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# PROPAGATION OF MULTIWAVELENGTH LASER RADIATION THROUGH ATMOSPHERIC TURBULENCE

J. Richard Kerr

Oregon Graduate Center for Study and Research

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Oregon Graduate Center for
Study and Research

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13. ABSTRACT

This program represents a continuation of a comprehensive experimental investigation of laser beam scintillations due to atmospheric turbulence. This report summarizes the efforts that are underway on three aspects of the problem: 1) multiwavelength scintillations over a long horizontal path, 2) turbulence intermittency effects, and 3) transmitter-aperture effects including the cancellation of atmospherically-induced beam wander.

The long-path horizontal measurements are expected to clarify the behavior of beam statistics at very high levels of integrated-path turbulence. The effects of fundamental turbulence intermittencies on data spread, confidence limits, and propagation analyses are postulated to be much more significant than generally realized. The cancellation of atmospherically-induced beam wander and the clarification of predictions from a recent theory of reciprocity for a turbulent path are of potentially great practical importance in the design of laser illumination systems.

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# PROPAGATION OF MULTIWAVELENGTH LASER RADIATION THROUGH ATMOSPHERIC TURBULENCE

J. Richard Kerr

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This technical report has been reviewed and is approved

Raymond P. Urtz

RADC Project Engineer

# SUMMARY

This program represents a continuation of a comprehensive experimental investigation of laser beam scintillations due to atmospheric turbulence. This report summarizes the efforts that are underway on three aspects of the problem: (1) multiwavelength scintillations over a long horizontal path, (2) turbulence intermittency effects, and (3) transmitter-aperture effects including the cancellation of atmospherically induced beam wander.

The long-path horizontal measurements are expected to clarify the behavior of beam statistics at very high levels of integrated-path turbulence. The effects of fundamental turbulence intermittencies on data spread, confidence limits, and propagation analyses are postulated to be much more significant than generally realized. The cancellation of atmospherically induced beam wander and the clarification of predictions from a recent theory of reciprocity for a turbulent path are of potentially great practical importance in the design of laser illumination systems.

TABLE OF CONTENTS

## I. INTRODUCTION

This program represents a continuation of a comprehensive experimental investigation of laser beam scintillations due to atmospheric turbulence. The efforts are now concentrated on three aspects of the problem: (1) multiwavelength scintillations over a long path, (2) turbulence intermittency effects, and (3) transmitter-aperture effects including the cancellation of atmospherically induced beam wander.

The long-path horizontal measurements are expected to clarify the behavior of beam statistics at very high levels of integrated-path turbulence. In particular, the behavior of a visible beam well "beyond saturation" is being investigated, and saturation of 10.6-micron scintillations has been demonstrated. The measurements have been completed and the data are currently being reduced; preliminary conclusions are discussed in Section II.

The effects of fundamental turbulence intermittencies on data spread, confidence limits, and propagation analyses are under study as outlined in Section III. An appropriate experimental program will be defined and carried out.

The cancellation of atmospherically induced beam wander in laser illumination systems will be investigated as described in Section IV. The effort will include the clarification of predictions of a recent theory of reciprocity over a turbulent path, and the resolution of certain contradictions between these predictions and those of published beam-wave propagation analyses.

## II. SCINTILLATION OVER A LONG PATH

A new field facility has been established for the measurement of multiwavelength scintillations over a long (4 mile) horizontal path with uniform terrain. The integrated-path turbulence level which is thus available is probably the highest that has been utilized in atmospheric scintillation experiments and represents a practical upper limit.

The transmitter emits coincident, simultaneous beams at 4880Å and 10.6 microns, with sufficiently small apertures to constitute virtual point sources at both wavelengths.[1] The facility, which is described further in Ref. 2, includes a provision for varying the initial beam height in response to variations in vertical beam refraction by the atmosphere. The receiver and data processing systems are described in the literature.[3]

The purpose of these measurements is to determine the parameter dependencies and scintillation statistics for this extreme case. The effort includes the measurement of log amplitude variances, covariances, probability distributions, scintillation spectra, and receiver aperture-smoothing. Goals include the demonstration of saturation at 10.6 microns, and the examination of very strong "supersaturation" at 4800Å.

Following a series of difficulties with the stabilized $CO_2$ laser which was used as the 10.6-micron source, successful measurements were made during the final hot, high-turbulence days of the summer. These data are currently being reduced and interpreted and will be presented in detail in the next Technical Report. The diurnal measurements were consistent over the several days considered, and the most interesting results are briefly summarized below.

Observations using the 4880Å beam and also with a sighting telescope indicated that very substantial vertical beam refraction occurs over such a path. In the early morning, when the turbulence is low, the ground is colder than the ambient air (inversion), and the beam curvature is parallel to that of the earth. This corresponds to the mirage phenomenon. However, by afternoon, the opposite thermal gradient is present, and the beam curvature is reversed. This raises the apparent horizon and determines the minimum fixed transmitter and receiver beam heights which may be used: these heights are chosen such that the midpath beams at mid-day are approximately 50 cm above the ground cover, or comfortably above the level at which partial midpath blockage is observed.

In all cases, the calculation of integrated-path turbulence level requires the use of thermal gradient data to determine the detailed beam refraction. It is apparent that the beam trajectory during the hot part of the day serves to further increase the effective turbulence level by maintaining the optical path nearer to the ground.

Results of interest include the following:

1. "Supersaturation" or the fall-off of log amplitude variance with increasing turbulence continues to occur without leveling off as the integrated-path turbulence increases to a very high level. The supersaturated variance at 4880Å has been observed to decrease to 0.06, which is an order of magnitude below the maximum value observed at lower turbulence levels.

2. Under this highly supersaturated condition, the 4880Å covariance curve broadened very substantially. Correspondingly, the spectral width of scintillations decreased, and aperture smoothing

in a receiver which was much larger than the Fresnel zone became quite ineffective.

3. Saturation of 10.6-micron scintillations was observed at log amplitude variances of approximately 0.5. Under high turbulence conditions, the covariance curve was seen to narrow substantially. This was supported by an increase in the scintillation spectral width and agrees with results obtained previously over a shorter path.[3]

4. No tendency towards Rayleigh--rather than log normal--statistics was indicated.

The interpretation and ramifications of these interesting results will appear in the next Technical Report. It is apparent that, from a theoretical standpoint, the characteristics of highly saturated scintillations are even more poorly understood than may be generally recognized.

## III. TURBULENCE INTERMITTENCY AND ITS EFFECTS ON SCINTILLATIONS

As we have discussed preliminarily in Ref. 4, it appears that the fundamentally intermittent nature of atmospheric turbulence may have substantial and largely unappreciated effects on scintillations. First, this intermittency relates to the typically large spread in experimental data on propagation through turbulence; and second, the highly nonuniform distribution of turbulence over the path at any given instant may require a modification of the fundamental theoretical predictions for scintillation. In this section, we reformulate the problem and outline the theoretical and subsequent experimental steps to be taken.

In order to isolate the effects of intermittency *per se*, we assume

(1) An infinite plane or spherical wave (neglect finite beam-wave effects)--the latter implies a point source and is easily approximated in experimental measurements.

(2) Applicability of the Kolmogorov or inertial subrange model of the turbulence[5].

(3) Applicability of the first-order theoretical approaches to the propagation problem (no saturation of scintillations), at least initially.

Given any instantaneous realization of the atmospheric path, the expression for the log amplitude variance of scintillations for smoothly varying turbulence is[5]

$$\sigma^2 = k^{7/6} \int_0^L C_n^2(z)\, f(z) \quad dz \quad , \qquad (1)$$

where k is the optical/infrared wavenumber, $C_n^2$ is the refractive index structure constant or turbulent strength, z is the distance from the transmitter, and L is the pathlength. The weighting function f(z) depends on the nature of the transmitter--i.e., plane or spherical wave source.

If the path is statistically homogeneous, the ensemble or (ignoring problems of diurnal stationarity) long-term time average is

$$\langle \sigma^2 \rangle = k^{7/6} \langle C_n^2 \rangle \int_0^L f(z) \; dz \qquad (2a)$$

$$= (\text{constant}) \times k^{7/6} \langle C_n^2 \rangle L^{11/6} \qquad (2b)$$

Let us now consider the measured values of $\sigma^2$ $(t,\tau)$ and $C_n^2$ $(z, t,\tau)$, where $\tau$ is the finite averaging time and these quantities have themselves become random functions of time (t). The basic question of optimal averaging times per se is under investigation by Collins and co-workers.[6-7] Here we point out that the highly intermittent nature of the turbulence may contribute substantially to this question and to the related matters of expected data spread, confidence limits, and diurnal stationarity problems. This occurs because the more intermittent the turbulence, the poorer the path-averaging and the more variable $\sigma^2$ $(t,\tau)$ is for reasonable $\tau$. In particular, a long-term average of $\sigma^2$ may obscure very important short-term signal fades which cause unacceptable error rates or non-operative intervals in real systems.

The first step is therefore to apply the appropriate theory of finite-time averages[8-11] to relate the statistics of $\sigma^2(t,\tau)$ and $C_n^2$ $(t,\tau)$. This will lead to the definition of suitable experiments involving the measurement of e.g. microthermal and optical autocorrelation functions, in order to establish an understanding of data spread and confidence limits.

An even more fundamental effect of the intermittencies may be to invalidate Eqs. (1) and (2) through the effects of a nonzero inner scale. To see this, we idealize the intermittency such that the nonzero turbulence is confined to a single, statistically uniform slab with length $\ell$, path position $z_1$, and internal turbulence level $C_n'^2$ (Figure 1). We let $\ell_o > (\lambda\ell)^{1/2}$, where $\ell_o$ is the inner scale of turbulence.[5]

To further simplify this illustration, we assume that the transmitter emits a large, collimated beam such that the conditions for plane-wave results are fulfilled.[1] The illumination of the turbulent slab is then independent of $z_1$. We may naively apply Eq. (1) by inserting the appropriate[5] $f(z)$:

$$\sigma^2 = 0.56\, k^{7/6} \int_0^L C_n^2(z)\, (L - z)^{5/6}\, dz \tag{3a}$$

$$= 0.56\, k^{7/6} C_n'^2 \int_{z_1}^{(z_1 + \ell)} (L - z)^{5/6}\, dz\ . \tag{3b}$$

However, due to the inner scale being larger than the Fresnel zone size for the slab, the true variance at the output end of the slab is given by[5]

$$\sigma_1^2 = 3.2\, C_n'^2\, \ell^3 \ell_o^{-7/3}\ , \tag{4}$$

where we assume no apriori knowledge of its position $(z_1)$. The resultant variance at the receiver will depend upon the further evolution of the optical field over the distance $(z - z_1)$ and may be determined as in the theoretical treatments of scattering from single slabs.[12-14] We denote this resultant receiver variance by $\sigma^2(z_1)$, where the dependence upon the slab position is explicit; we may then recognize $\langle\sigma^2\rangle$ as the expected value of $\sigma^2(z_1)$ with a uniform probability distribution of $z_1$ over the path. The result will certainly not agree with that of Eq. (3b).

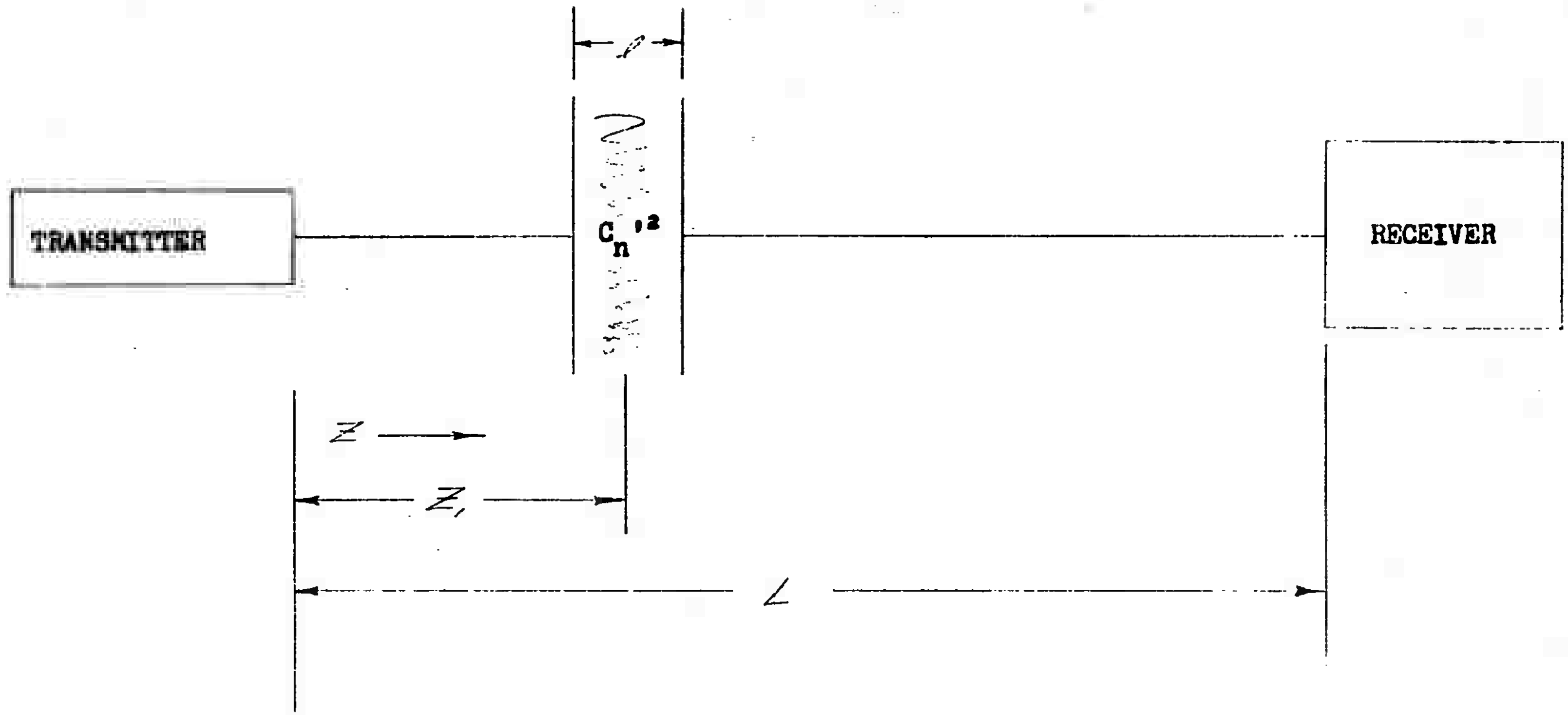


FIGURE 1. Idealization of intermittent turbulence.

These considerations will be expanded, utilizing a reasonable model for the intermittencies.

After a final definition of the statistical quantities of importance, experiments will be performed to relate optical/infrared scintillation measurements or short term averages over a statistically homogeneous path, to corresponding microthermal quantities taken at one or more points on the path. Our existing facilities permit the FM tape recording of $\sigma^2$ (t, τ) and $C_n^2$ (t, τ), from which analog-to-digital conversion and digital processing may be readily implemented.

## IV. TRANSMITTER-APERTURE EFFECTS AND THE CANCELLATION OF ATMOSPHERICALLY INDUCED BEAM-WANDER

### A. Basic Motivation

This project was stimulated by recent theoretical work on reciprocity through a turbulent atmosphere,[15] from which it was inferred that a relatively simple technique may be utilized to cancel atmospherically induced beam wander. The reciprocity is based on a simple mathematical consequence of linearity of the medium, and is independent of such factors as strength of turbulence or applicability of a Kolmogorov model. The theory may also be used to infer the conditions under which receiver or target illumination will be substantially improved by the cancellation of wander, as opposed to situations where the beam is badly spread or broken up and correctable only through fully adaptive compensation at the transmitter.

The reciprocity theory basically equates the performance (Figure 2) of a heterodyne receiver (B) from a point source (A) to the illumination of a point target (A) by a coherent transmitter (B), where the transmitter and heterodyne receiver optics are identical.[16] A further equivalence applies to the performance of an imaging system (B) from a point source (A).

These equivalences obviously establish the validity of adaptive techniques to (in principle) totally overcome turbulence degradation in target illumination systems. However, it also suggests that for a transmitter that is not too large, very substantial improvements in illumination may be achieved simply by tracking the target image position (incoming wavefront angle-of-arrival) in the transmitter optics, and steering the outgoing beam along the same angle.

The attainable improvement in target illumination is closely related to the improvement in the signal obtained in a conceptual reciprocal heterodyne system[17-19] with local-oscillator tracking of the mean angle of arrival (Figure 2). This in turn depends upon the relative size of the optics diameter D and a correlation parameter $r_o$, where $r_o$ applies to the radiation from a target point through the turbulence path to the conceptual heterodyne. This parameter is given by

$$r_o^{5/3} = \frac{2.4}{C_n^2 L k^2} \qquad (5)$$

For $D<r_o$, the image of a target point is predominantly seen to "dance" rather than blur, and good improvement is predicted. This also implies that the outgoing beam is primarily described by wander rather than spread or breakup. For stronger turbulence or longer pathlengths, $r_o$ may be less than D, so that the image of a target point is primarily blurred, implying that the outgoing beam is substantially spread by the turbulence; wander-cancellation is then less helpful. Note that the former condition is more apt to apply at longer (e.g. 10.6-micron) wavelengths.

This approach also suggests a realizable discrete approximation to a true adaptive transmitter: the system would consist of N angle-tracking elements, each of a diameter on the order of $r_o$.

B. Transmitter Aperture Smoothing

The above considerations are closely related to the question of the transmitter-aperture smoothing of scintillations. As discussed in Ref. 2, the degraded performance of a large heterodyne receiver implies similar degradation in a large transmitter system, which contradicts the results obtained from theoretical treatments of beam-wave propagation in turbulence. Part of the present effort will be devoted to resolving this contradiction. In addition, a physical explanation of transmitter aperture smoothing is under study.

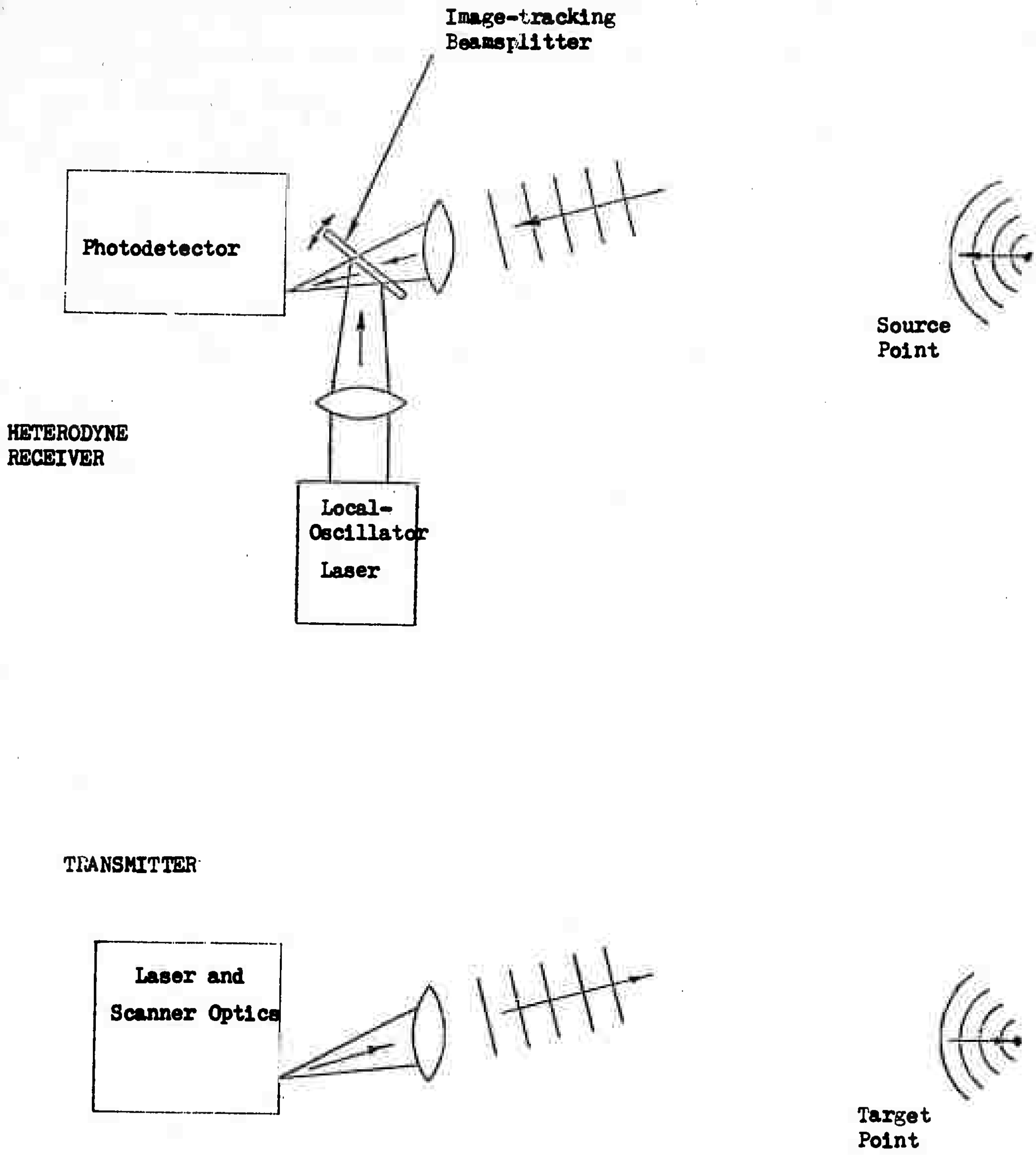


FIGURE 2. Illustration of reciprocity through turbulence.

C. Experimental Design

The cancellation of atmospheric beam wander will be demonstrated using the system shown in Figure 3. The beam from a Model 125 Spectra-Physics He-Ne laser is spatially filtered and sent through a two-dimensional galvanometric scanner and 15 cm Cassegrain telescope to a small retro-reflector target located e.g. 1 km away. The return beam traverses the scanner and is split into a quadrant photodetector which controls the scan angle. Atmospherically induced beam wander results in an apparent displacement of the target, which is sensed by the quadrant device and cancelled by the scanner. The scanner elements have good transient response at frequencies of several hundred Hz, which are substantially higher than those involved in the wander phenomenon.

A simplified schematic of the electronics is shown in Figure 4. The image photosignal is amplified in four low-input-impedance, low-drift operational amplifiers which incorporate FET gain-switching. The outputs from opposite diagonals of the quadrant device are then fed into differential amplifiers and variable-gain stages. These are in turn fed into integrators which include provisions for tracking-acquisition and electronic fine-steering of the scanners. The final elements are the scanner-drive circuits which provide clean transient response while current-driving the large scanner inductances. Low pass filters may be employed as shown, to reduce higher-frequency noise. The complete system is depicted in the photograph of Figure 5 and has successfully demonstrated target-tracking as of this writing.

The scanning elements which are employed have a maximum angular range of 0.1 radian, which is demagnified in the (50X) output telescope to 2 mRad.

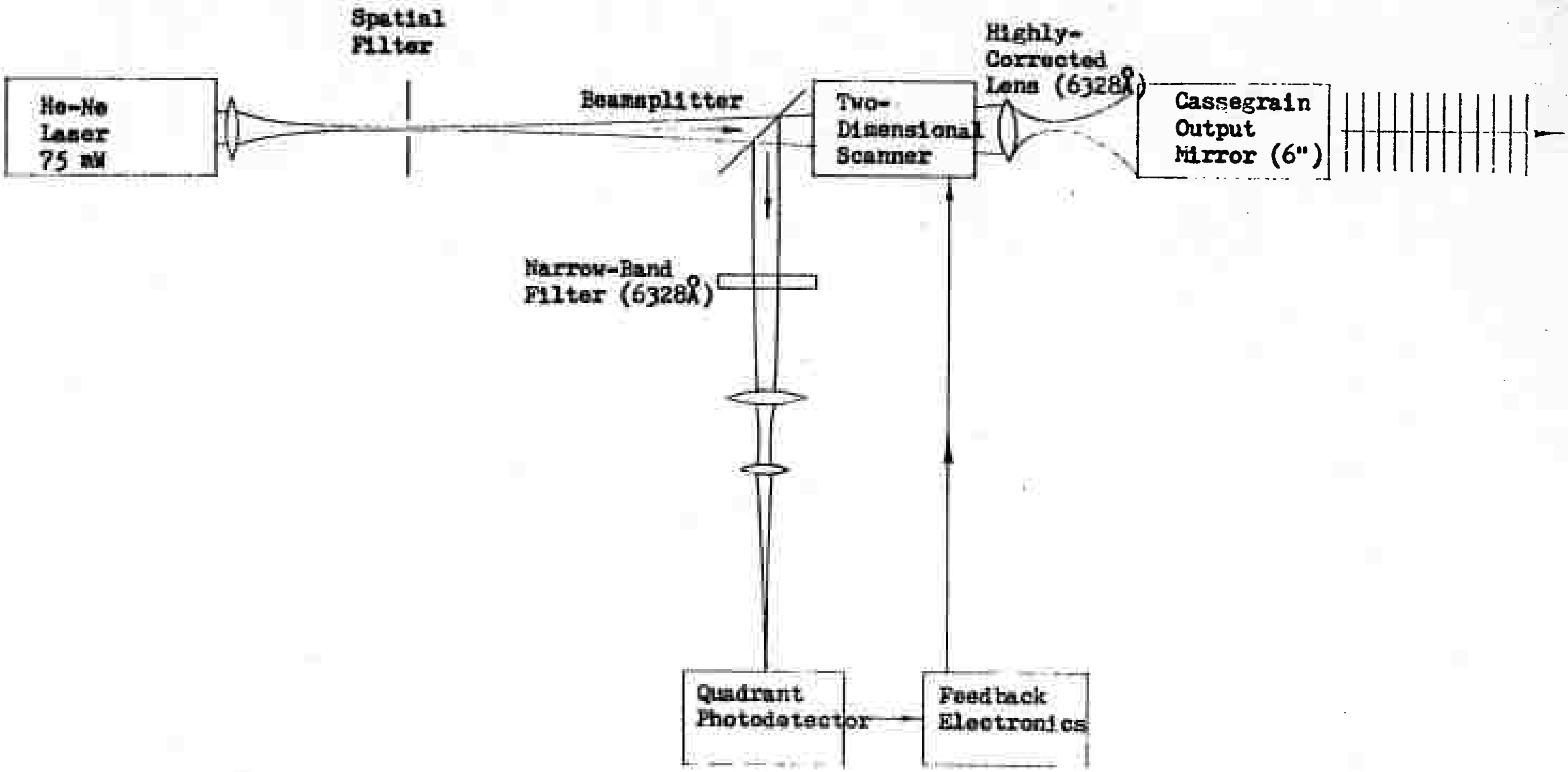


FIGURE 3. Tracking system for cancellation of atmospherically-induced beam wander.

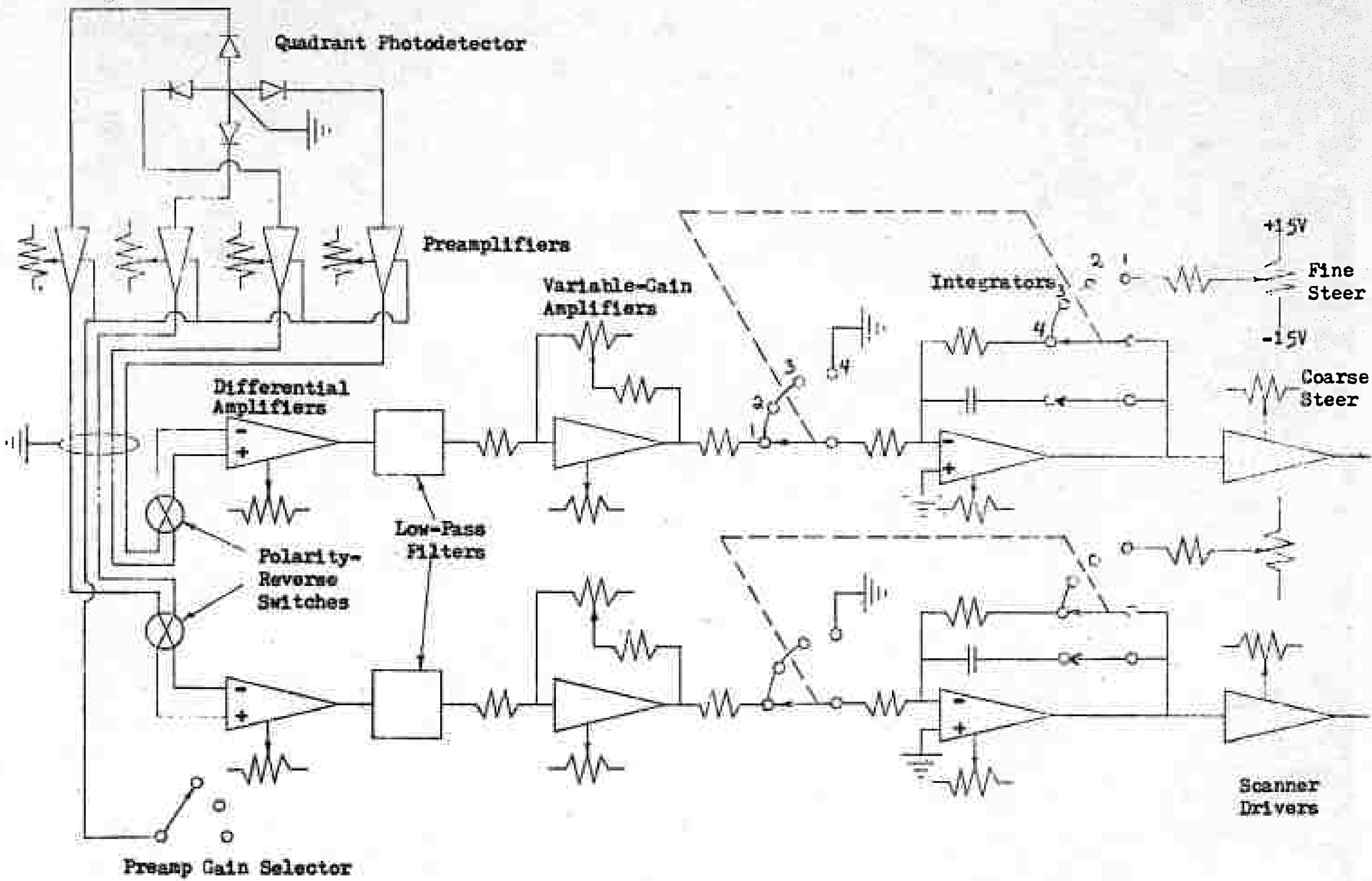


FIGURE 4. Simplified schematic of feedback electronics.

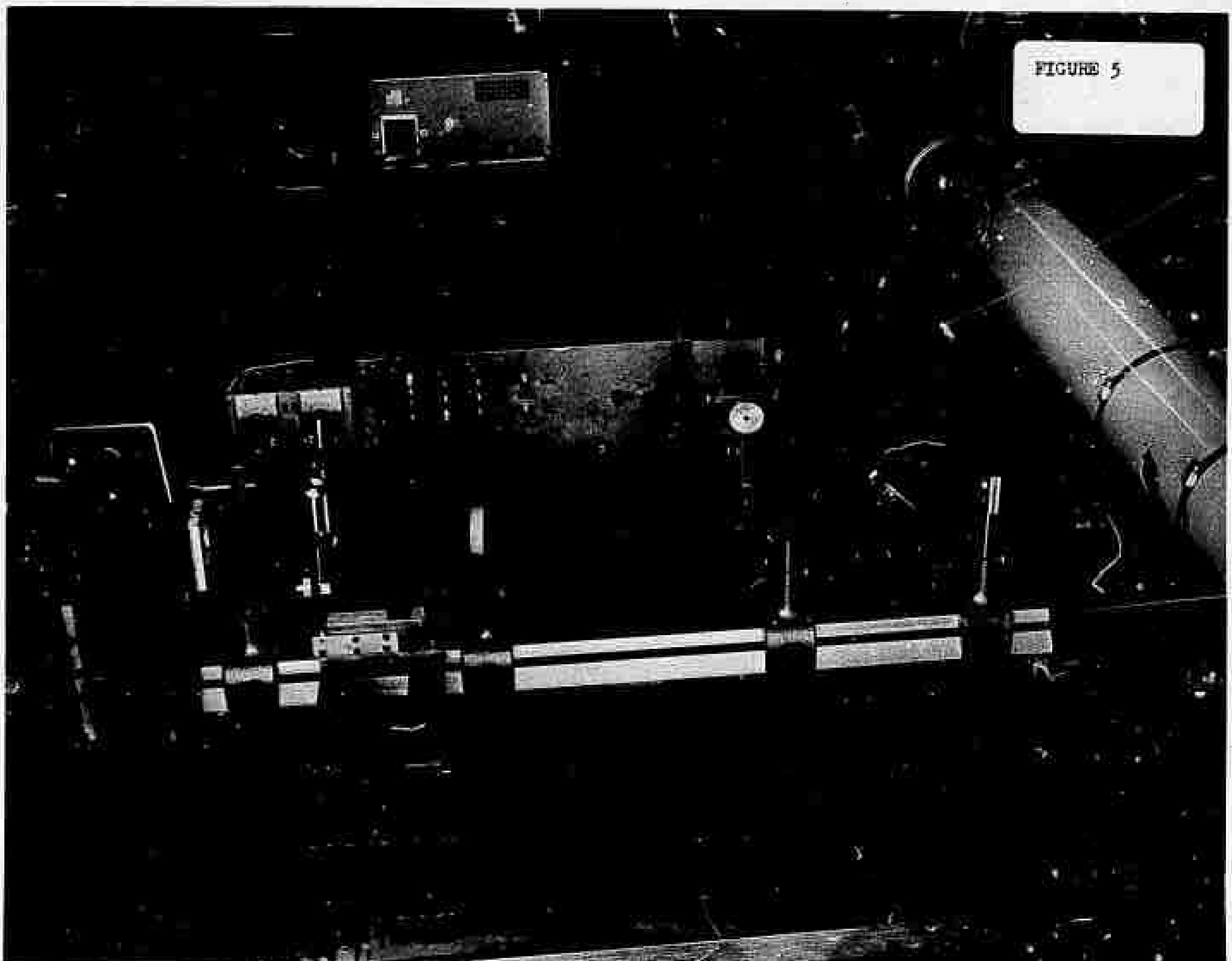
FIGURE 5

Experiments have shown that the scanners are free of "sticktion" effects for a square-wave drive signal which is three to four orders of magnitude below this level, indicating a scanner resolution of less than a microradian. On the returning beam, the apparent angular motion of the target is multiplied by 50X and 16X respectively in the two telescopes, with a resultant image size and motion which is appropriate for the quadrant device. Precise adjustments are provided for the pinhole spatial filter, the output telescope focus, and the optical coincidence of the quad-detector center and spatial filter axis.

The system comprises a simple, single-integrator control system in each plane as shown in Figure 6. As such, the overall closed system exhibits a single (negative real) pole in the s-plane, with a corresponding characteristic time constant or frequency which is determined by gain settings and the round-trip optical transmission. The front-end drift and noise is on the order of 10 picoamps, and is orders of magnitude below the photocurrent level. It appears that optical chopping and photocurrent demodulation will not be required.

The effectiveness of the wander-cancellation will be determined initially from motion pictures and measurements of fading in a small detector at the center of the retroreflector. Following this, a one-dimensional array may be utilized to provide an electronic analog of center of gravity motion of the beam. The results will be correlated with measurements of $C_n^2$ and corresponding predictions of the size of the parameter $r_o$ under various meteorological conditions.

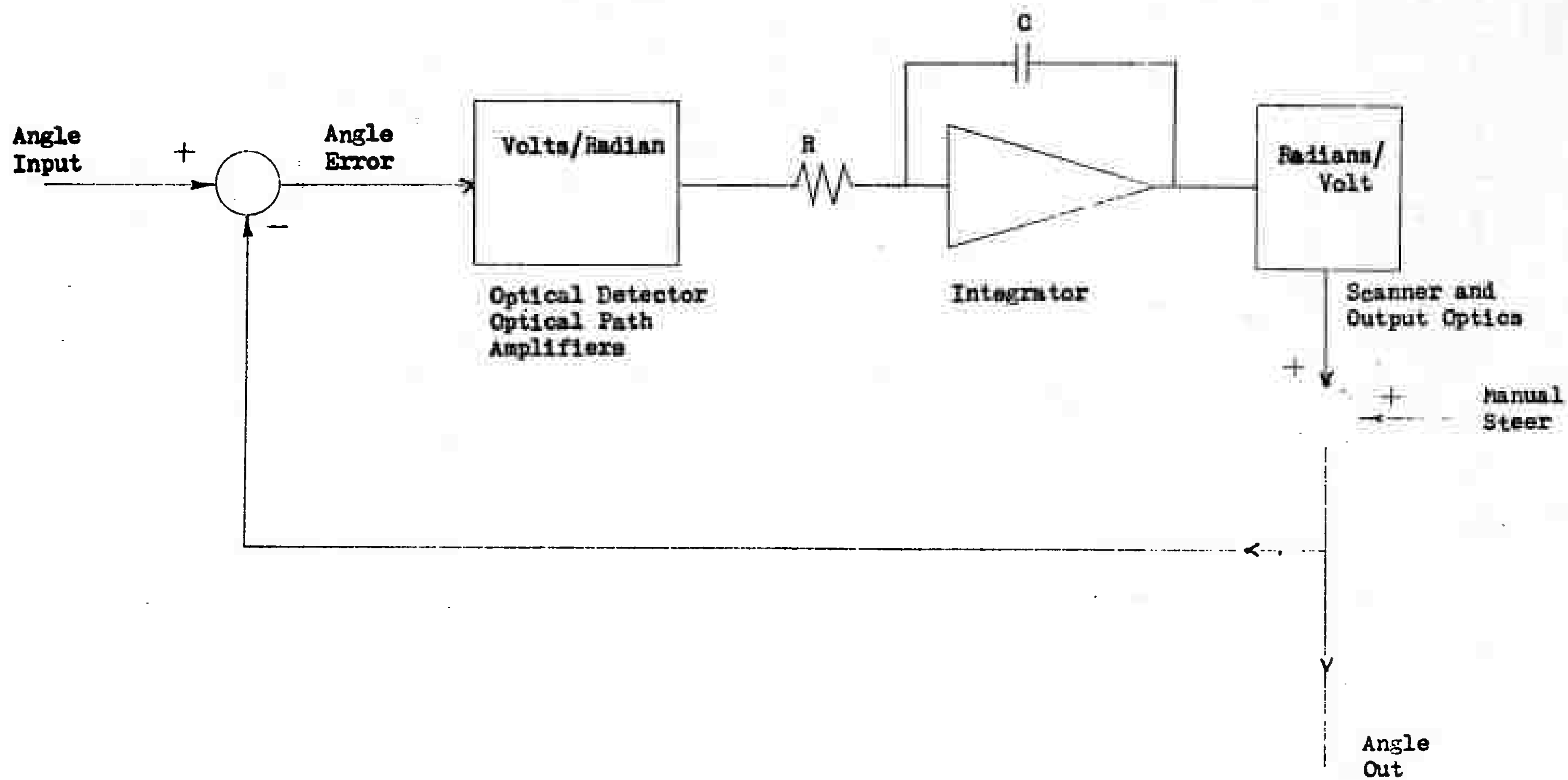


FIGURE 6. Feedback diagram of beam-wander tracking system.

## V. PERSONNEL

The personnel currently engaged on these projects are as follows:

| | |
|---|---|
| Principal Investigator: | Prof. J. Richard Kerr |
| Long-Path Experiments: | James R. Dunphy, Research Assistant |
| | Carl T. Miller, Engineer |
| Intermittency: | Phillip Pincus, Research Assistant |
| | Gerald J. Throop, Postdoctoral Associate |
| Beam-Wander and Transmitter Aperture Effects: | Prof. Gail A. Massey |
| | James R. Dunphy |
| | Carl T. Miller |

## VI. PUBLICATIONS

The following publication appeared during this report period:

J. Richard Kerr, "Experiments on Turbulence Characteristics and Multiwavelength Scintillation Phenomena," J. Opt. Soc. Am. 62, September 1972, pp. 1040-1049.

The following paper has been accepted for publication:

J. R. Kerr and J. R. Dunphy, "Experimental Effects of Finite Transmitter-Apertures on Scintillations," to be published in J. Opt. Soc. Am.

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