Accession No. 10812-65

8

SID 65-1468

# LASER SPACE COMMUNICATIONS STUDY (LACE) Final Summary Report

12 November 1965

NORTH AMERICAN AVIATION, INC.
SPACE and INFORMATION SYSTEMS DIVISION

## FOREWORD

This document is the Final Summary Report of the Laser Communication System (LACE) Study. It was prepared by the Space and Information Systems Division of North American Aviation, Inc. This report is submitted in accordance with requirements of Contract NASw-977, Supplemental Agreement, dated 15 February 1965.

NORTH AMERICAN AVIATION, INC. SPACE and INFORMATION SYSTEMS DIVISION

## TECHNICAL REPORT INDEX/ABSTRACT

| ACCESSION NUMBER | DOCUMENT SECURITY CLASSIFICATION |
|---|---|
| 10812-65 | UNCLASSIFIED |

| TITLE OF DOCUMENT | LIBRARY USE ONLY |
|---|---|
| LASER SPACE COMMUNICATIONS STUDY (LACE)— FINAL SUMMARY REPORT | |

AUTHOR(S)
R.N. HATHAWAY

| CODE | ORIGINATING AGENCY AND OTHER SOURCES | DOCUMENT NUMBER |
|---|---|---|
| | NAA-S&ID | SID 65-1468 |

| PUBLICATION DATE | CONTRACT NUMBER |
|---|---|
| 11-12-65 | NASw-977 |

DESCRIPTIVE TERMS

*LASER COMMUNICATIONS EXPERIMENT, *ATMOSPHERIC OPTICAL PROPAGATION.

ABSTRACT

The results, conclusions, and recommendations of the total program effort performed under the Laser Space Communications System (LACE) Study are summarized. The study objective was to develop a plan for the implementation of an experimental program to determine the atmospheric effects on laser space-ground communication. The study program consisted of four tasks: Task I - Problem Definition; Task II - Experiment Specification; Task III - System Implementation Study; and Task IV - Program Specification.

FORM 131-V REV 11-64
PUBLICATIONS USE ONLY

## ABSTRACT

The results, conclusions, and recommendations of the total program effort performed under the Laser Space Communications System (LACE) Study are summarized. The study objective was to develop a plan for the implementation of an experimental program to determine the atmospheric effects on laser space-ground communication. The study program consisted of four tasks: Task I - Problem Definition; Task II - Experiment Specification; Task III - Svstem Implementation Study; and Task IV - Program Specification.

# CONTENTS

## ILLUSTRATIONS



## TABLES

# INTRODUCTION, CONCLUSIONS, AND RECOMMENDATIONS

## INTRODUCTION

This report summarizes the results, conclusions, and recommendations of the total effort performed under the Laser Space Communications System (LACE) Study. The overall objective of this study program has been to develop a plan for the implementation of a comprehensive experimental program to determine atmospheric effects on laser propagation, with particular emphasis on effects that would influence the design of optical space-ground communication. The contractual period was divided into two parts over a one and one-half year period, with a brief break in the middle.

To satisfy this objective the study program was divided into four tasks. These tasks, along with the technical reports that were published and submitted on the respective tasks during the contractual period, are:

Task I - Problem Definition

> Definition of Optical Atmospheric Effects on Laser Propagation, Vol. I. NAA S&ID, SID 64-1894-1 (9 October 1964).
>
> Experimental Laser Space Communications Program, Task I, Problem Definition, Vol. II. NAA S&ID, SID 64-1894-2.
>
> Definition of Optical Atmospheric Effects on Laser Propagation, Vol. III, NAA S&ID, SID 65-1084 (4 August 1965)

Task II - Experiment Specification

> Specification of Atmospheric Laser Propagation Experiments, Vol. I, NAA S&ID, SID 64-2085 (16 November 1964).
>
> Specification of Atmospheric Laser Propagation Experiments, Vol. II, NAA S&ID, SID 65-1275 (15 September 1965).

Task III - System Implementation Study

> Requirements for Implementation of Atmospheric Laser Propagation Experiment Program, Vol. I, NAA S&ID, SID 64-2118 (25 November 1964).

Requirements Study for System Implementation of an Atmospheric Laser Propagation Experiment Program - Vol. II. NAA S&ID, SID 65-1466 (8 November 1965).

Task IV - Program Specification

Program Plan for Atmospheric Laser Propagation Experiments - Vol. I, NAA S&ID, SID 64-2119 (25 November 1964).

Program Specification Plan for Determination of Atmospheric Effects on Laser Space Communications - Vol. II, NAA S&ID, SID 65-1467 (9 November 1965).

This report summarizes the effort. The contents of this report are organized so that each section contains the objectives of the particular task and discussions of its significant results and conclusions.

## CONCLUSIONS

1. The general accuracy of the optical propagation theoretical results of several workers using different approaches, but employing Rytov's method, appear valid. The results of studies, using a solution of the mutual coherence function, are also in agreement with those obtained by Rytov's method.

2. Exact theoretical predictions, from propagation statistics, of optical system performance have been developed for a sufficient number of cases to indicate that all cases of interest can be assessed by a fairly straightforward approach.

3. The availability of data on the optical parameters of clouds, and statistical analysis of interparametric relationships of synoptic weather conditions, cloud cover, and optical conditions on a temporal and spatial basis is scarce or nonexistent.

4. The theory of turbulence is still primitive and limited to the surface layer, thus limiting the potential of relating existing meteorological measurements to propagation theoretical analysis.

5. Present atmospheric temperature measurements and statistical meteorological compilations are conducted on too gross a basis to give accurate quantities for theoretical work. Correlations between vertical temperature profile data and local conditions are virtually nonexistent, and quantitative relationships between in situ temperature measurements and large-scale synoptic conditions are scarce.

6. The 13 experiments that have been proposed in this study program can all be implemented for stationary ground-based links using available system components, and do not require the application of any unusual or exotic measurement techniques.

7. Uncertainties in experimental equipment performance, arising from potential inaccuracies pointed out in the error analysis, suggest a reasonable period of preliminary field "proofing" type experimentation prior to large-scale testing.

8. Thorough field-testing with ground-based and airborne platforms is necessary as a basis for optimizing the design of satellite-link atmospheric-propagation measurements program. (This conclusion is based on economic considerations as well as on experimental program flexibility.)

9. Well-instrumented, accessible sites suitable for carrying out a measurement program of this type are available in a variety of climatological and topographical locations. The first phase of the measurement program should be conducted over long, topologically uniform horizontal ground links. Such links are included among the available sites.

10. Aircraft and balloon platforms with the required instrumentation and logistic support are available for use in making vertical-link measurements during the later stages of a pilot-type program.

11. The immediate program approach for satisfaction of the overall goals of LACE requires validation of the theoretical models developed; the performance of limited system "proofing" and atmospheric effects experiments; and the systematic acquisition of a broad-scale statistical base, from diverse climatological and topographical locations, in order to facilitate system performance prediction. (Such a program approach has been summarized in the Program Specification section of this document.)

## RECOMMENDATIONS

1. A pilot test experimental program should be initiated to validate some of the theoretical approximations and to examine a comprehensive range of experiments and experimental variables over ground-to-ground and ground-to-airborne links.

2. A measurement and analytical program of micrometeorological measurement and interparameter statistical correlation (e.g., correlations between synoptic and microscale conditoons) should be initiated within the framework of a pilot program.

3. As results become available from related concurrent space optics programs, they should be integrated into the atmospheric effects experimental program.

4. Further studies should be performed on the propagation of light through clouds (and their temporal and spatial statistical distributions) as related to laser operational considerations.

5. Additional theoretical research should be performed on the time-dependent fluctuations of a laser beam through the atmosphere.

6. Study effort should be initiated to develop, or at least establish a foundation for, a handbook of atmospheric effects for system designers. This would include the organization of the great body of results (including Tartarski) into a stream-lined monograph covering the effects and techniques for application calculations.

## PROBLEM DEFINITION

The effort under this task was fundamental to the performance of all tasks of the program. The basic objectives of this task, as well as the total study rationale, indicated the following necessary subtasks, which were performed in this portion of the program:

1. An examination of the qualitative nature of atmospheric effects
2. An examination of previous experimental results to determine their applicability to the LACE program
3. An examination of the interrelationship of meteorological phenomena to optical propagation effects
4. Development of a theoretical model of optical effects that would permit prediction of system performance
5. An examination of means of validating the theoretical model
6. An examination of some of the system performance characteristics of an optical link as they relate to requirements for experimental data

Three reports (References 1, 2, and 3) were prepared and submitted in the performance of this effort. All three should be examined as a unit to get the full implications of the problem definition analysis. This section summarizes the work performed under the Problem Definition Task.

## ATMOSPHERIC EFFECTS

Atmospheric turbulence was examined in terms of its effect on optical propagation in general and lasers in particular. The effects of a turbulent atmosphere have been categorized for astronomical sources as shown in Table 1. The effects on optical propagation-inducing laser systems are shown in Table 2.

Table 1. Astronomical Categorization of Atmospheric Turbulence

| Common Astronomical Terminology | Optical Propagation Effects |
|---|---|
| Image dancing | Change of place |
| Pulsation | Change of size |
| Scintillation | Change of intensity |
| Shadow pattern | Spatial and temporal variation of light intensity |

Table 2. Effects of Atmospheric Turbulence on Optical Communication Systems

| Optical Systems in General | Laser Systems in Particular |
|---|---|
| Modulation noise (fluctuation in received intensity and phase) | Loss of transmitter collimation |
| Tracking noise (angular fluctuations in the position of the target or source) | Loss of efficiency in coherent (heterodyne) detection due to misalignment of local oscillator and signal phase fronts |
| Signal fading (power received below an acceptable threshold) | Doppler spread of power around the carrier frequency produced by the index of refraction inhomogeneities and relative motion of the receiver-transmitter |

Because optical effects in the atmosphere are related to meteorological conditions, considerable emphasis was placed on this subject. An understanding of the meteorological concepts basic to atmospheric visibility and atmospheric turbulence is essential for the following reasons:

1. It provides a better understanding of optics effects

2. It enables the medium to be described independently of the optical effects

3. It suggests some of the criteria for choosing sites

4. It implies the possibility of including optical phenomena within meteorological predictions

A complete analysis of the meteorological optics phenomena of visibility and turbulence was presented as part of the Task I effort. This included a discussion of the factors, properties, phenomena, and mathematical description as it relates to the LACE problem.

## ATMOSPHERIC VISIBILITY

The basic processes of absorption and scattering, which determine visibility in the atmosphere, were discussed in detail. In absorption, some of the radiant energy disappears as light because it is transformed into a different kind of energy. It is said to be absorbed at the place where the transformation takes place. In scattering, the direction of propagation of the light is changed. Together absorption and scattering reduce the transfer of radiant energy by a light beam because part of the radiant energy is transformed and part is scattered out of the beam. The diminution of radiant energy carried by the beam is called attenuation or extinction.

The basic absorbers and scatters are gas molecules and liquid and solid particles. The latter are classified into aerosol, or haze, particles and cloud, or fog, particles. The aerosol particles have radii ranging from hundredths of a micron to a micron. They are solids of varied composition, sometimes coated with water. Clouds and fog are made up of water droplets or ice crystals. Droplet radii are typically about 5 to 10 microns.

The operational properties of the medium are described in terms of extinction coefficients and scattering functions. The coefficients are defined in terms of the fraction of energy lost from a beam per unit distance of propagation and are designated according to the process taking place.

The analysis pointed out some of the sources, extent, and limitation of the visibility data and theory as applicable to laser propagation. Some of the problem areas and limitations pointed out in the visibility analysis were:

1. The scarcity of data on the optical parameters of clouds, and the statistical analysis of cloud data

2. The requirement for additional study of the propagation of light through clouds to permit the analysis of the effects of cloud transmission on signal strength and error rates

3. The need for laser experiments to supply data on absorption, scattering, and extinction coefficients

4. The performance of statistical studies on the probability of occurrence of different types of clouds (from 1 and 2) on a spatial basis for operational consideration

## ATMOSPHERIC TURBULENCE

A discussion of the basic processes of turbulence pointed out that turbulence creates refractive index inhomogeneities by stirring the air along a temperature gradient which produces fluctuations in amplitude and phase of light waves propagating through the medium. The basic factors that produce refractive index inhomogeneities are tubulence and non-adiabatic lapse rate of temperature. Turbulence is characterized by randomness of the velocity field. The temperature lapse rate is the rate of decrease of temperature with respect to altitude.

It has been pointed out that it would be desirable to be able to describe or relate optical communication system performance in terms of readily measurable or standard meteorological phenomena and conditions. It would be advantageous, for example, if it were possible to relate micrometeorological phenomena (local wind field, turbulence, temperature) and therefore system performance to the state of the atmosphere revealed by synoptic charts, upper air charts, and vertical cross sections (all of which are standard meteorological tools).

The relationship of synoptic meteorological conditions to the optical properties of the air is illustrated in Figure 1. Synoptic refers to conditions that prevail simultaneously over a large area and summarize the situation, such as pressure patterns, air masses, fronts, cloud formations, and precipitation areas. These large-scale features influence local conditions such as the lapse rate, turbulence, wind, pressure, and humidity. However, the terrain also helps to determine the lapse rate and turbulence in the lower layers. The local conditions produce temperature fluctuations, affect the concentration of molecules and the formation of clouds, and, in conjunction with various sources of air pollution, produce aerosols. The pressure, temperature, and humidity determine the refractive index. The temperature fluctuations lead to refractive index homogeneities, which may be described

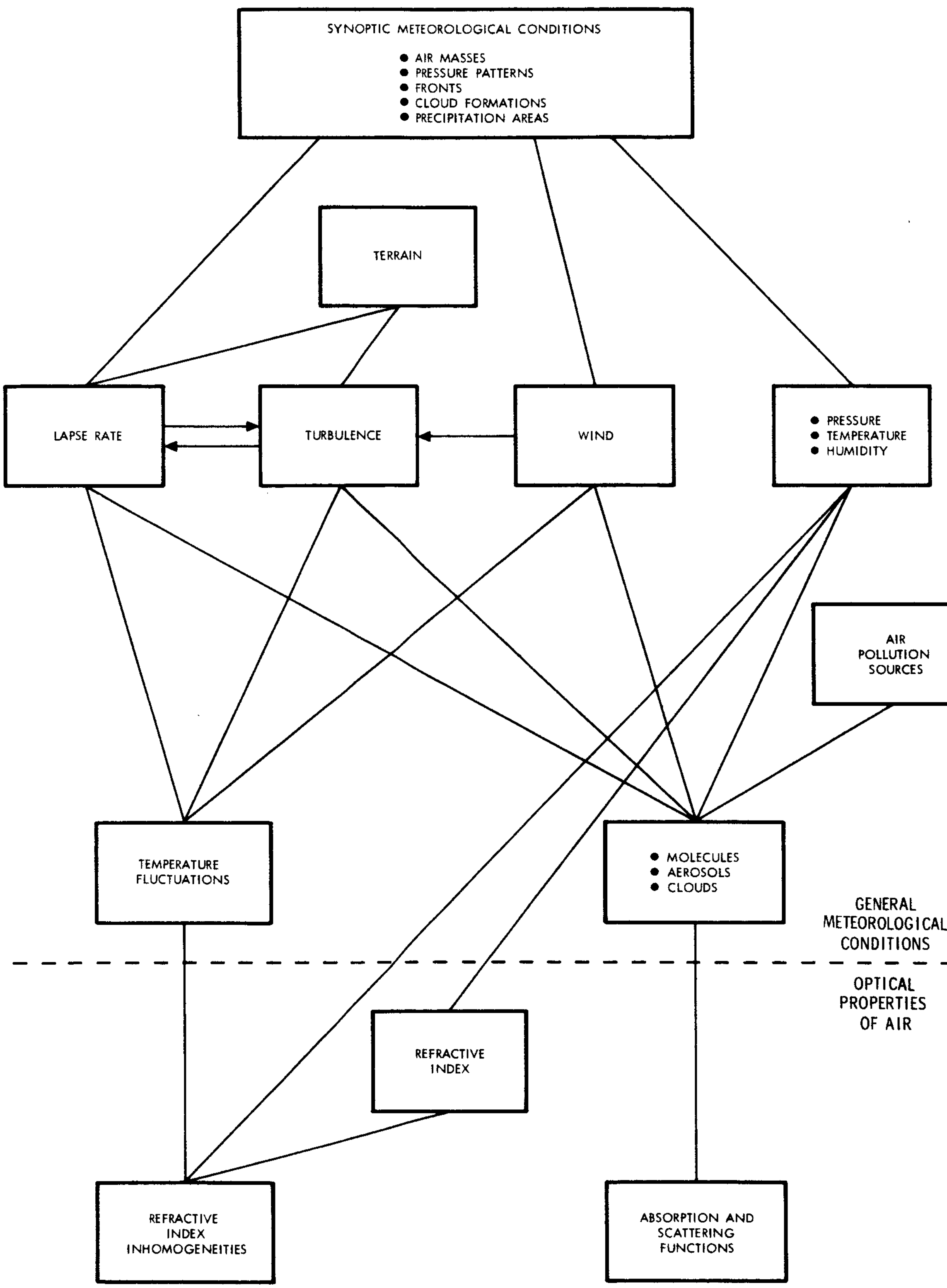


Figure 1. Relation of Meteorological Condition to Optical Properties

as optical properties in terms of the variance and structure function. The molecules, aerosols, and clouds produce optical properties described by absorption, scattering, and extinction coefficients and by scattering functions. In summary, the lowest three boxes represent optical properties of the air and the boxes above them show their relationship to general meteorological conditions by way of various factors.

At present, there are limitations to relating synoptic conditions to local micrometeorological conditions sufficient for use in theoretical expression of optical propagation system performance. The limitations are as follows:

1. The theory of turbulence is still primitive and limited to the atmospheric surface layer.

2. Temperature data at different altitudes for a variety of meteorological situations (i. e., relating temperature fluctuations at all altitudes to the local conditions) are scarce.

3. Existing observations on temperature fluctuations and related phenomena from airborne platforms have been connected only qualitatively with large-scale conditions.

4. Conventional sampling of the atmosphere is on too gross a scale in space and time to give accurate lapse rates or Richardson numbers, for example, at the locations and times of turbulent studies, and most fluctuation studies have not measured the local parameters.

# THEORETICAL ANALYSIS

## GENERAL

The approach taken in the theoretical analysis of optical effects was to separate the problem into the following parts:

1. Derivation of the log-amplitude correlation function and phase structure function from statistics of a turbulent atmosphere, based upon Rytov's approximation

2. Examination of the way the phase and log-amplitude fluctuations manifest themselves in the performance of various types of optical instrumentation

The work in the first case consisted of relating the statistics of the fluctuation of the phase and amplitude of an optical wavefront, after traveling through some path in the atmosphere, to the statistics of atmospheric turbulence. These mathematical relationships of the log-amplitude function and phase-structure function to turbulence of refractive index fluctuation statistics were presented in Task I (References 1, 2, and 3) in terms of formal expressions, tables, charts, and "simple" usable equations.

As a part of this optical propagation theoretical analysis, a comparison was made of the broad classifications of theoretical work of the following approaches:

1. Solutions based on Rytov's methods

2. Propagation of mutual coherence

3. Ray optics

4. Two-level (tropopause, ground-layer) generating mechanism

5. Born approximation

The general accuracy of the results by several workers (including the NAA approach) using Rytov's method appear valid. Though some of the many details obtained by Tartarski are questioned (a completely revised and condensed text has been recommended), it is believed that many of his results may be used as standards against which all other approaches may be judged. It was shown that Hufnagel and Stanley's result, using a solution to an equation for the mutual coherence function, is in perfect agreement with those obtained by Rytov's method. It was pointed out that ray-optics methods probably provide a good approximation to phase problems, but not to amplitude problems. It was indicated that more experimental data are needed to verify the conclusions concerning the two-level generating mechanism, and that the Born approximation is not applicable.

The theoretical work performed by NAA, either on this contract or on directly related company-sponsored R&D, has been reported in the Task I reports. This work, involving both propagation analysis and instrument effects, was generally in the form of complete technical memos and is listed in Appendix A.

The theoretical study covering the relationship between the results of the propagation study and the performance of an optical instrument involved the following general effects:

1. Signal fluctuation in an optical intensity detector, studied in terms of rms fluctuation versus collector diameter

2. Signal-to-noise ratio attainable in heterodyne detection of a distorted wave front optical signal versus receiver diameter

3. Angular resolution of a lens as limited by wave-front distortion; the attainable resolution was found to be different for long-time exposures and for high-speed exposures, with the latter being a function of lens diameter; both aspects of the resolution problem were studied

4. Frequency spread of a coherently detected optical signal due to phase fluctuation

5. The statistics of the "shape" of the distorted wave front

From the propagation statistics exact predictions of optical system performance have been developed in a sufficient number of cases to lead to the conclusion that all cases will yield a fairly straightforward approach. A summary of the status of the theoretical work is shown in Figure 2. Detailed examples are given in Appendix B.

All these results are seen to depend on the refractive index structure constant, $C_N^2$. The limitations of knowledge of this factor were discussed previously under meteorological optics. There are some admittedly crude estimates for typical values of $C_N^2$ at various altitudes. There is little information about the magnitude of the error in these values, and no data

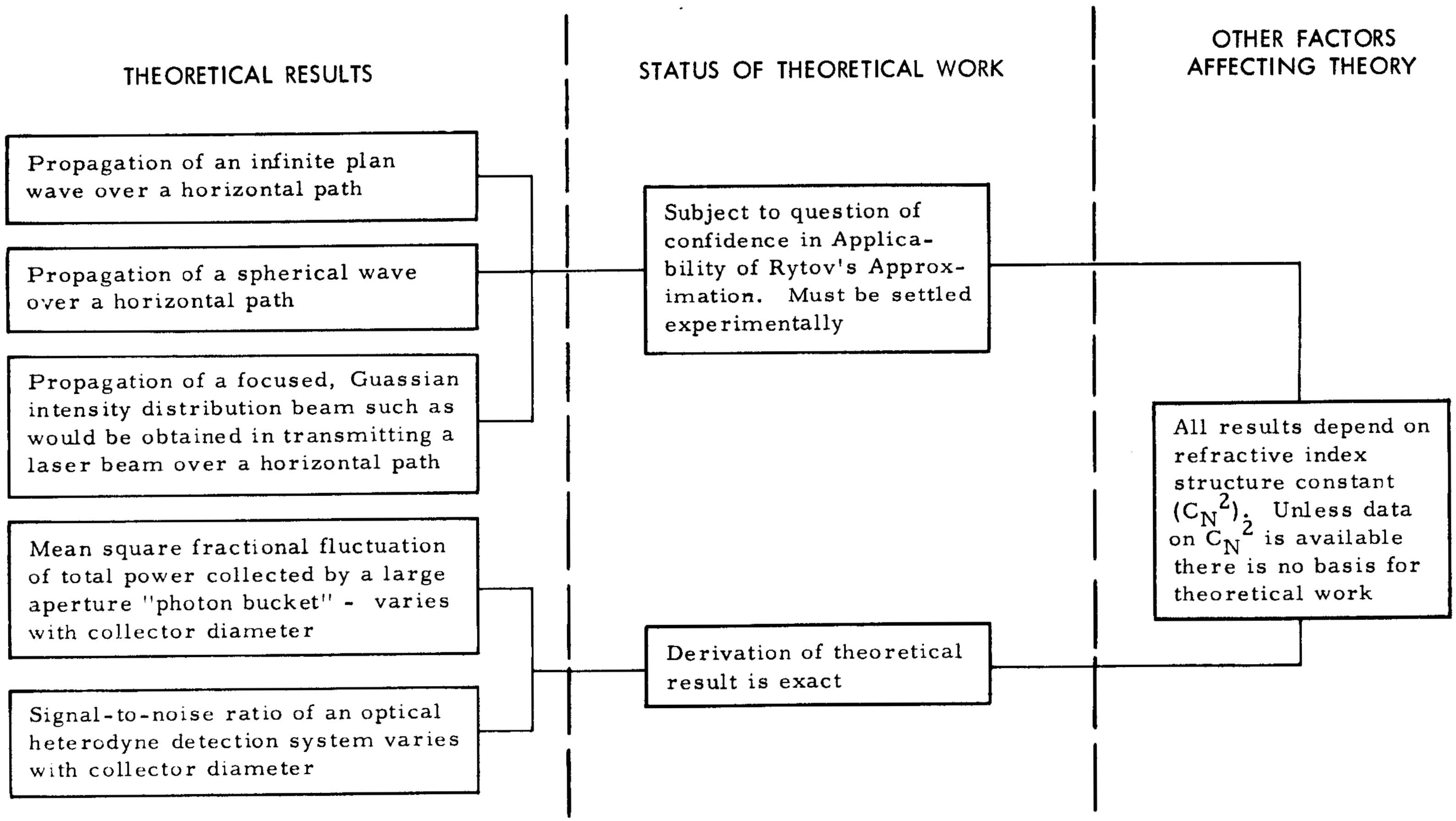


Figure 2. Status of Theoretical Results

on how $C_N^2$ varies with synoptic weather conditions, geographical location, or local terrain features (as indicated in the Atmospheric Effects section). Therefore, a systematic study of the refractive index structure constant should be undertaken.

## SIGNAL TRANSFER CHARACTERISTICS

An analysis of the signal transfer characteristics of the atmospheric transmission medium were performed to determine the extent to which it influenced the definition of an experimental program. To provide a realistic basis for the selection of one particular information transfer for a given mission, an investigation of the channel was undertaken from an information theory standpoint. The principal part of this analytical effort was directed toward extending existing work to account for the random time-varying nature of the atmosphere. The effort included, in addition to the foregoing, a description of an adaptive system capable of self-biasing to account for channel changes, and a comparison of the performance of PCM amplitude versus PCM polarization modulation.

As far as the random time-varying channel analysis is concerned, it was concluded that, for all but the simplest cases, the classical analytical-numerical approach would be quite costly and of questionable accuracy.

Accordingly, it appears obvious that empirical results, based on detailed measurements on an actual atmospheric link, would provide the most realistic solution to the problem.

In designing a system utilizing automatic-carriers-amplitude-correction, the importance of knowing the probability that any given data will be in error at the receiver because of the effect of the product noise (amplitude scintillation) was shown. It was indicated that an empirical distribution of this probability of error in any given data signal could be estimated from calculations arising from an analysis of an experimental situation that included the recording of the amplitude of a received signal involving no signal modulation.

Calculations, based on expressions derived in the analysis, were made of the signal-to-noise ratio to attain a given error rate for PCM-POIM versus PCM-AM. It was shown that the signal-to-noise ratio required for PCM-POIM was approximately 3 decibels lower than PCM-AM (if both have the same peak power) for lower error rates.

# EXPERIMENT SPECIFICATION

The second major task of the program consisted of the formulation and specification of experiment concepts to satisfy the requirements defined in Task I. This Task II effort was published in two separate reports (References 4 and 5). The first report (Reference 4) placed emphasis on the preliminary design of a number of experiments that permit the acquisition of sufficient information about atmospheric effects on laser propagation to allow system designers to include such effects in the synthesis of future operational laser systems. The experiments derived in Reference 4 were directed, therefore, toward obtaining fundamental propagation data upon which system performance predictions can be based, and included methods of measurements, pertinent test signals, analysis, and associated block diagrams for each measurement concept. The extension of this initial effort, as reported in Reference 5, included the following main areas of investigation:

1. The description of a measurement approach based on the integration of optical effects, experimental variables, basic interpretations of beam fluctuations, and a limited glossary of terms related to the study

2. Modifications to the earlier proposed meteorological measurement approach

3. The establishment of experiment and measurement requirements based on a detailed accuracy analysis of each experiment

4. The analysis of alternate approaches to the experiment design

Initially a total of 18 experiments were defined covering a range of measurements applicable to the laser atmospheric propagation problem. In the later analysis and modification of the meteorological experiments the total number of potential experiments were reduced to 13, but the original numbering was maintained for comparison purposes.

Figure 3 illustrates the relationship between the recommended experiments and the principal optical atmospheric propagation effects of scattering and absorption, and random modulation of the amplitude, phase, and polarization of the laser beam by refractive index inhomogeneities produced by atmospheric turbulence. The numbers indicate the particular experiments.

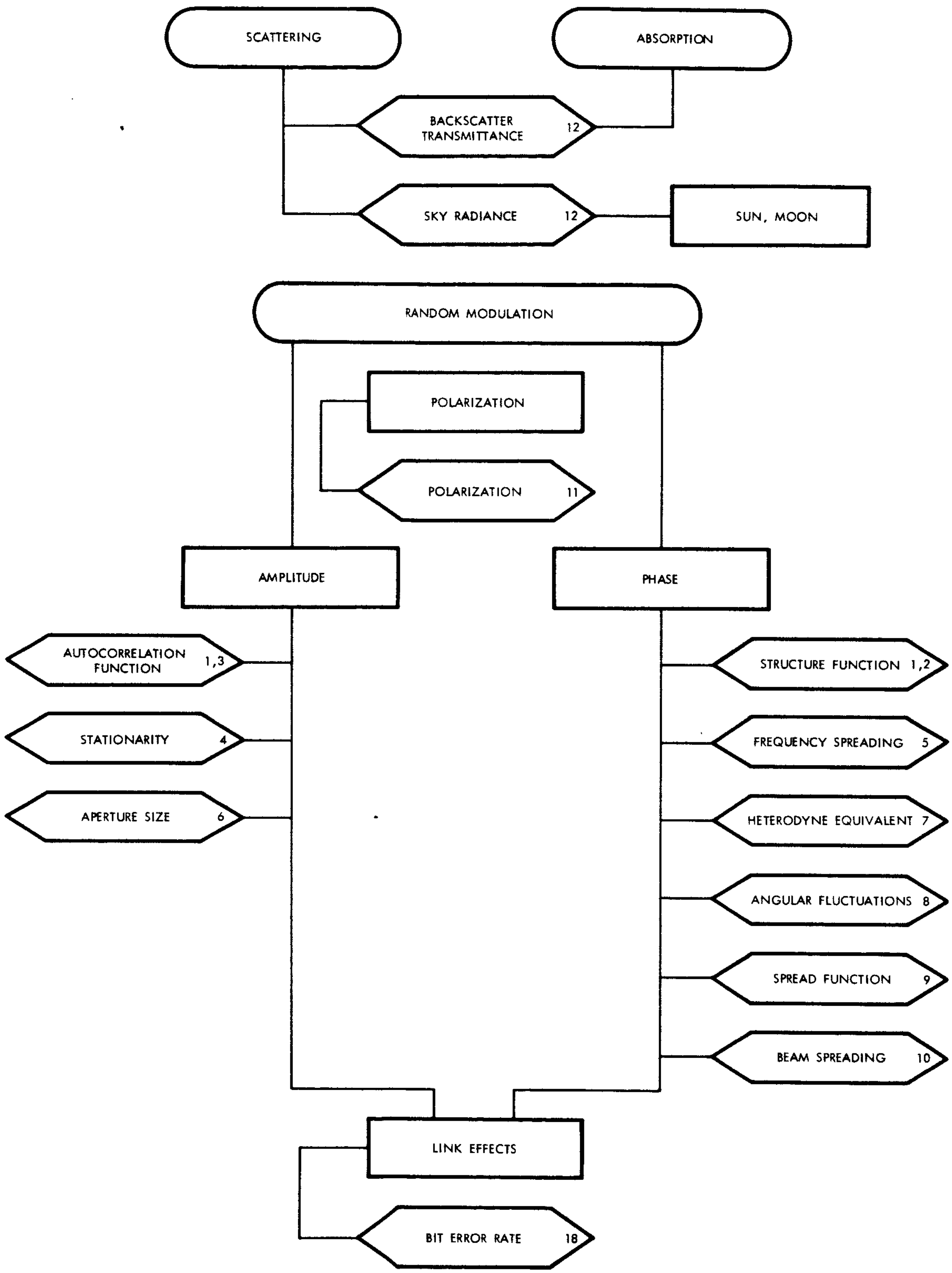


Figure 3. Relationship of Experiments to Atmospheric Optical Effects

As Figure 3 shows, most of the experiments deal with various aspects of amplitude and phase fluctuations. One each is allocated to polarization fluctuations, communication link effects produced by amplitude and phase fluctuations, and the better known area of absorption and scattering phenomena.

The four amplitude fluctuation experiments are concerned with the statistics of the fluctuations as exemplified by the spatial autocorrelation function of the logarithm of the amplitude, with the stationarity and isotropy of the statistics, and with the modification of them by the entrance aperture of the optical system.

The seven phase fluctuation measurements look at the phase fluctuations from the point of view of the spatial structure function, frequency spreading of the laser line, heterodyne efficiency, angular fluctuations, atmospheric spread function, and beam spreading.

The communication link effects experiment, which measures bit error rates, is concerned with system effects of amplitude and phase fluctuations.

The scattering and absorption experiment measures backscatter, transmittance, and sky radiance. The last mentioned depends on the relative positions of extraneous light sources such as the sun during the day and the moon at night.

Some of the variables common to all the experiments are listed in Table 3.

Table 3. Experimental Variable Summary

| Environment | Laser Beam | Receiver | Path |
|---|---|---|---|
| Synoptic conditions | Wavelength | Aperture size and shape | Length |
| Local weather | Radiant intensity | Detector time constant | Zenith angle |
| Terrain features | Distribution | | Height |
| | | | Motion relative to air |

The environment is the atmosphere, which can be described in terms of synoptic or large-scale weather conditions, local conditions, and terrain features that affect the atmosphere. Important laser beam parameters are wavelength and the distribution of radiant intensity as a function of angle off the beam axis. The principal characteristics of the receiver are the size and shape of the entrance aperture and the detector time constant. Significant features of the optical path are its length, zenith angle, height above the ground, and motion relative to the air. The relative motion, which affects the fluctuation temporal spectrum, depends on wind speed and the velocities of the transmitter and receiver.

Other variables are important for particular experiments: the separation of the two apertures in the correlation and structure function measurements and the polarization in the polarization experiment. These special variables are revealed in the experiments in which they apply.

A summary of the specification analysis for each experiment is presented in Table 4. Further discussion of the experiments is presented in the discussion of the results of the Task III, the System Implementation Study section.

| Experiment Number | Title | Objective | |
|---|---|---|---|
| 1 | Measurement of Spatial and Temporal Log Amplitude Correlation Function and Phase Structure Function | To obtain the spatial and temporal statistics of amplitude and phase of coherent (laser) light after propagation through the atmosphere. | The laser beam is sam by placing a square wa and using a beam split of two photomultiplier |
| 2 | Phase Structure Function Measurement | To measure directly the phase difference within a wavefront in a laser beam, for simple evaluation of the phase structure function. | A laser beam is sampl optical frequency of on the phase difference in sured by means of a pl |
| 3 | Amplitude Correlation Measurement | To obtain the log amplitude correlation function for a laser beam, after transmission through the atmosphere, from irradiance measurements made at two points within the received beam. | The irradiance of the l two photomultipliers t of processing the sign amplitude at two point |
| 4 | Stationarity Measurement | To test the stationarity of the log amplitude correlation function $C_{LL}(\bar{\rho})$ of a laser beam after transmission through the atmosphere and to measure the spatial wandering of the beam. | A Fresnel lens interce a field lens on the phot image tube (vidicon or pictures of the instant function of time. |
| 5 | Spectral Spreading Measurement | To measure the frequency spreading $\Delta f$ of laser light transmitted through the atmosphere, resulting from fluctuations in the refractive index of the air along the transmission path. | The laser beam is spli paths that are sufficie an amount $\omega_a$. After t a single PM tube, the |
| 6 | Power Fluctuation Measurement | To measure the received light power and its fluctuations as a function of the aperture size of the receiver. | The incoming laser lig ture. The light power for later evaluation of |
| 7 | Heterodyne Equivalent Measurement | To measure the average irradiance at the center of the image of a focused laser beam, as a function of the diameter of the entrance aperture. | The transmitted beam ture. The diffraction and imaged in the plan received power is mea known sizes. |
| 8 | Angular Fluctuation Measurement | To determine the probability distribution and the frequency spectrum of the angular fluctuations of a laser beam after transmission through the atmosphere. | The experimental proc pinhole with a moving spot from its center p trace describes the an |
| 9 | Spread Function Measurement | To measure the spreading of the intensity pattern of a laser beam transmitted through the atmosphere, as a function of the distance and the size of the transmitter aperture. | A laser is focused ont tance from the transm distances and transmi measured from the de |
| 10 | Beam Spreading Measurement | To measure the spread of a laser beam, its total power and power distribution at a distance, and as a function of the transmitter aperture. | A laser transmitter h Experiment No. 9. At No. 9), the irradiance measured for differen |
| 11 | Polarization Fluctuation Measurement | To detect and measure any changes in the state of polarization of a laser beam which may result from transmission through a turbulent atmosphere. | A linearly polarized li at the receiver, reduc whose polarization ve measure the intensity ence between them is outputs should be zero indicated by a nonzero |
| 12 | Atmospheric Backscatter, Transmittance, and Sky Radiance Measurement | As indicated in the title. | The laser beam is tra of transmitted power reflector at a great di multiplier current at from different volume column. |
| 18 | Communication Link Error Rate | To measure the effect of atmospheric propagation on the information transfer ability of an optical communication system. | See Task III discussio |

Table 4. Summary of Experiment Objectives, Procedure, Potential Error Sources, and Related Factors

| Procedure Summary | Block Diagram Figure Number Task II Report (SID 65-1275) | Summary of Potential Error Sources | Remarks |
|---|---|---|---|
| pled at two points $\bar{x}$ and $\bar{x} + \rho$ lying in its cross-section; e driven, mirrored piezoelectric crystal in one channel er in both, the two waves can be mixed on the surfaces ubes. | 2 | Receiver aperture size, beam splitter inaccuracies, detector and background noise, inaccuracies in piezoelectric phase shifts, angle tracking error, number of measurements, differences in channel gain | The information that could be gained from the experiment is substantial, but its implementation would be quite difficult. |
| d at two positions separated by a distance $\rho$. The sample point is altered by a modulator, preserving the beam frequency. The phase fluctuation is then measse detector used in conjunction with a phase-locked loop. | 3 | Receiver aperture size, phase tracking, modulation and loop, averaging time, signal-to-noise, angle tracking | Considered as a simpler alternative method for the phase structure function measurement 4 of Experiment No. 1 |
| ser light at two points within the beam is measured by it are separated by a variable distance $\rho$. Three ways s, which are proportional to the square of the light are shown. | 5 | Receiver aperture size, nonlinearity of the PM tubes, computation and multiplication of the logarithms, background light and internal noise, number of measurements | Considered as an alternate method for the amplitude correlation measurement of Experiment No. 1. |
| ts the incoming laser beam and is imaged by means of sensitive surface of a high resolution, delayed scan orthicon). The function of the image tube is to obtain neous intensity distribution across the beam, as a | 6 | Resolution, uncertainty of magnitude of amplitude, receiver noise, background light, variance of the correlation function | A check of the isotropy of $C_{LL}(\rho)$ is a secondary objective. |
| into two beams of equal intensity over two equal length tly separated. The frequency of one beam is shifted by flection from identical corner reflectors, focusing on esulting beat frequency between $\omega_a$ and $\Delta f$ is measured. | 7, 8 | Path distance, amplitude fluctuations, laser frequency drift, receiver noise | |
| it is captured with a receiver of large and variable aper- P is measured with a PM tube, amplified and recorded P>, <$P^2$>, and the power (frequency) spectrum $P(\omega)$. | 9 | Signal-to-noise, number of measurements | Experiments have been performed over S&ID link. |
| s received with a collector of large and variable aperattern appearing at the focus of the collector is magnified of a pinhole that forms the aperture of a PM tube. The ured for a series of receiver apertures of varying but | 10 | Beamwidth, pinhole size, ratio of pinhole diameter, optics (must be diffraction limited), PM tube | Should be conducted in conjunction with Experiment No. 8. |
| dure of No. 7 can be used by replacing the PM tube and ilm and chopper, respectively. Excursions of the focal sition are recorded on the film as a locus of points whose ular fluctuation of the beam as a function of time. | 10 | Drive speed of the film, chopper speed, width of the integrating slit, fluctuations in intensity of transmitted light, ensemble size | A variation to the procedure described would use a PM tube in place of the film and record its output on a moving tape. |
| a recording film (without optics) placed at a known dister. This procedure is repeated for a series of different er apertures, and the size of the focused image, as eloped film, and recorded as a function of these variables. | 12 | Intensity distribution within laser beam overrides possible errors from other sources | The most reliable measurements may be expected for horizontal links, such as a long flat road or dry lake bed. |
| ring a variable aperture and focal length is used, as in series of far distances (greater than in Experiment of the beam and, when possible, its total power are settings of the transmitter aperture. | 12 | Same as above | This experiment differs from Experiment No. 9 only in its implementation, which enables beamspreading data to be obtained at greater distances and for large beamwidths. |
| ht from a laser transmitted through the atmosphere is, d in size, filtered, and divided into two components ors are perpendicular to each other. Separate PM tubes f each component and the output of each, and the differecorded. Over short paths the difference in the PM Any atmospheric polarization effects present would be difference in outputs. | 13, 14 | Noise in the PM, optics of the receiver | |
| smitted along the axis of a telescope (a small fraction used for comparison) and reflected from a corner tance. The laser is turned on and off, and the photofferent times indicates sky radiance, backscatter along the light path, and transmittance of the air | 15 | Measurement limitations, calibration drift and instability, movement of retro-reflector, sky radiance | This experiment was revised from the original Task II (SID 64-2085), and is presented in place of Experiments 12, 13, 14, 15, 16, and 17. |
| . | See Task III (SID 65-1466) | See Task III discussion | |

## SYSTEM IMPLEMENTATION STUDY

Task III was concerned with a broad range of topics—from the detailed experiment component analysis to analysis of siting and link requirements. The objectives of this portion of the LACE study, as determined from the contractual task breakdown, resulted in the following main areas of study:

1. The comprehensive assessment of the performance of components of each measurement experiment defined in Task II, including the system block diagram, equipment, complement tabulation, component analysis and performance, significant operating characteristics and constraints, and alternate implementation configurations

2. The evaluation of alternative measurement approaches through a measurement system synthesis analysis

3. The analysis of system configuration and implementation requirements, including the availability and applicability of existing equipment and facilities with respect to siting support equipment, measurement platforms, and propagation links

# SYSTEM COMPONENT ANALYSIS

The component analysis performed under this task should provide the basis for the next phase: actually conducting the final system design leading to the field test implementation. Emphasis in this portion of the study was placed on provision of sound preliminary design analysis to solidify the experiment implementation procedure and performance of the component parts, including the effects of the main sources of error, limitations on performance, and related operational requirements. Table 4 gives a summary of some of the highlights of the individual experiments, including objectives, procedure summary, and main sources of error. Block diagrams of each experiment can be examined in the Task II report (as noted), and in more detail in the Task III report (Reference 6).

## EXPERIMENT HIGHLIGHTS

The following is a brief discussion summarizing the system component analysis highlights of the individual experiments.

### Experiment No. 1 - Measurement of Spatial and Temporal Logarithmic Amplitude Correlation Function and Phase Structure Function

An analysis was presented on the sample aperture size, since too large a hole will introduce an average over the very quantities being measured. The selection of sampling hole size will be more critical for phase measurements than for amplitude measurements, and given the size constraints of the averaging effect, the sampling hole should be so large that diffraction effects are not present. This is shown graphically in Reference 6. Other analyses dealt with filters, lens system, beam splitters, mirrors, piezoelectric crystals, and sampling rates. Requirements on the laser source and optical detector were established (detailed appendixes on the analysis of these components were presented). For example, the laser must be single frequency and single mode and have good coherence (both temporal and spatial); the detector should have high quantum efficiency at the laser frequency, low dark currents, and a photo cathode whose area has equal sensitivity.

### Experiment No. 2 - Phase Structure Function Measurement

A good deal of the analysis of Experiment No. 2 and later experiments drew on the analysis and appendixes prepared under Experiment No. 1.

It was indicated in the system definition analysis that this experiment could be carried out without the complex data reduction of Experiment No. 1 through the use of automatic gain control and phase-locked loop circuitry. The optics are straight-forward, and the only unique components are the electronic circuitry and Debye-Sears modulator. The selection of the later frequency modulator was based on the following requirements: (1) being able to build an IF amplifier whose bandpass is large enough to accommodate the spectrum of the random signal; (2) having photodetectors with an acceptable frequency response; (3) having the unwanted diffraction modes (or orders) separated in angle from the usable mode so that they may be easily blocked out; and (4) being able to drive the modulating medium at the selected IF frequency.

Experiment No. 3 - Amplitude Correlation Measurement

Three alternative approaches were presented. Particular attention in this experiment was given to the need for good component linearity; large dynamic range, high-gain stability, good matching of channel gain characteristics on post-measurement analysis configuration; the probable values of the component-induced errors; and the circuitry for on-site data reduction.

Experiment No. 4 - Stationarity Test

The analysis considered two basic classes of prospective detectors: film and electronic image tubes. (In this regard a rather comprehensive appendix on recording materials was included in Reference 6). It was concluded that either a suitably chosen film or a slow-scan vidicon showed the most promise, the latter being favored because of its real-time readout capability.

Experiment No. 5 - Spectral Spreading Measurement

Fluctuations in the instantaneous difference frequency are a major concern in the implementation of this experiment. The major components at the transmitter end of this experiment are the He-Ne (6328 Å line) gas laser and Debye-Sears acoustic modulator. This particular laser was recommended because it is the only available optical source having sufficient short-term frequency stability to permit measurement of frequency fluctuations induced by the propagation path. A reasonable degree of stability in the laser output intensity is required.

Experiment No. 6 - Power Fluctuation Measurement

The system definition analysis of this experiment was based on power fluctuation measurements performed over the S&ID five mile optical link.

Experiments No. 7 and No. 8 - Heterodyne Equivalent and Angular Fluctuation Measurement

The analysis indicated the requirement for two types of collecting optics to examine the full range of heterodyne efficiency versus aperture size (i.e., both a reflective and refractive configuration). These experiments are conducted together simply by including a beam splitter.

Experiments No. 9 and No. 10 - Spread Function and Beam Spreading Measurement

These two experiments were considered together because the main difference lies in the recording technique: film recording for Experiment No. 9 and the use of a photomultiplier for Experiment No. 10.

Experiment No. 11 - Polarization Fluctuation Measurement

The distinguishing features of this system are a stationary Wollaston prism and two separate PM tubes and recorders. A comparison of three alternate approaches was presented.

Experiment No. 12 - Atmospheric Backscatter, Transmittance, and Sky Radiance Measurement

The optics and electronics for this system are fairly straightforward, with the principal function of the optics being to increase the amount of backscattered light collected beyond the capability of the unaided receiver, and to keep out unwanted light by limiting the field of view.

Experiment No. 18 - Communication Link Error Rate

A system configuration was described that measures bit error rates induced by the turbulent medium, noise in the detectors and amplifiers, and vibration and miscellaneous biases. The design attempted to minimize the errors induced by the latter two factors, and made use of a Kerr cell modulator, a photomultiplier detector, and integrated digital logic circuitry (to eliminate the need for storage tapes, magnetic drums, etc.). The entire measurement configuration is compatible with variable "information" bit rates up to 1 megacycle.

## TEST SITE ANALYSIS

Conclusions reached during the problem definition task indicated the requirement for flat, uniform propagation paths for initial testing. The siting analysis indicated the availability of a number of well-instrumented facilities that could support both initial pilot testing and extended experimental programs. Figure 4 gives the location of some of the potential sites

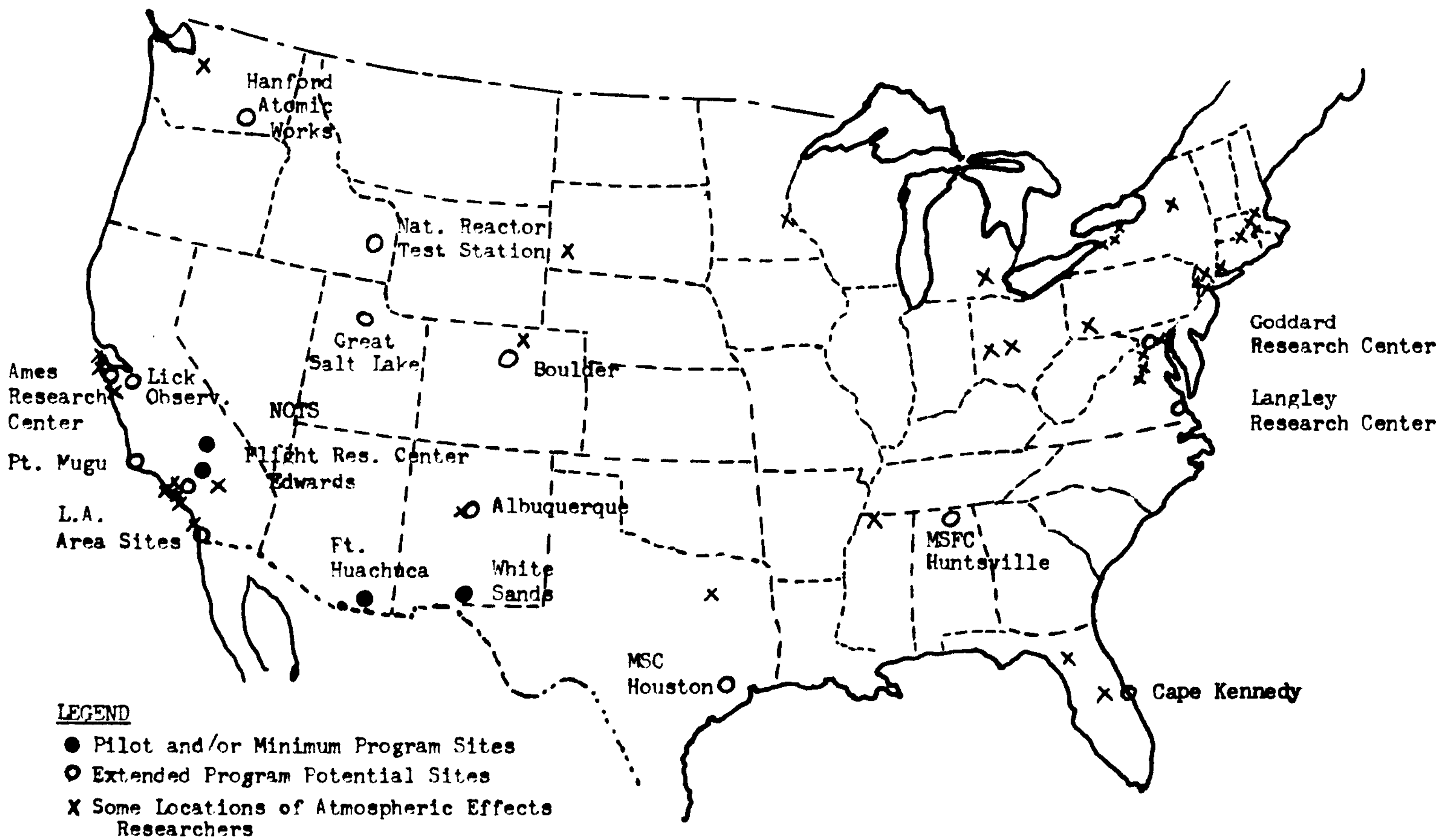


Figure 4. Examples of LACE Implementation Sites

in the continental U.S. The analysis in Task III provided considerable detail on existing facilities and climatological background data (e.g., cloud-cover statistics) and sources for additional information. Additional data were given on tracking equipment and supporting equipment at sites abroad.

## PROPAGATION LINKS

This portion of the study presented an analysis of requirements for ground, airborne, and satellite links. In addition to considerations indicated in the test site analysis, the ground-link discussion presented a detailed listing of supporting equipment required (i.e., tracking, test, recording, and general-purpose). The airborne-link analysis was divided into discussions of aircraft and balloon test planning factors. The satellite-link analysis outlined the main points and requirements to be considered in preparing for this phase, and included detailed appendixes outlining a study approach for final space payload definition, space vehicle summary, and space tracking capabilities.

## SYSTEM SYNTHESIS ANALYSIS

A number of alternative measurement approaches were analyzed for ground-to-ground links, and four experiment groupings were prepared. The groupings, summarized in Table 5, relate the consideration of factors such as similarity of objectives, potential applications, ease of implementation, limitation and constraints, and some general value judgements.

The first group is a basic application-oriented approach, and contains Experiments 3, 6, 9, 10, 12, and 18. The first four experiments of this group are concerned with power fluctuations within the beam. Experiments 12 and 18, while not fundamental from the theoretical point of view, provide background data necessary for system design. Experiment 11 is considered as optional depending on the interest in polarization effects.

In Group II, the potential of theoretical approach validation is included by adding the phase structure function measurements from Experiment 1 or 2. The option is offered because Experiment 1 alone is equivalent to the combination of Experiments 2 and 3, but is more difficult to implement. (It is noted that a bare minimum theoretical program, to validate Rytov's approximation, could be achieved with a combination of Experiments 2 and 3 or 1.)

Group IIa includes the same experiments as Group II plus Experiments 7 and 8, and is defined as a subclassification of Group II because it is still in the basic experimentation approach category, but the addition of Experiments 7 and 8 excludes it from the theoretical approach validation category.

Group III includes the addition of Experiments 4 and 5 to Group IIa and constitutes the maximum measurement approach.

The applicability of the individual experiments was also discussed in terms of vertical links (i.e., airborne and satellites). The following problem areas were pointed out in this connection:

1. Tracking becomes particularly acute for experiments that make use of heterodyne detection (Nos. 1, 2, and 5). These experiments cannot be successfully carried out with aircraft or nonsynchronous satellite platforms on either the up-link or down-link.

2. The correlation distances in the laser beam are quite large at synchronous satellite altitudes, which means the linear separation between sampling apertures used in correlation measurements must be on the order of up to tens of meters before sensible differences in the measured quantities can be expected.

3. Available power levels (irradiance) are reduced when long vertical links are considered.

A summary of the feasibility of the 13 LACE experiments, from the point of view of these vertical links, is considered in Table 6.

Table 5. Experiment Groupings for Stationary Ground-to-Ground Links

| Group | Rationale | Experiments by Number |
|---|---|---|
| I | Basic Application-Oriented | 3, 6, 9, 10, 12, 18, [11]* |
| II | Basic Theory-Oriented | Group I + 1 and/or 2 |
| IIa | Augmented Theory-Oriented | Group II + (2), 7, 8 |
| III | Complete | Group IIa + 5, 4 |
| *Optional - see text | | |

Table 6. Experiments Suitable for Satellite-Link Measurement

| Experiment No. | Remarks |
|---|---|
| 3 | Up- and down-links; becomes equivalent to No. 6 for g-ss* |
| 4 | g-ss,* ss-g* only |
| 6 | Up- and down-links; little value for ss-g* |
| 9, 10 | Up- and down-links |
| [11] ** | Up- and down-links, contingent on detection of polarization effect over g-g* links |
| 12 | Up-link only |
| 18 | Up- and down-links |

Note:

(1) All the experiments can be done over a-g and g-a links
(2) No. 2 marginally possible for a-g link

*g-ss = ground-to-synchronous satellite
ss-g = synchronous satellite-to-ground
g-g = ground-to-ground

**Optional - see text

# PROGRAM SPECIFICATION PLANNING

## INTRODUCTION

The areas of investigation included under the Task IV, Program Specification, portion of the study included the following:

1. The analysis, comparison and recommendation of program implementation approaches

2. The specification of a complete test program including objectives, experimental design, scheduling, resource requirements, and procedures for implementation

3. Management approach considerations

In developing the rationale for the plan, it was necessary to break these broad areas of study down into detailed considerations of experiment grouping and approaches; availability of resources, sites, links, vehicle; operational techniques and data handling; phasing and schedule factors; and management interrelationships. Most of the background for the Task IV analysis was obtained from the first three tasks of this study, with Task IV playing the role of integrator of the total program.

## PROGRAM SPECIFICATION FACTORS

The analysis, as indicated above, pointed out a number of factors bearing directly on the nature of the approach adopted. These factors were as listed and summarized below:

1. Requirement for theoretical model validation with a reasonable balance between the theoretical and experimental

2. Recognition of the need for a statistical base of empirical data, for performance prediction, which would require extensive testing

3. Necessity for diversity in siting to provide climatological and orographic variability

4. Recognition of uncertainties in technique procedures, and expermental equipment configuration performance that implies the necessity for much preliminary field experimentation prior to large-scale testing

5. Final definition of the configuration and utilization of space tests can reasonably be made only after a well-planned series of nonspace experimentation.

## PROGRAM APPROACH DEVELOPMENT SUMMARY

Based on the foregoing consideration of the program objective, rationale, and factors derived from the various task analyses, three basic program approaches were developed for evaluation. These approaches vary in scope and complexity and, quite naturally, in the amount of data expected to be obtained and degree to which the overall objectives of LACE can be satisfied. These approaches vary from a minimum experimental program to comprehensive, extended experimental sub-programs. The highlights and scope of these approaches are given in the following:

### Minimum Experimental Program

Preliminary data to verify theory only

Single site and link

Limited experiments, minimum test duration and variables

### Pilot Experimental Program

Minimum experimental program objectives

Comprehensive range of experiments and experimental variables

Equipment configuration check-out and comparative analysis

Several test cycles (replications)

Multiple paths and links (horizontal, mountain terminus, airborne/balloon)

Background for expanded testing (i. e., multiple sites, satellites)

### Extended Experimental Sub-Programs

Minimum and pilot experimental programs necessary prerequisites

Multiple site, link, environment, and experimental variable

Large sample empirical data

Extensive system operational experience

One of the most significant facets of these approaches is that each progressively more complex program contains the previous recommended program approach as a basis (or subset). The approaches were structured in this manner mainly because of the basic need for theoretical model validation through field experimentation, the high dependence of any extended program on a basic pilot program, and the conduciveness to incremental implementation.

## EXPERIMENTAL VARIABLES - MINIMUM PROGRAM

The basic experimental variables and measurements suggested for the minimum program are given in Table 7. Measurements with these variables should provide a fairly comprehensive basis for establishing the nonvalidity, validity, or limits of validity of the Rytov approximation.

Table 7. Experimental Variables and Measurements - Minimum Program

| Experimental Variables | | Measurements | |
|---|---|---|---|
| Source | Path | Receiver | Path |
| Laser (e.g., 6328Å, 1.15μ, 3.39μ)<br>Variable diameter<br>Focused or unfocused | Up to approximately 10 miles along dry lake bed | Log intensity variance<br>Beam spread | Temperature profile and power spectrum<br>Wind velocity<br>General synoptic meteorology |

It is also suggested that a comprehensive micrometeorological measurement program be initiated in conjunction with the minimum program, and that full-scale implementation of such a program commence during the pilot program. This program would be based on determining the distribution of the refractive index structure constant, $C_N^2$ over the path.

## PILOT PROGRAM

The pilot program was established to satisfy the following basic objectives:

Development and test of basic measurement techniques

Acquisition of preliminary atmospheric effects data

Provision of background and a basis for an extended experimental sub-program phase

## Pilot Program Tasks and Tests

The pilot program would be divided into the following interrelated tasks and tests that should satisfy the foregoing objectives:

Tasks

Equipment evaluation and development - performance and measurement program suitability

Site survey and activation

Detailed test procedure preparation

Data collection and analysis plan development

Preparation for sub-program implementation (including detailed test design and analysis plan)

Tests

Measurement configuration and concept check-out

Preliminary atmospheric effects data acquisition

Operational procedure testing

Development of preliminary system performance factors

## Pilot Test Experimental Design

A summary of pilot test experimental variables is given in Table 8.

A typical experimental design phasing for the pilot program was developed, which suggested the establishment of three sub-phases of two to three weeks in length, interspersed with analysis periods of approximately three weeks following each sub-phase. This typical design, which uses the experimental variables depicted in Table 8 is illustrated in Table 9.

## EXTENDED EXPERIMENTATION SUB-PROGRAMS

The extended experimentation sub-programs would consist of an expansion of the pilot program to examinations of a larger range of propagation parameters at a number of geographic locations, climatological regions, up- and down-links, and platforms. It would be premature at this time to plan a complete extended program much beyond what has been discussed earlier as being planned for the pilot program.

Table 8. Pilot Test Experimental Variable Summary

| Experiment | Receiver | | Path Length (R) | Transmitter | | |
|---|---|---|---|---|---|---|
| | Aperture | Spatial Separ. ($\rho$) | | Aperture, Focal Length, & Beam Width | Wavelength | Other |
| 1. Spatial & Temporal Correlation Function<br>2. Phase Structure Function<br>3. Amplitude Correlation Function | 1. As small as possible (approx 1 mm)<br>2. May be increased as S/N decreases | 1. Should range from 0 cm to 1 meter with emphasis on 0 to 20 cm<br>2. Range of $\rho$ might be larger for long paths | 1. Since $D_{\phi\phi} \sim R$, equal intervals are satisfactory<br>2. Since $C_{LL} \sim R^3$, intervals at large R should be smaller<br>3. Horizontal path 1, 2, 5, 10, 15 km<br>4. Long near vertical links 12, 15, 20, 30 km | Variable | 6328Å<br>1.15 μ<br>3.39 μ<br>or as established at a later date | — |
| 4. Stationarity Test | 1. Not an experimental variable<br>2. A function of Fresnel lens | 1. Not applicable | 1. Same path lengths as above | Same as above | | — |
| 5. Spectral Spreading | 1. A range of variation would be desirable<br>2. 0.1 cm, 1 cm, 2 cm, 10 cm, 25 cm, 100 cm | 1. Not applicable | 1. Same path lengths as above | Same as above | | — |
| 6. Power Fluctuation | 1. For short ranges should be larger than beam<br>2. Same sizes as No. 5 | 1. Not applicable | 1. Same path lengths as above | Same as above | | — |
| 7. Heterodyne Equiv<br>8. Angular Fluctuation | 1. Same as above | 1. Not applicable | 1. Same path lengths as above | Same as above | | — |
| 9. & 10. Spread Function & Beam Spreading | 1. Same as above<br>2. Fresnel lens may be used at longer distances | 1. Not applicable | 1. Same as above | Same as above except beam width focused to minimum at receiver | Same as above | — |
| 11. Polarization | 1. Same as No. 5 | 1. Not applicable | 1. Same as above | Same as above | | Linearly & circularly polarized |

Table 9. Pilot (Ground-to-Ground Link) Test Program - Summary of Objectives and Scope

| Typical Test Week | 1 2 | 3 4 5 | 6 7 | 8 9 10 | 11 12 | 13 14 15 16 17 18 19 20 | 21 22 23 24 25 26 |
|---|---|---|---|---|---|---|---|
| Activity | Test Sub-Phase (T-I) | | Test Sub-Phase (T-II) | | Test Sub-Phase (T-III) | | |
| Test Sub-Phase Scope | Parts of experimental configuration No. 2 and 3, *no* spatial correlation measurements | Analysis of test results | Spatial correlation measurements of exp. No. 2, 3, Testing Experimental Groups B. 4, 5, 6 C. 7 and 8 D. 9 and 10 E. 11 | Analysis of test results | Same as Category II except use mountain top links. Add exp. No. 18 | 1. Test analysis and evaluation 2. Preparation for ground to air pilot tests 3. Initiate sub-program experimental planning | Report preparation |
| Experimental Variables (No. of Levels) | Path length (2) Frequency (3) Aperture size Receiver-fixed Trans-variable Beamwidth-variable | | Same as I except add 3 spatial separations for experiments 1 and 2 | | Same as I and II except path length to several mountain tops included | | |
| Secondary Testing | Experiment No. 12 config. (Absorption - scattering) | | Same as I | | Same as I and II | | |
| Test Observation Support | 1. Local meteorology 2. Remote indication along path | | Same as I plus tethered meteorology balloon observation | | Same as II | | |
| Objectives | Evaluate Rytov's approximation and determine $C_N^2$ | | 1. Inter-experiment correlation 2. Equip. and procedure analysis 3. Atmos data acq. | | 1. Long and near vertical link eval. 2. Final equip. config eval. | | |

For planning purposes, however, it has been envisioned that it would be desirable to consider about four fixed locations (of different characteristics) for multivariable experimentation and two semimobile sites. An example of a sub-program specification for a potential fixed location is given in Table 10 (presented simply as an example of the approach that will be taken toward development of the extended program experimental design).

Table 10. Sub-Program Experimentation Specification Example

| Summary of Test Specification Items | General Requirements |
|---|---|
| Objective | Near-vertical up- and down-link laser amplitude characteristics |
| Location | White Sands Missile Range, New Mexico |
| Vehicle(s) | Low-altitude tethered balloon and variable-altitude aircraft |
| Contractor | To be established (e.g., University of New Mexico);<br><br>Balloon and aircraft operations by AFCRL |
| Parameters | Laser frequency and beamwidth, receiver aperture, dual-aperture separation, range, zenith angle |
| Expected Results | Spectrum of amplitude fluctuation, probability density of amplitude, log-amplitude correlation function |
| Problem Areas | Balloon-borne laser pointing, target tracking, limited altitude at reasonable cost, equipment reliability |

## PROGRAM SCHEDULING

Figure 5 summarizes the recommended program sequencing. As indicated, the pilot test program, which starts with the minimum experimental program, would follow the present LACE program planning study. It has been determined that detailed specification of the particular elements of the experimental program much beyond the ground-to-ground links of the pilot program would be impractical at this time. However, a general discussion of airborne

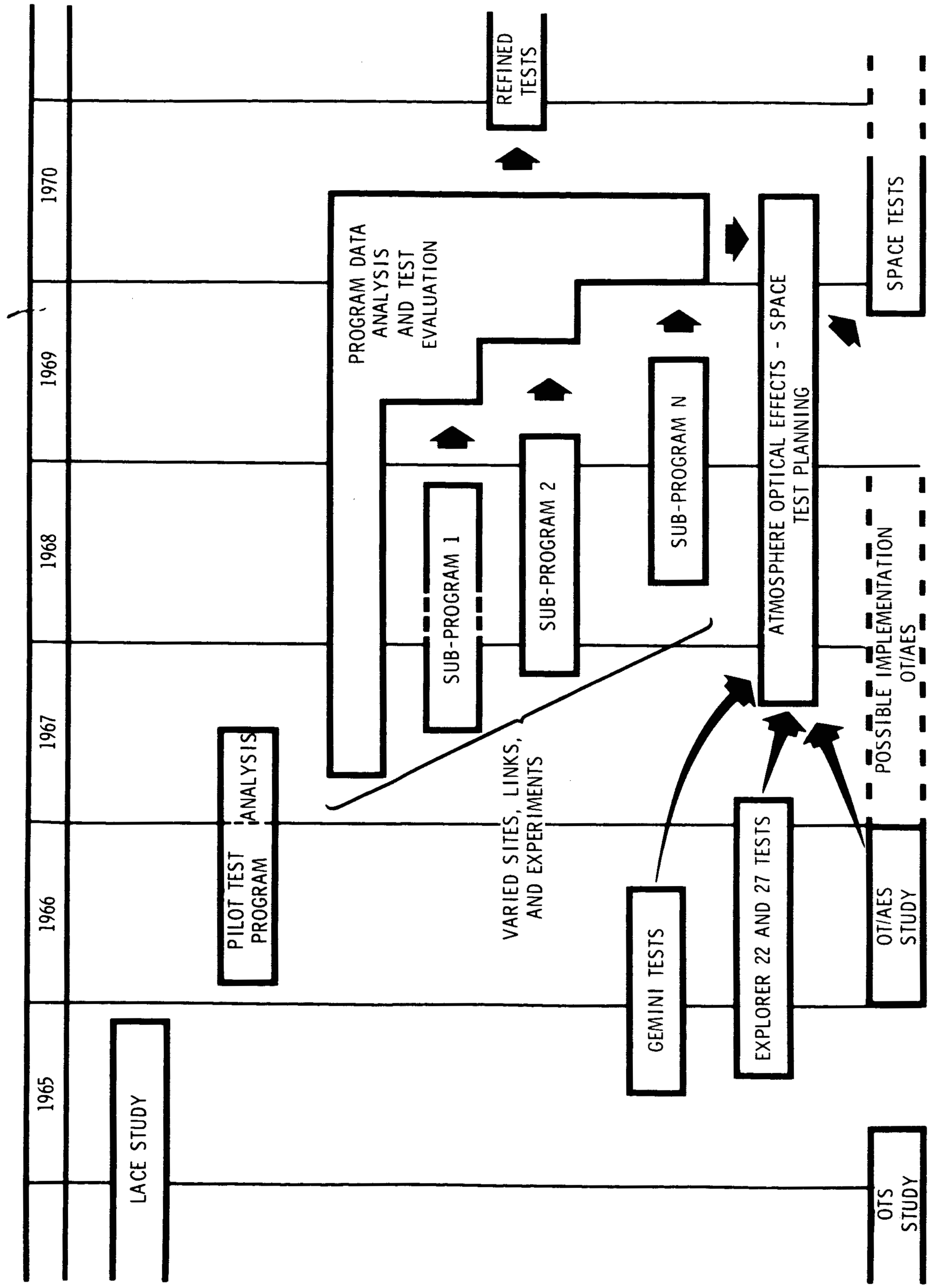


Figure 5. Representative Total Program Schedule

and satellite links, along with a suggested study approach, was presented in the Task III report. The procedure recommended, instead, is to proceed through the pilot phase with broad-scale objectives for the later phases and gradually firm up these objectives of the subsequent phases as the evaluation of the experimental results indicate the specific requirements.

At present, it is felt that a pilot program, of the magnitude indicated, could be accomplished in approximately 18 months (Figure 6 ). This typical schedule would allow for an overlap in ground-to-ground and ground-to-airborne links. Additionally, the program phasing recommended allows for the parallel development of the extended experimental sub-program. It is strongly felt that this later effort should be initiated sufficiently early in the pilot program to gain the maximum benefit from the pilot test "lessons," to identify long-lead development items, and to provide a smooth transition into the extended experimental sub-program.

## MANAGEMENT APPROACH

It has been determined that the exploratory nature of the pilot testing dictates the requirement for close coordination, with prime management responsibility for planning, development, and field experimentation centrally located. A typical functional organization of the pilot test program is shown in Figure 7 to illustrate the relationship of various program tasks.

The extended experimental sub-program, because of its diversity of objectives, dispersion of test sites, and resource requirements, indicates the requirement for multiple parallel sub-programs and the use of existing experienced experimentalists. Inasmuch as management of the desired type of effort would require a sizable technical and administrative effort to integrate the many necessary separate small tests, it is felt that a prime contractor should be selected to work with NASA in providing this management support.

## PROGRAM COSTS

In order to obtain an indication of the funding required to support a pilot program of the scope indicated, a very gross cost estimate analysis was prepared. Figure 8 summarizes this cost estimate. It should be noted that it does not include any estimate for extended sub-program experimentation or space (satellite) testing. A more detailed breakdown of this estimate is given in Reference 7.

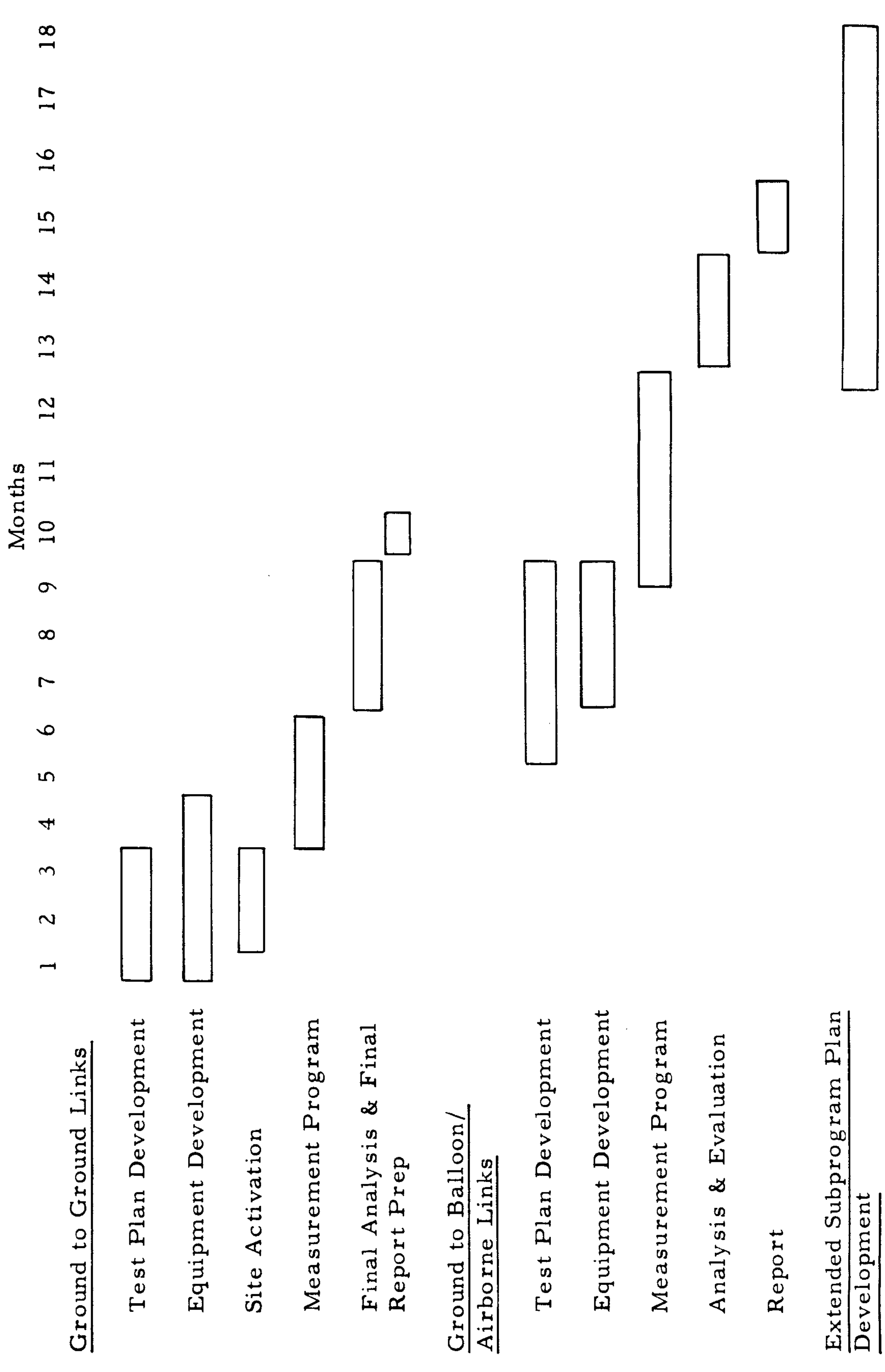


Figure 6. Total Pilot Test Program Summary (Typical Schedule)

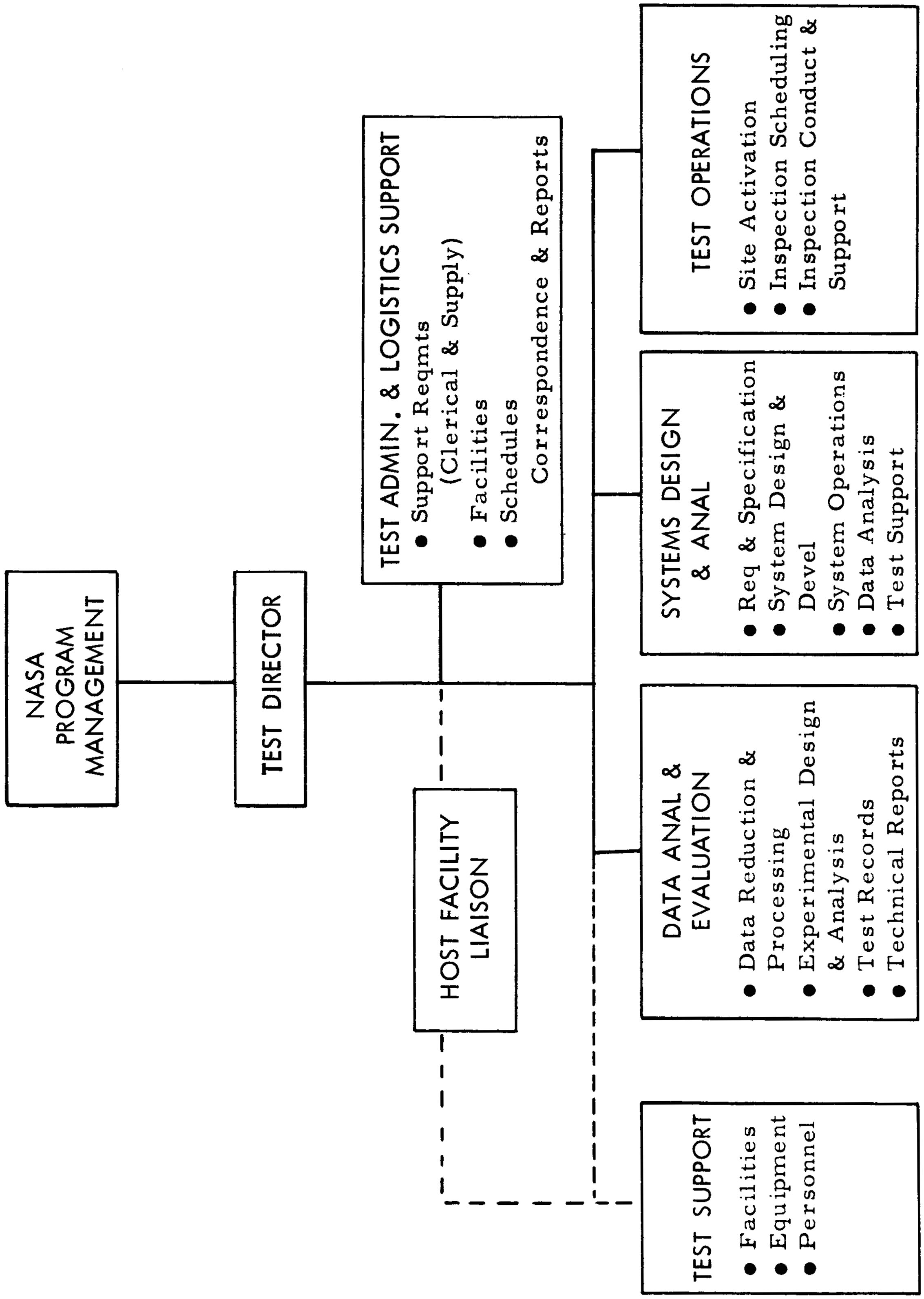


Figure 7. Pilot Test Functional Organization

| | Calendar Years | | | | |
|---|---|---|---|---|---|
| | 1st | 2nd | 3rd | 4th | Total |
| Personnel | $290K | $ 130K | | | $ 420K |
| Equipment & Support | 175 | 25 | | | 200 |
| Other Costs | 60 | 60 | | | 120 |
| | $525K | $ 215K | | | $ 740K |

Figure 8. LACE Implementation Costs - Pilot Program Summary

# APPENDIXES

## APPENDIX A. NAA THEORETICAL STUDIES ON OPTICAL PROPAGATION

The following Theoretical studies on optical propagation were performed by NAA in support of the LACE program and reported in Task II.

TM 91. Atmospheric Turbulence and Its Effect on Laser Communications Systems: Second Report

TM 89. The Relationship Between Random Optical Wave Front Distortion and Optical System Performance

TM 118. Optical Heterodyne Detection of an Atmospherically Distorted Signal Wave Front

TM 119. The Statistics of Geometrical Interpretation of Wave Front Deformation

TM 120. The Significance of the Inner Scale of Turbulence to the Phase Structure Function

TM 125. Extension of Results for Phase- and Log-Amplitude Correlation: Higher-Order Terms in the Near-Field Series and Coverage of the Far-Field

TM 127. Further Evaluation of Phase and Amplitude Correlation Functions for an Atmospherically Distorted Wave Front

TM 131. The Angular Scintillation Correlation Function

TM 132. RMS Angular Resolution by the Wave Front Approximation Technique

TM 135. Atmospheric Optical Doppler: An Approximate Evaluation

TM 176. Propagation of a Focused Laser Beam Through a Turbulent Atmosphere

TM 224. Means, Variances, and Covariances for the Propagation of Laser Beams Through a Turbulent Atmosphere

# APPENDIX B. EXAMPLES OF THE STATUS OF THEORETICAL RESULTS

## PROPAGATION OF AN INFINITE PLANE WAVE OVER A HORIZONTAL PATH

$$C_\ell(\rho) = 0.307\, k^{7/6} C_N^2 Z^{11/6} \left\{ -7.531\left(\frac{k\rho^2}{4Z}\right)^{5/6} + 1 + 6.842\left(\frac{k\rho^2}{4Z}\right) - 0.382\left(\frac{k\rho^2}{4Z}\right)^2 - 0.026\left(\frac{k\rho^2}{4Z}\right)^3 + 0.001\left(\frac{k\rho^2}{4Z}\right)^4 + \ldots \right\} \quad (1)$$

$$D(\rho) = 2.91\, k^2 C_N^2 Z \rho^{5/3} \quad (2)$$

where

$C_\ell(\rho)$ = the covariance of the log amplitude of the signal detected at two points a distance $\rho$ apart located in the plane at the end of the propagation path

$D(\rho)$ = the wave structure function, a measure of the mean square phase and log amplitude difference between two points a distance $\rho$ apart

$k$ = the wave number (i.e., $2\pi/\lambda$)

$C_N^2$ = the turbulent refractive index structure constant and the constant of proportionality associated with the Kolmogoroff theory

$Z$ = the length of the path of propagation

PROPAGATION OF A SPHERICAL WAVE OVER A HORIZONTAL PATH

$$C_{\ell}(0) = 0.123\, k^{7/6}\, C_N^2\, Z^{11/6} \tag{3}$$

$$D(\rho) = 0.545\, k^2\, C_N^2\, Z\, \rho^{5/3} \tag{4}$$

PROPAGATION OF A FOCUSED, GAUSSIAN INTENSITY DISTRIBUTION BEAM, AS THE TRANSMISSION OF A LASER BEAM OVER A HORIZONTAL PATH

$$C_{\ell}(\rho) = -\frac{k^2}{8\pi} \mathrm{Re} \int_0^Z du \int_0^\infty d\sigma\, 8.16\, C_N^2 \sigma^{-11/6}$$

$$\times J_0\left(\sigma^{1/2} \rho \frac{u - ik\alpha^2}{Z - ik\alpha^2}\right) \left\{ \exp\left[\frac{\sigma}{ik} \frac{(Z-u)(u - ik\alpha^2)}{(Z - ik\alpha^2)}\right]\right.$$

$$\left. - \exp\left[\frac{\sigma}{2ik}\left(\frac{(Z-u)(u-ik\alpha^2)}{(Z-ik\alpha^2)} - \frac{(Z-u)u + ik(\alpha^*)^2}{Z + ik(\alpha^*)^2}\right)\right]\right\} \tag{5}$$

$$D(\rho) = -\frac{k^2}{4\pi} 8.16\, \mathrm{Re} \int_0^Z du \int_0^\infty d\sigma\, C_N^2 \sigma^{-11/6} J_0\left(\sigma^{1/2} \frac{u - ik\alpha^2}{Z - ik\alpha^2}\right)$$

$$\times \exp\left[\frac{\sigma}{ik} \frac{(Z-u)(u - ik\alpha^2)}{(Z - ik\alpha^2)}\right] \tag{6}$$

where

$$\frac{1}{\alpha^2} = \frac{1}{\alpha_0^2} - \frac{ik}{R} \tag{7}$$

$\alpha_0$ = the standard deviation for the Gaussian beam of the amplitude of the beam at the source

R = the radius of curvature imposed on the beam to bring it to focus a distance R from the transmitter

MEAN SQUARE FRACTIONAL FLUCTUATION OF TOTAL POWER COLLECTED BY A LARGE-APERTURE "PHOTON BUCKET"

$$\sigma^2 = \frac{16}{\pi} \exp \left| - 2 C_\ell (0) \right| \int_0^1 u \, d u \left| \cos^{-1} u - u \sqrt{1 - u^2} \right|$$

$$x \exp \left| 4 C_\ell (u\Delta) \right| \tag{8}$$

where $\Delta$ is the collector diameter

The results of Equations 1, 3, or 5 can be inserted into Equation 8, according to which may be applicable, to obtain an explicit answer. All that must be known is $C_N^2$.

SIGNAL-TO-NOISE RATIO OF AN OPTICAL HETERODYNE DETECTION SYSTEM AS A FUNCTION OF COLLECTOR DIAMETER

Substitute the appropriate expression for $D(\rho)$ into the following expression to obtain an explicit answer

$$S/N \simeq \frac{16}{\pi} \Delta^2 \int_0^1 u \, d u \left| \cos^{-1} u - u \sqrt{1 - u^2} \right| \exp \left| - \frac{D(u\Delta)}{2} \right| \tag{9}$$

In the results presented for a horizontal path, $C_N^2$ is constant and can be extracted as a factor. For nonhorizontal paths, $C_N^2$ appears in one of the integrals leading to the final result, and must be integrated over.

Similar results are available for problems of angular scintillation of a target, photographic resolution, and other related areas.

# REFERENCES


1. Definition of Optical Atmospheric Effects on Laser Propagation, Vol. I. NAA S&ID, SID 64-1894-1 (9 October 1964).

2. Experimental Laser Space Communications Program, Task I, Problem Definition, Vol. II. NAA S&ID, SID 64-1895-2.

3. Definition of Optical Atmospheric Effects on Laser Propagation, Vol. III. NAA S&ID, SID 65-1084 (4 August 1965).

4. Specification of Atmospheric Laser Propagation Experiments, Vol. I. NAA S&ID, SID 64-2085 (16 November 1964).

5. Specification of Atmospheric Laser Propagation Experiments, Vol. II. NAA S&ID, SID 65-1275 (15 September 1965).

6. Requirements Study for System Implementation of An Atmospheric Laser Propagation Experiment Program - Vol. II. NAA S&ID, SID 65-1466 (8 November 1965).

7. Program Specification Plan for Determination of Atmospheric Effects on Laser Space Communications - Vol. II. NAA S&ID, SID 65-1467 (9 November 1965).