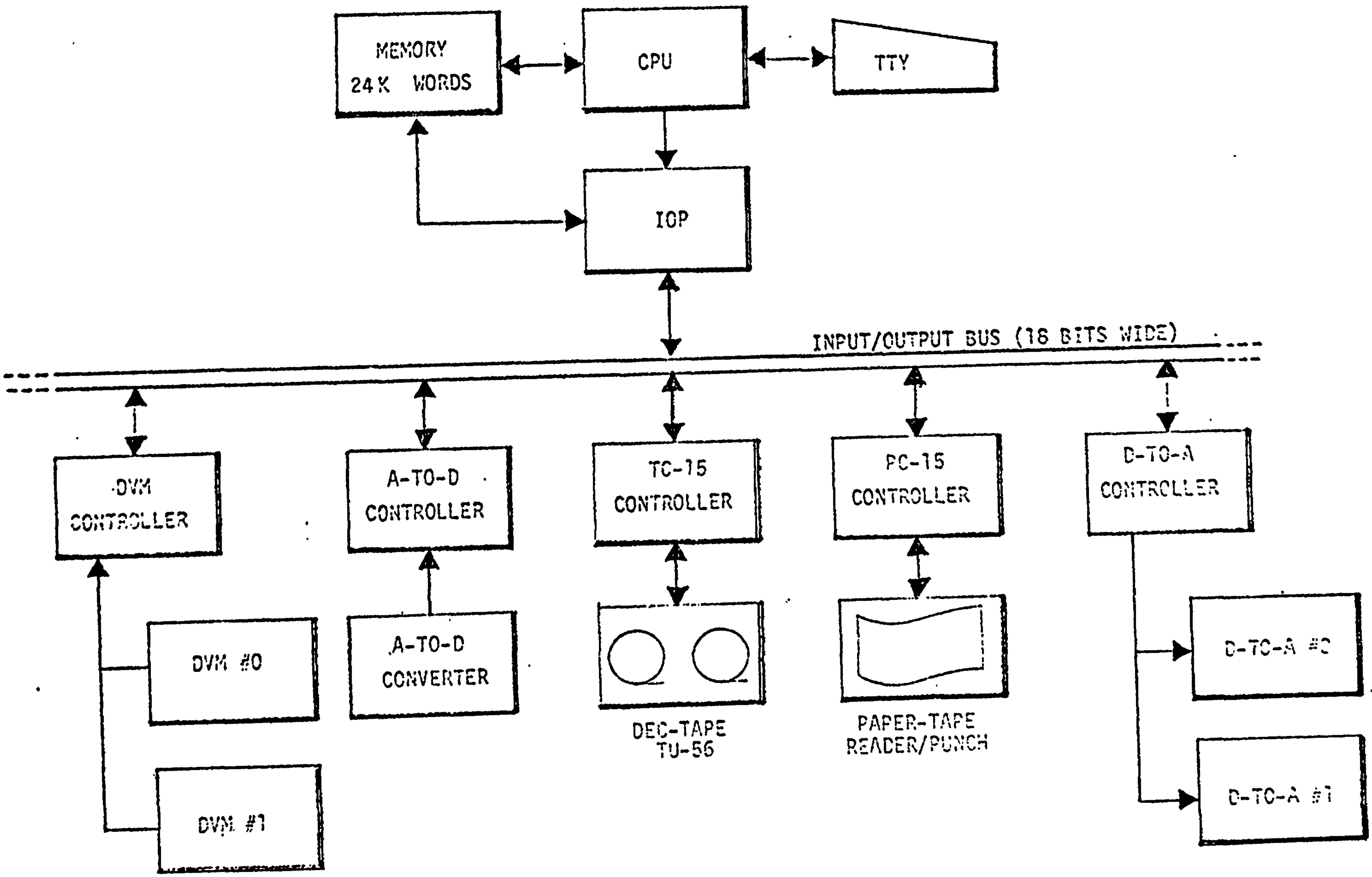
Fig. 1.2 outlines the basic software configuration as cu -ently implemented at the School of Engineering of the University of California, Irvine. The system consists of a FOCAL language interpreter which is used to process the FOCAL language programs generated by the user, edit these programs using the Teletype and provide an overall control over the operational structure of the

IECS. Working in conjunction with the FOCAL interpreter is the utilities pavkage which transforms the original FOCAL interpreter into the IECS. This package consists of special functions needed to provide full control over the data acquisition and display processes (the computational ability is contained within the original interpreter). The third major portion of the IECS is the run-time software required to interface to the mass storage devices, control the Teletype and provide floating point computation capabilities needed during the execution of FOCAL language programs (the current installation of the PDP-15 does not have a hardware floating point processor).



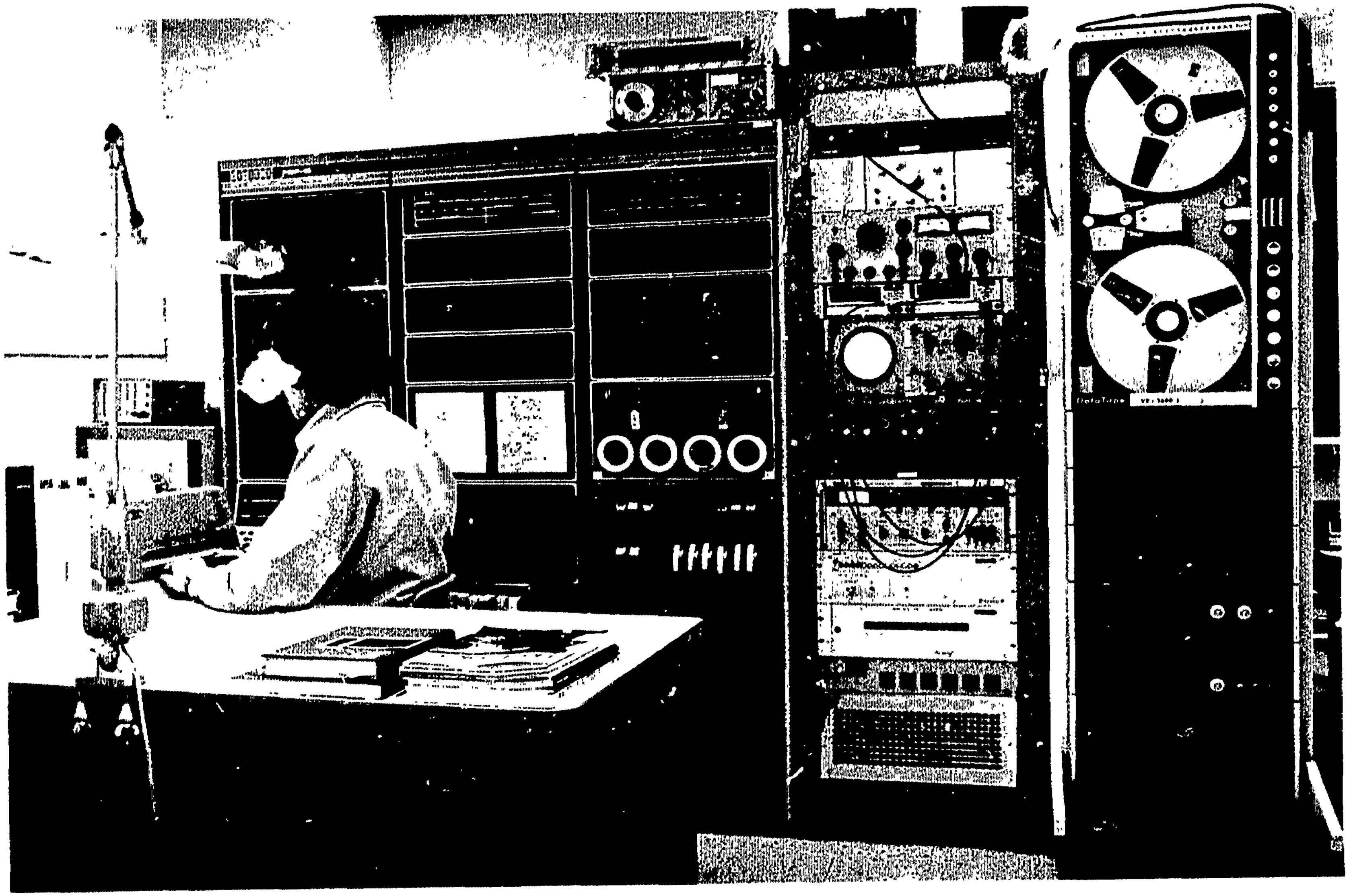
SOFTWARE CONFIGURATION

FIGURE 17



HARDWARE CONFIGURATION

FIGURE 13



PDP 15/20 DATA ACQUISITION SYSTEM

FIGURE 19

REVIEW OF PERTINENT RESEARCH

A pseudo-thermal light source was used for simulating the Brown-Twiss intensity interferometer by Martienssen and Spiller[1] and later by Haner and Isenor.[2] From the intensity interferogram in the form of the transparency obtained by the system similar to those mentioned above, the image of a pseudo-thermal light source was reconstructed by applying the Fraunhofer diffraction, an optical analog of Fourier transform.[3] The design and results of Narrabri intensity interferometer constructed in Australia by R. Hanbury Brown was described in his book on the intensity interferometer.[4] In this book, Hanbury Brown emphasized the freedom of the system from the atmospheric scintillations as a remarkable and important property of the interferometer and mentioned that, "It would be worthwhile to refine both the analysis and the observations to establish these effects more precisely." (P. 72, Reference 4).

The unique determination of the image of an arbitrary incoherent object is not possible by using the Hanbury Brown intensity interferometer because the phase of mutual intensity cannot be obtained. One of the interferometric systems which can recover the phase information is Jennison's phase sensitive interferometer, which measures interferences between three beams of incident radiation field.[5] Both R.C. Jennison interferometer and the triple intensity are not sensitive to the atmospheric phase disturbances. Further detailed investigation of this effect is worthwhile.

Another type of intensity interferometer which will not be disturbed by the atmospheric phase fluctuations and can uniquely reconstruct the incoherent object is the intensity interferometer with a coherent background due to the principal investigator. The astronomical interferometer using the heterodyne detection is intimately related to this interferometer. The heterodyne interferometer for the astronomical observation was studied by Nieuwenhuijzen,[6] Van de Stadt[7,8] and Johnson, et al.[9] The laboratory experiment also related to the interferometer was performed by Soemarjona and Hirano.[10] The compound intensity interferometer which measures the intensity correlation between one beam and the product of two beams with a small seperation proposed by Mc Phie[11] is also pertinent to the subject of this research grant.

The magnitude of mutual intensity due to an incoherent source such as a star can also be determined by measuring the ensemble average of spatial autocorrelation functions of the instantaneous image intensity under the influence of atmospheric turbulence. This was pointed out independently by Labeyrie[12] and Asakura, et al.[13] This method is called the speckle interferometry and has recently been reviewed by Dainty.[14] Note that the phase information of mutual intensity cannot be determined by the speckle interferometry in general.

Certain classes of pattern of incoherent light sources can be determined by observing only magnitude of mutual intensity by the Hanbury Brown and Twiss intensity interferometer, if the phase of mutual intensity can be derived from its magnitude uniquely or phase information of certain patterns are predetermined. The relations between phase and magnitude of the mutual intensity are given by the Hilbert transforms. Phase problems in coherence and theory and intensity interferometry were studied by Nussenzvieg[15] and Bates.[16] It should be noted that some results on the analogous relations extensively studied in the electric network theory may become very useful in optical problems. Some symmetric patterns which can be detected without additional phase information were studied by the principal investigator in conjunction with the optical pattern recognition.[17]

The image reconstruction from the modules of mutual intensity function were studied by Kohler and Mandel[18] using the analytical properties of mutual intensity function.[19] The phase determination of mutual intensity in the presence of atmospheric seeing has been discussed by Rogstad with respect to multi-element interferometry along the line of Jennison interferometry.[20] An optical telescope array for intensity interferometer was treated.[21] A method for recovering phase information which is missing in the speckle interferometry was treated by using the autocorrelation of Fourier transform of image intensity influenced by the atmospheric fluctuations.[22] The phase errors in Michelson interferometer, their indentification and the removal was treated by using the concept of complex zeros of the interferogram.[23] A more unified approach to the imaging viewed through randomly fluctuating media based on interferometry and holography was presented.[24]

Important review articles and books on wave propagation in the turbulent atmosphere are referenced in 24-29. The English translation of V.I. Tatarski report[25] has been utilized extensively in our recent research. Reference 27 is useful to provide the up-to-date overview of current research activities on the optical propagation in the atmosphere in many countries. The forthcoming book by A. Ishimaru[29] includes C_υ^2 in the turbulent atmosphere due to the solar wind as well as the most up-to-date review of multiple scattering. The wave propagation in the turbulent atmosphere plays an essential part in adaptive optical system, which is very well covered in the recent special issue.[30]

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