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A PROPOSAL FOR THE COHERENT PROPAGATION STUDIES PORTION OF THE 10.6-MICROMETER LASER COMMUNICA EXPERIMENT ADVANCED TECHNOLOGY SATELLITE-F TECHNICAL PROPOSAL

Nelson McAvoy, et al.

Goddard Space Flight Center
Greenbelt, Maryland

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NELSON McAVOY
PETER O. MINOTT
ROBERT S. LAWRENCE
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TECHNICAL PROPOSAL

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Nelson McAvoy and Peter O. Minott
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Environmental Services Sciences Administration

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INTRODUCTION

The Advanced Technology Satellite (ATS) Laser Communications Experiment (LCE) has two broad objectives: to develop and test a space-space two-way simultaneous video link between two synchronous satellites, and to establish the influence which the atmosphere has on a coherent plane wave for space-earth communications systems. All of these experiments will be carried out at the 10.6-micrometer wavelength band of the carbon-dioxide laser.

Heretofore, the ground stations for the latter of the two objectives, operations of the ground stations, and the associated data analysis were to be the responsibility of Bell Telephone Laboratory (BTL), but BTL has discontinued its plans to perform the experiment. This proposal is submitted for the portion of the LCE which was to be performed by BTL.

The LCE will have a 5-MHz video transmitter aboard the ATS. Included in the same package is a receiver with the same information capacity as the transmitter. Table 1 shows salient characteristics of the transceiver. During the first six to nine months after the launch of ATS-F, a two-way simultaneous video link between ATS-F and a functionally identical ground transceiver will be established. During this same period the transmitter on ATS-F will be used in a cw mode to irradiate various ground stations for the purpose of demonstrating the atmospheric effects on the signals.

Our proposed measurements will permit, for the first time, comparison of the effects of atmospheric turbulence on a space-to-earth 10.6-micrometer beam with those conventional ground-based observations that might be expected to best predict and characterize the quality of a 10.6-micrometer communication channel. Specifically, for example, we shall determine to what extent stellar scintillations observed in the visible are related to the amplitude scintillation of the 10.6-micrometer beam, and to what extent high-speed temperature fluctuation measurements are related to the phase fluctuations of the 10.6-micrometer beam.

Table 1. Salient Characteristics of ATS-F LCE Transceiver.

Carrier Frequency	
Down Link	28,306,251,420 kHz
Up Link	28,412,615,720 kHz
Modulation Mode	FM
Video Bandwidth	5 MHz
Antenna Aperture	7 in.
Antenna Gain	95 dB
Prime Power Required	20 W
Mass (with Redundancy)	50 lb
Minimum Detectable Signal per Hz Bandwidth	-160 dBm
Intermediate Frequency	30 MHz
LO Power	25 mW
Transmitter Power	500 mW
Transmitter Efficiency	5 percent
Signal-to-Noise Ratio After Optical Mixer	25 dB
Range	3×10^7 m
Atmospheric Loss	4 dB

These measurements were to be made by BTL using one semi-portable ground station. The station was to operate at four locations: two locations in the United States with different climatic conditions prior to ATS-F relocation over Africa, and two locations in Europe with different climatic conditions after ATS-F relocates over Africa.

The basic optical arrangement consisted of two separately steerable 51-cm-aperture telescopes directed onto different mixers. Both mixers would use the same local oscillator (LO). The two telescopes would be mounted on a rail to provide for variable separation between the two telescopes up to a maximum of 5 m. A 51-cm aperture was required for measurement of large signal losses through fog and clouds, which was one of the BTL experiment objectives. Also required for measurement through clouds was a 10-W beacon, instead of the 500-mW beacon through a 7.5-cm-aperture telescope normally employed for cloudless situations.

Under the present proposed scheme, the experiment will be carried out with a completely different ground-station arrangement. The experiment will be performed from two separate ground stations, each with its own coinvestigator. As will be explained in the proposal, these ground stations are not redundant. One ground station will be collocated with the ATS site at Goldstone, California; the other will be located at the GSFC Optical Research Facility, Greenbelt, Md. Mr. Robert S. Lawrence, Chief Optical Propagation Program Area, Wave Propagation Laboratory, ESSA Research Laboratories, Boulder, Colorado, will be a coinvestigator and will be responsible for making measurements and analyzing data at the Goldstone site. The optical and mechanical equipment for this site will be furnished by GSFC. The GSFC-furnished equipment includes the optical-mechanical systems, shelters, infrared mixers, and IF strips. Microthermal sensors, analysis equipment, and the actual operation of the equipment in the field will be furnished by ESSA under contract to GSFC. Mr. Peter O. Minott, Head, Optical Instrumentation Section, Optical Systems Branch, will be co-investigator at the GSFC Optical Research Facility.

Two infrared receiver systems will be used at the Goldstone site for propagation studies:

A. The communications receiver system which is functionally identical with the ATS flight equipment. This receiver will be used for the measurement of intensity and intensity fluctuations of the ATS signal. Even though the primary function of this receiver is communications studies, these measurements can be made while the ATS transmits a cw signal to the special-purpose receiver.

B. The special-purpose receiver at Goldstone will have small dual apertures, with dual mixers and a single LO. This receiver will be used primarily to measure relative fluctuation of phase and amplitude of the signal between two points on the earth with a variable separation of up to 16 feet.

The optical system for the receiver to be used at the GSFC Optical Research Facility is designed around a 76-cm aperture, Coude-focus, precision tracking telescope. It is particularly appropriate for this experiment because of the nature of the Coude arrangement; this allows for the LO, mixer, and all other miscellaneous terminal optics to be located at a fixed image plane at the base of the telescope while the telescope tracks from horizon to horizon. Requirements for vibration isolation of the LO do not permit the use of conventional tracking or astronomical telescopes. This receiver system will enjoy a 70-dB carrier-to-noise ratio in clear weather. It is, therefore, ideally suited for measuring signal losses caused by clouds, fog, and rain. For this reason, it will be fitted with a 20-W beacon transmitter which transmits through the same 76-cm-aperture antenna as is used for the received beam. In addition, this system can measure relative fluctuation in phase and amplitude of the received beam from ATS-F; this is due to the variable separation of smaller apertures imaged through the large telescope.

The above described plan is particularly attractive for the following reasons:

(1) All optical and mechanical subsystems that will be used in both stations have been extensively tested and used in the Optical Systems Branch, GSFC. Consequently, there will be no development cost to the program.

(2) Some of the more expensive optical, mechanical, and electronic subsystems that will already have been extensively used and tested in the Optical Systems Branch will be directly available to this project. Among these are the 76-cm-aperture precision tracking telescope and associated equipment, five infrared mixers with associated cryogenic and electronic equipment, three local-oscillator lasers, and a complete stellar-image-monitoring system which has been used for optical site selection. In addition, much of the meteorological and data analysis equipment at ESSA will be available to the program.

(3) The quasi-simultaneous operation of two separate propagation sites at locations with very dissimilar climatic conditions, during the whole of the time the ATS-F is in view of the United States, allows for sufficient data to render unnecessary plans for propagation work at a European site. Cost of site relocation in the United States is thereby eliminated.

(4) The participation of two coinvestigators will increase the scope of measurements made and decrease the likelihood of omissions in the experiment.

(5) The communications ground station will now be more closely associated with the propagation experiment and be more extensively utilized.

This proposal is written in two parts. Part 1 describes the experiments to be done at the Goldstone, California, ground station. It is a cooperative venture between GSFC and ESSA. Part II describes the experiment to be conducted by GSFC at the Optical Research Facility Ground Station.

PART I: GOLDSTONE, CALIFORNIA, GROUND STATION

Experiment Objectives

Background.—Fluctuations in the refractive index of the atmosphere, caused by winds, thermal currents, gravity waves, etc., are always present in various combinations of layers, waves, and well-mixed random variations. The statistics of these fluctuations vary significantly with time and space; in other words, the refractive-index fluctuation in the atmosphere is neither statistically stationary nor homogeneous. Unfortunately, the only atmospheric phenomenon for which we have a well developed model is homogeneous, isotropic turbulence.

This model is generally used, but each practical problem must be examined to determine the significance of departures from the ideal.

Turbulence-induced irregularities in the refractive index of the clear atmosphere are responsible for the twinkling of stars and the dancing and blurring of stellar images in an astronomical telescope. The spatial spectrum of the turbulent irregularities in the atmosphere is very broad, often closely approximating the Kolmogoroff (Reference 1) model of turbulence in which the power spectrum varies as the -5/3 power of the spatial wave number. The theory of optical propagation through such a turbulent medium has been well developed, but only for isotropic, locally homogeneous turbulence, and only for sufficiently weak turbulence and/or sufficiently short optical paths. A critical review of this theory has been prepared by Strohbehn (Reference 2). Lawrence and Strohbehn (Reference 3) have described the atmospheric model and reviewed present knowledge of the propagation effects relevant to optical communications.

The spatial spectrum of turbulence commonly follows the Kolmogoroff -5/3 power law for irregularity sizes ranging from about a millimeter to perhaps tens or hundreds of meters. The diffraction process responsible for the optical effects of the turbulent atmosphere acts very much as a spatial filter, accentuating the effect of irregularities of certain sizes and suppressing the effect of others. For example, the intensity fluctuation (scintillations) observed on the ground displays a predominant scale size $d = \sqrt{\lambda h}$, where h is the height of the turbulent layer and λ is the optical wavelength. This spatial filtering was discussed by Little (Reference 4) and is the central theme of the book by Tatarski (Reference 5).

The fact that spatial filtering exists and is dependent on the height of the turbulent irregularities suggests that an analysis of the scintillation pattern on the ground will provide information as to the strength of turbulence at various levels in the atmosphere. In addition, velocities of the various spatial components in the scintillation pattern will yield the wind velocities at the corresponding heights.

We have described (Reference 6) the physical mechanism responsible for this spatial filtering, and the possibilities of its use in remotely sensing the position of the turbulence and velocity of the wind. Closer examination of the method has convinced us that the wind velocity will be determined sensitively, but determination of the distribution of turbulence will be disturbed by small variations from a Kolmogoroff spectrum of turbulence. Fried (Reference 7) has suggested the use of starlight to make ground-based measurements of winds aloft and the distribution of turbulence with height. Examination of his proposal reveals that he has underestimated the difficulties introduced by the nonstationary statistics of the atmosphere and that it will be necessary to use a better light source, such as that from a laser on a geostationary satellite.

There is at present very little information available concerning the distribution of turbulence with height. Hufnagel (Reference 8) offered an atmospheric model that generally agrees with the published data on stellar scintillations.

Measurements were recently made (Reference 9) with a high-speed temperature sensor mounted on an airplane (Figure 1). These measurements have demonstrated that the turbulence in the real atmosphere at any one time is distributed in a very complex way, and that simple models for its distribution are not valid. There is real need for a ground-based method to probe continuously the structure and motions of the atmosphere. The important national problems of clear-air turbulence and of numerical weather forecasting provide two of the most dramatic applications of such information. Contributions to such fields as radio-wave propagation and diffusion of pollutants may also result.

The statistical non-stationarity and inhomogeneity of atmospheric turbulence, referred to earlier, pose grave problems in the design of propagation experiments intended to improve our understanding of turbulent effects. On the one hand, a short period of observation, even if it lasts for half an hour, will most likely not be representative of an average or ordinary situation. On the other hand, long periods of observation may be influenced by steadily changing atmospheric conditions; the variances, spectra, and correlations of such data, produced blindly by a computer, may be altogether misleading. Our approach to this difficult situation has been to use simple analog or digital circuits to average the desired statistical quantities for 1 minute, and to record the 1-minute averages for subsequent analysis, continuing this process for several hours or days at a time. The first step (often the only step needed) in the subsequent analysis is the plotting of temporal sequences of the 1-minute values (see below, Figure 12) and scatter diagrams showing the relationships among the quantities of

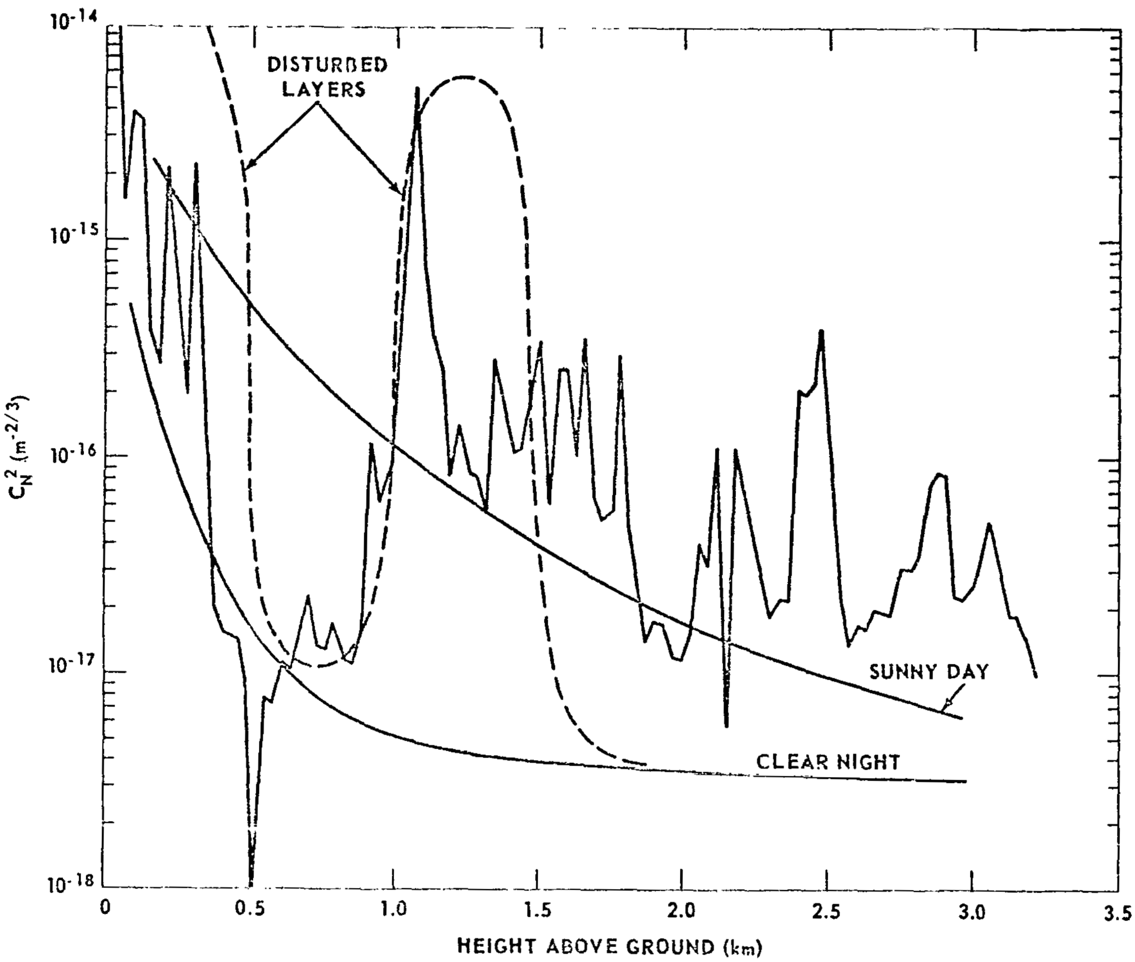

Figure 1—Measurements, made with an airborne high-speed temperature sensor, of the refractive-index structure parameter in the first 3 km above the ground. The jagged curve is the measurement; the smooth curves are idealized models taken from Reference 8.

interest. Figure 2 is such a scatter diagram; the individual dots represent the 1-minute values of log-amplitude variance measured during a 22-hour period (February 14-15, 1970), selected according to wind speed and compared with temperature structure-function measurements. Note the groups of points well separated from the mean trends, indicating that for many minutes at a time the

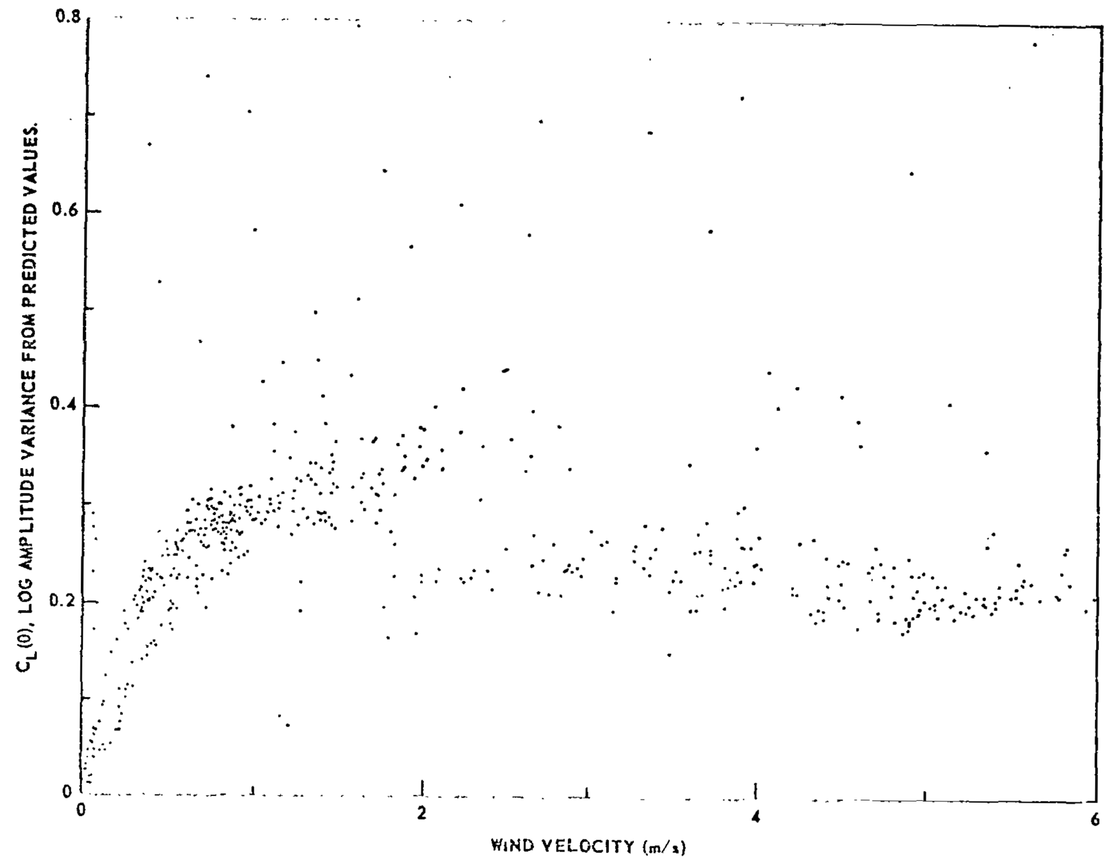

Figure 2—Computer-generated scatter diagram of 1-minute averages of propagation data produced by an analog preprocesser. Log amplitude variance from predicted values (λ =0.6328 micrometers).

effects were anomalous. Also note how much more we can learn about the relationship between the two quantities plotted than we could learn from a correlation coefficient or other simple statistical parameter.

Expected Results of the Proposed Experiments.— The measurements we propose for the ATS-F satellites will contribute substantially to an understanding of the causes of any atmospherically induced errors detected by the experimental laser communications system. In addition, our measurements will provide information needed to assess the practicability of remotely sensing winds and turbulence in the atmosphere. The results we expect to obtain can be grouped in the following four categories:

(1) Measurements of the statistical properties of the 10.6-micrometer signal reaching the ground will contribute substantially to the optimum design of optical and infrared systems that must operate on near-vertical paths through the atmosphere. The necessary information, namely the variance and covariance functions of amplitude and structure function of phase, cannot be obtained in the daytime for starlight, even for the visible portion of the spectrum, because of poor signal-to-noise ratio, and this information is quite unknown for the 10.6-micrometer band.

(2) Measurements of the state of the turbulent atmosphere, made simultaneously with measurements (1) will test the feasibility of predicting, from the state of the atmosphere, the perturbations of a space-to-earth laser beam. Conversely, the same data will test the feasibility of remotely probing the turbulence and winds in the atmosphere, using laser-beam observations. The necessary measurements of the state of the atmosphere are—

(A) Conventional meteorological measurements, including wind, temperature, humidity, and pressure near the ground, also routine winds-aloft data taken from the nearest regular United States Weather Bureau observing station.

(B) Observations near the ground, and occasional airborne observations in the first 4 km above the ground, of the temperature-structure function, made with high-speed temperature sensors. These temperature measurements are expected to relate to the phase fluctuations observed at 10.6 micrometers.

(C) Observations of starlight scintillation. The stellar scintillation measurements are expected to relate to the fluctuations in amplitude of the 10.6-micrometer beam. If measurements of stellar image size and image motion can be made, they are expected to compare closely with the phase fluctuation of the 10.6-micrometer signal.

(3) Insofar as atmospheric measurements (2) can be made during test of the 10.6-micrometer laser communications system, they can be used to test the feasability of predicting, and to learn which measurements are most useful in predicting, the performance of such a space-to-earth communications system at arbitrary geographical locations and under arbitrary weather conditions.

(4) Simultaneous measurements (1) and (2) will permit a critical evaluation of the adequacy of the atmospheric models and the propagation theories that are now available.

Measurements to be Made and Description of Equipment

Signal Processing and Receiver Equipment.—The Dual Receiver Interferometer System, in conjunction with the LCE communications receiver will be used to measure the following functions:

(1) Statistics of the log-intensity at a single point, including—

(A) log-intensity variance

(B) temporal power spectrum

(C) distribution function of intensity.

(2) Spatial covariance function of log intensity.

(3) Pattern velocity component parallel to interferometer spacing.

(4) Variance of optical phase difference as a function of interferometer spacing.

From these basic measurements it is possible to deduce the effects of the turbulent atmosphere upon an arbitrary receiving system or arbitrary aperture size.

Figure 3 describes schematically the optical mechanical portion of the receiver. Two mirrors with apertures variable from 1 to 3 in. and separation variable up to 5 m reflect the signal coming in from space onto a 6-in., off-axis, parabolic telescope. The telescope is afocal for convenient use of the image motion compensator (IMC). The IMC consists basically of two torque motors each carrying a 45-degree mirror and a spring as shown in Figure 4. The torque motors have 15 oz-in./amp response and the springs provide a restoring force of 0.2 oz-in./degree. The afocal telescope has a 0.4-degree field of view and a power of 10. Thus, the maximum swing required on the torque motors is 2.0 degrees. This is well within the current limitation of the torque motors. Figure 5 shows the measured sensitivity in degrees per amp of beam deflection and phase shift as functions of frequency response. The figure shows a 16-Hz resonance frequency and a usable flat range up to about 5 Hz. Returning to Figure 3, we see that the beams coming out of the IMC and reflected off the beam splitter are focused onto separate mixers and combined with the same LO (mixers No. 2 and No. 3). The outputs of these two mixers are then sent to the

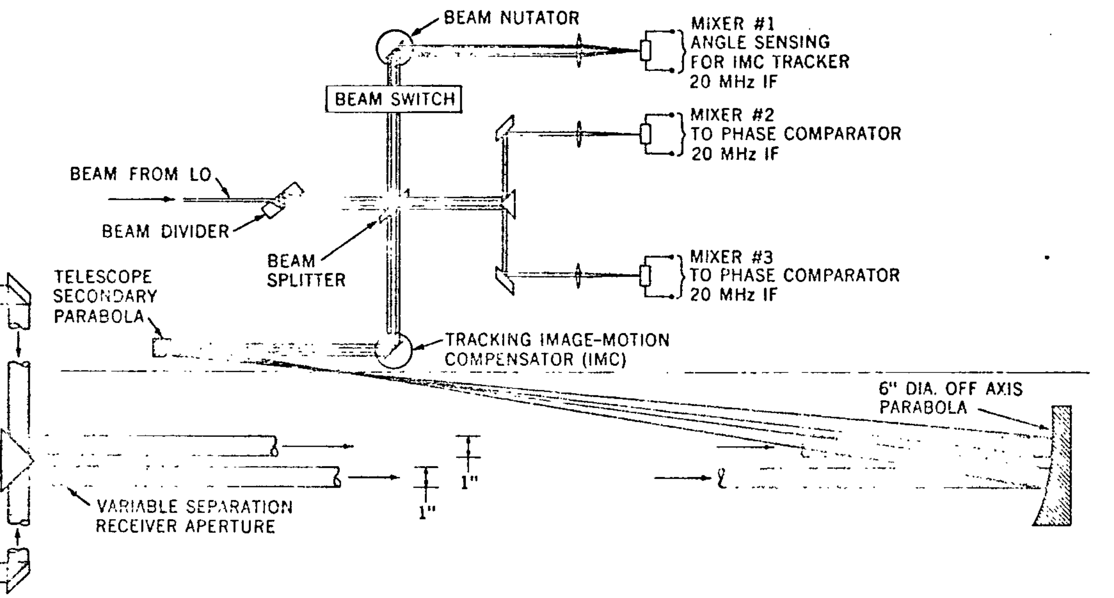

Figure 3–Dual receiver interferometer, schematic.

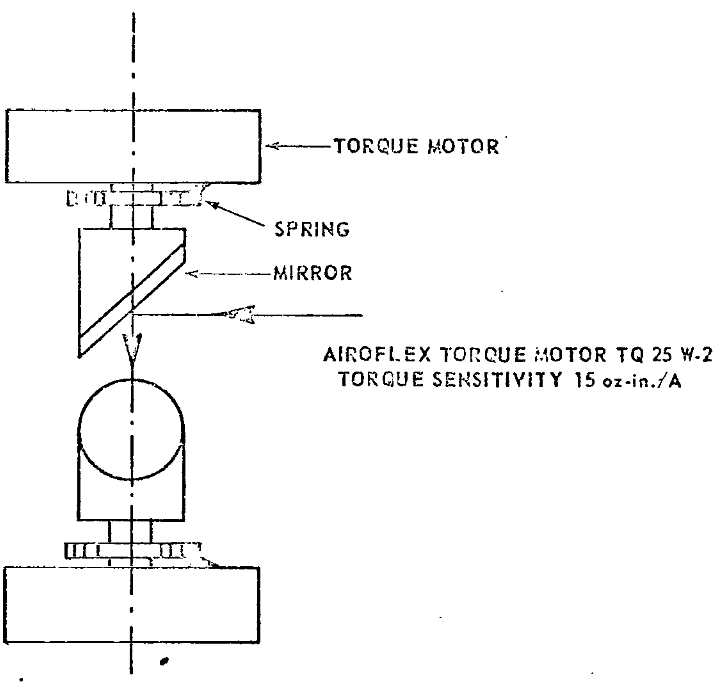

Figure 4–Image motion compensator, schematic

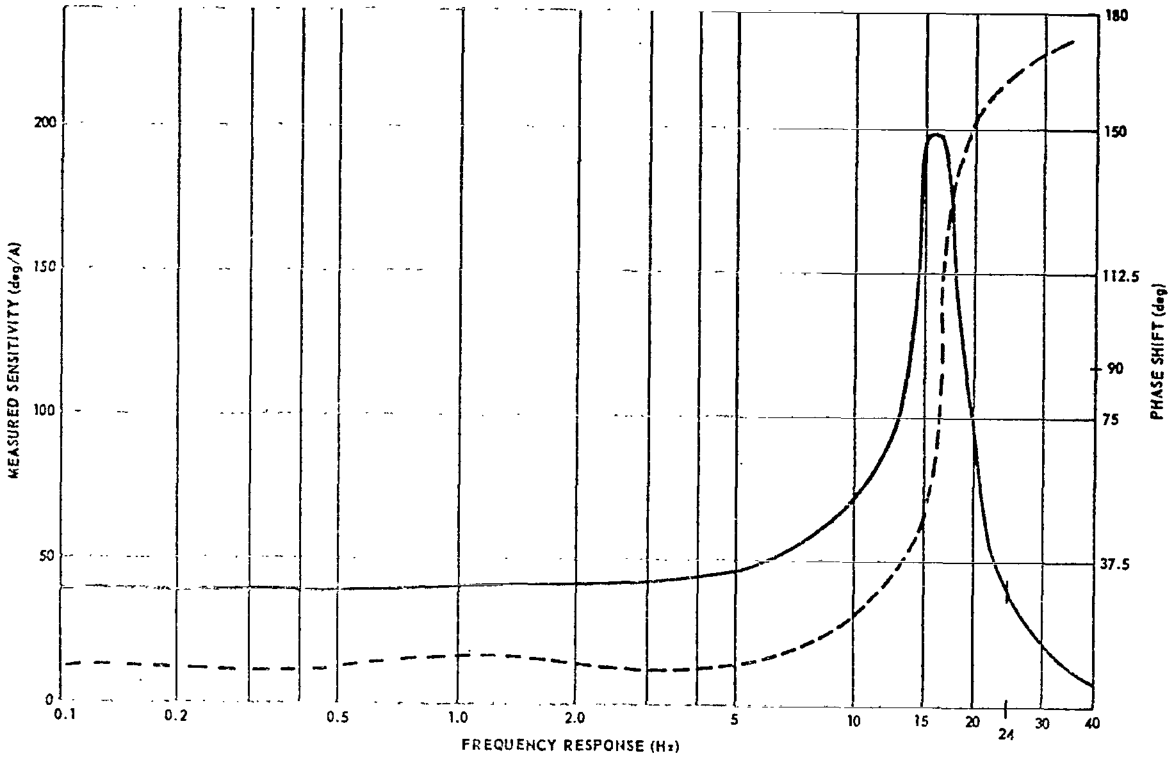

Figure 5–Measured sensitivity and phase shift of IMC versus frequency response.

terminal electronics and used for propagation analysis. The signal beams that pass through the beam splitter, combined with the same LO are focused onto a third mixer (No. 1 in the figure) through a beam nutator. The output of this mixer is used to servo-drive the IMC. The nutator is mechanically identical with the IMC, but is driven by an audio oscillator so that the focused beam on the mixer sweeps out a circle to eliminate beam deflection ambiguity.

The basic telescope and IMC components are shown in Figure 6. Figure 7 is an artist's conception of the Dual Receiver Interferometer System. The optical mechanical system will be mounted on a vibration isolation granite table, 1-1/2 x 3 x 13 ft in dimension. This is imperative to ensure that there is no

Figure 6–Basic telescope and IMC components.

varying path difference between the mixer and optical system caused by seismic and other vibrations.

We have had a ground-vibration analysis of the Goldstone ATS site made specifically for this experiment (Reference 10). The study shows longitudinal and vertical ground vibration displacements ranging from 0.4 to 0.08 wavelengths of our carrier in the 1- to 80-Hz frequency range. Therefore, phase comparison from two apertures can be made only if the optics, mixers, and LO are located on one vibration isolation table.

A test transmitter will be used over a horizontal path of about one mile to completely test the Dual Receiver Interferometer at the ESSA Laboratories, Boulder, Colorado, prior to installation at the ATS site. The test transmitter, shown in Figure 8, consists primarily of a visible-light laser and a CO_2 28-,

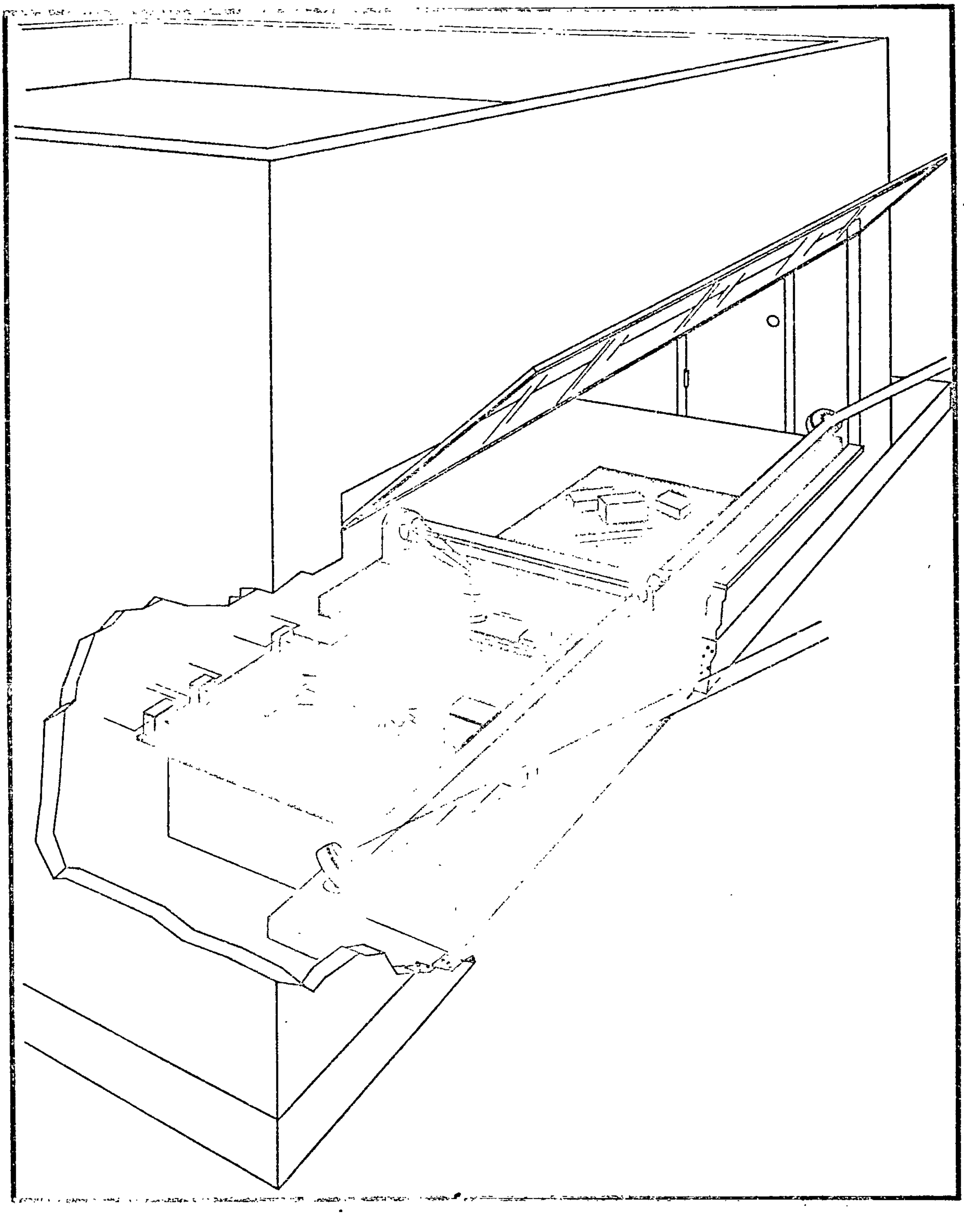

Figure 7–Dual receiver interferometer, artist's conception.

Figure 8—Test transmitter.

306-, 251-, and 420-kHz oscillator coaligned and collimated through a 12-in.-aperture telescope. The visible light laser serves as a collimated source which allows for ease in receiver optical element alignment.

The carrier-to-noise ratio out of each mixer is +38 dB, if we assume a 1-in. receiver aperture and a noise bandwidth of 10 kHz. This estimate is based on the expected 25-dB carrier-to-noise ratio, through a 18-cm-aperture antenna and a 10-MHz noise bandwidth realizable in the LCE communications receiver collocated at the Goldstone ATS site. The LCE communications transceiver will provide the beacon for this receiver.

The dual receiver interferometer up to and including the 20-MHz IF electronics, shelters, and auxiliary equipment for telescope pointing will be provided by GSFC.

As mentioned previously, we plan to make extensive use of analog computations so that the data may be recorded at a low bit rate and observing periods may continue for extended periods. We shall make direct analog magnetic-tape recordings intermittently to check the analog computation equipment and make those measurements not easily performed in an analog manner (irradiance amplitude distributions, for example). Averaged results of analog computations will be recorded for each channel, at approximately 1-minute intervals, on punched paper tape or incremental digital magnetic tape, and printed out by means of an analog-to-teletype converter connected to a teletype printer. Examples of optical propagation measurements made in this manner have been given by Ochs (Reference 11).

The 20-MHz signals will be converted, in the ESSA-furnished equipment, to 10 kHz before further processing. Figure 9 is a block diagram of the signal-processing equipment.

Concerning phase-fluctuation measurements, it must be recognized that phase differences of the two signals may exceed π radians; hence a system is proposed that will delay one signal by a variable time with respect to the other. This variable delay will be several tens of radians and will be controlled by means of a servo system, so that one signal is always in quadrature with the other. The variation in the delay required to maintain this relationship is then a measure of the fluctuation in phase difference between the two inputs and will function over many radians of change. We plan to obtain both the phase difference and the rms fluctuation of phase difference by this arrangement.

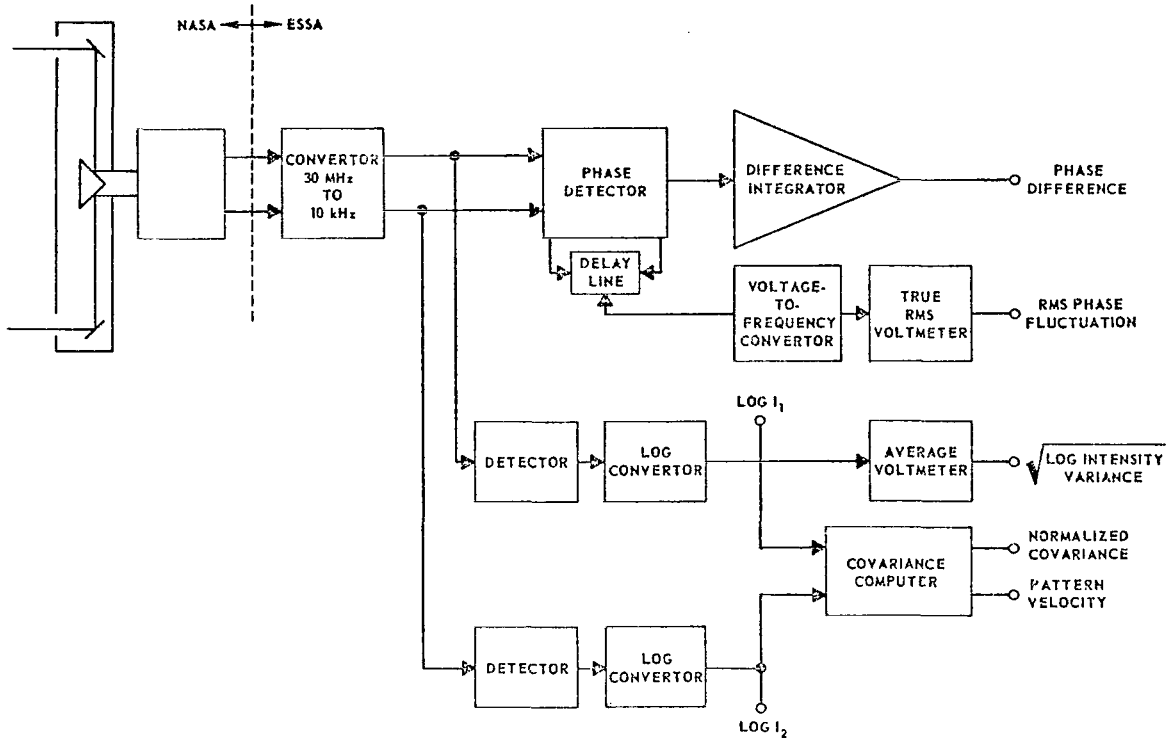

Figure 9–Signal-processing equipment, block diagram.

The irradiance fluctuations will be measured with instrumentation very similar to what we have already developed and used in horizontal-path optical propagation studies. The 10-kHz signals will be detected with linear detectors and passed through logarithmic amplifiers. If we assume that the signal irradiance is log-normally distributed, then from the absolute value of the average of the logarithm of the signal we may derive the log amplitude variance of the fluctuating signal.

We have also used analog instrumentation to measure covariance functions on ground-to-ground optical paths (Reference 12). The main component of this instrumentation is the so-called one-bit correlator (Reference 13). In the case of ground-to-ground paths, the receivers may be spearated vertically (i.e., perpendicular to the wind) so that maximum covariance occurs for zero time delay between the signals, regardless of the separation of the sensors. In the proposed satellite observations, the line joining the receivers will have an unknown orientation with respect to wind, and maximum covariance will occur at other than zero time delay. As has been demonstrated by our recent work on remote wind measurement by laser-beam techniques, one signal may be delayed with respect to the other under servo control to maintain a maximum correlation of the input signals. In this way, we obtain both the spatial covariance function of the optical signal (as a function of receiver separation) and the component, parallel to the receiver separation, of the scintillation pattern velocity (related to wind velocity).

Figure 10 sketches the arrangement of the Covariance Computer. If the time delay to point b, the maximum of the time-lagged covariance function, is t, then the normalized covariance of the logarithm of the optical signals is measured at points a and c where the time delays are (2/3) t and (4/3) t, respectively. The delay t is adjusted by a servo to maintain the covariance at and equal to that at c. The maximum covariance then occurs with delay time t, and both the delay and the covariance may be monitored continuously. The entire covariance function will be displayed on-line so it can be observed during the data recording. This is necessary because it will occasionally become skew or even biomodal, depending on the complexity of the vertical wind profile of the atmosphere.

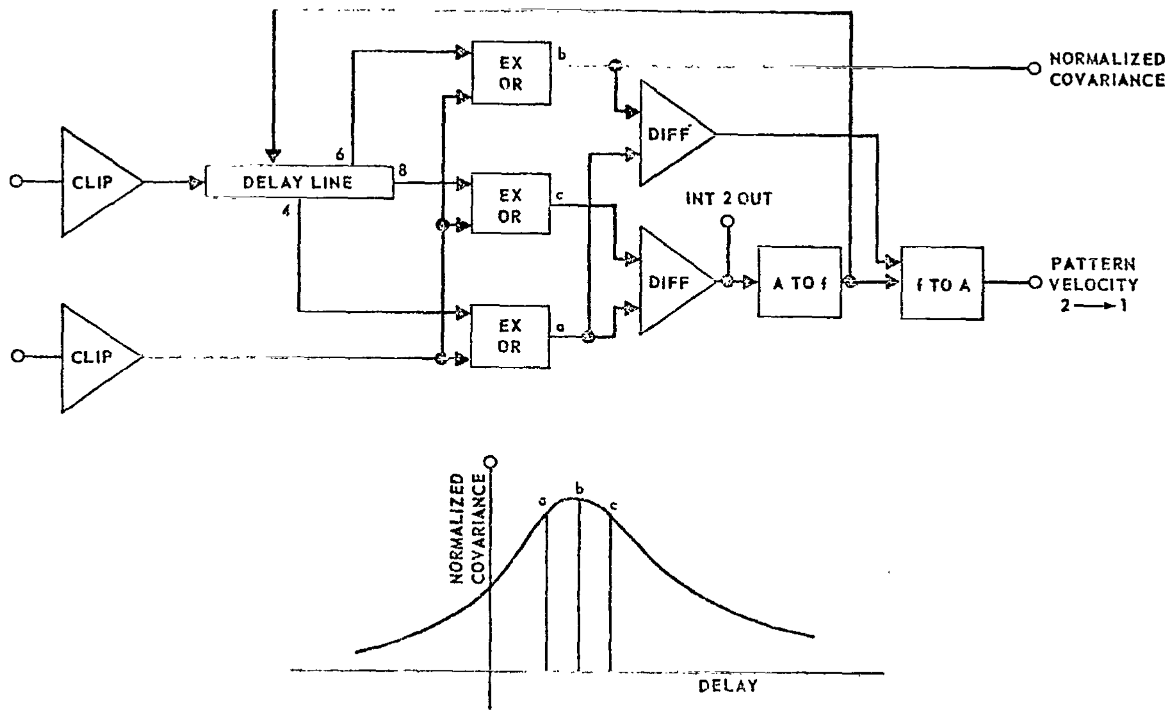

Figure 10—Covariance computer, block diagram.

Meteorological Observations.—We assume that standard meteorological observations (wind speed and direction, temperature, relative humidity, and barometric pressure) and measurements of an aerosol content will be available from equipment supplied by the ground-station contractor. In addition, ESSA will make measurements of temperature structure function, both near the ground and, from time to time, throughout the lowest 4 km of the atmosphere. There seems to be no reason why the sensors cannot be mounted on a jet aircraft to obtain measurements all the way up to the tropopause. A few such measurements might be a valuable supplement to the stellar scintillation monitoring of high-level turbulence, but they are not included in the present proposal.

The characteristic of the atmosphere most significantly affecting the propagation of an infrared wave front is the small, fast, refractive-index fluctuation of the atmosphere. Pressure, temperature, and humidity variations can all cause refractive-index fluctuations. Pressure variations propagate with the speed of sound and are rapidly dissipated, but temperature and humidity variations are dissipated by the slower processes of conduction, convection, turbulent mixing, and diffusion. It is clear that temperature variations are an important contributor to the fluctuation of refractive index, and that pressure variation is not. The contribution of water-vapor variation with scales of a few decimeters to a few meters is uncertain, and there seems to be no good way to measure it at present. Thus, we propose to measure temperature variations, as described below, but not humidity variations.

It seems unsatisfactory to ignore the humidity problem, and we plan to investigate the matter thoroughly in the time available before the ATS experiments begin. Several possibilities exist. Derr (Reference 16) is experimenting with Raman-effect, pulsed light radar with which he hopes soon to be able to measure remotely the water-vapor-structure function of the atmosphere with resolution as small as a centimeter and at a range of tens or hundreds of meters. A less promising possibility is the use of spaced radio refractometers, though the spatial resolution is poor and the bulky refractometers are likely to affect the small-scale structure of the atmosphere. Barium-fluoride strips are too slow and inaccurate to be useful for our problem. As a final resort, we expect to be able to deduce the effect of irregularities in water vapor by assuming that it depends on the mean value of humidity and examining our data for a humidity-related loss of correlation between temperature fluctuations and 10.6-micrometer effects.

Ochs 1967 (Reference 14) has developed a high-speed platinum-resistance thermometer for measuring small-scale atmospheric temperature fluctuations. Pairs of such sensors are used with appropriate analog circuitry, as shown in Figure 11, to measure the temperature-structure function, emphasizing the scale sizes most effective in disturbing the optical signal. The bottom curve of Figure 12 is an example of the output of such an instrument for a 24-hour period. This particular measurement was made 2 m above the ground and is averaged with a 100-second time constant. (Figure 1 shows the results of similar measurements made with the sensor carried aloft on a light airplane.)

Observation of Starlight.–Observation of starlight will provide data on stellar scintillations and stellar image size and stellar image motion. Stellar scintillations are effects produced primarily in the upper atmosphere. Stellar image motion and size changes are effects produced primarily in the lower atmosphere. A NASA-furnished stellar image monitor designed, developed, and used for optical site selection by Bufton (Reference 15) will be used. We shall add an ESSA-furnished data-processing system and it will be connected to the ESSA-furnished data-recording system.

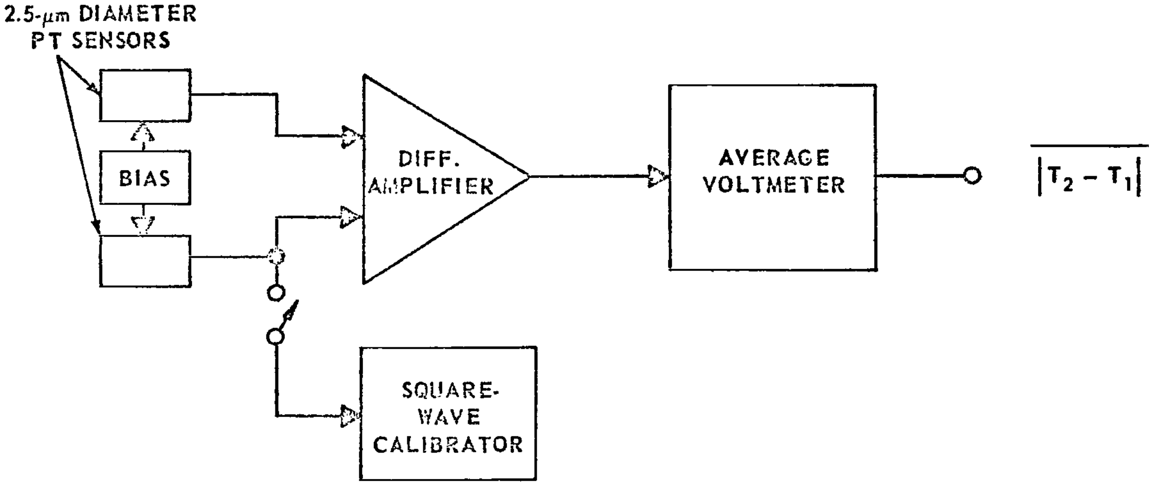

Figure 11—Temperature-structure-function amplifier, block diagram.

Analysis of the Measurements

Most of the data will have been summarized by preprocessing equipment at 1-minute intervals. These 1-minute summaries will be entered into a computer to provide, as appropriate—

(1) Scatter diagrams, such as that of Figure 2, selected according to various criteria.

(2) Time-series plots such as that shown in Figure 12.

(3) Correlation and regression analyses of selected data where they can be useful in checking atmospheric models or propagation theories.

Samples of the data will be recorded on magnetic tape and digitized at kilobit rates. These data will be processed on a computer to check and monitor the assumptions built into the preprocessing equipment and to make special studies for which preprocessing is unsuitable.

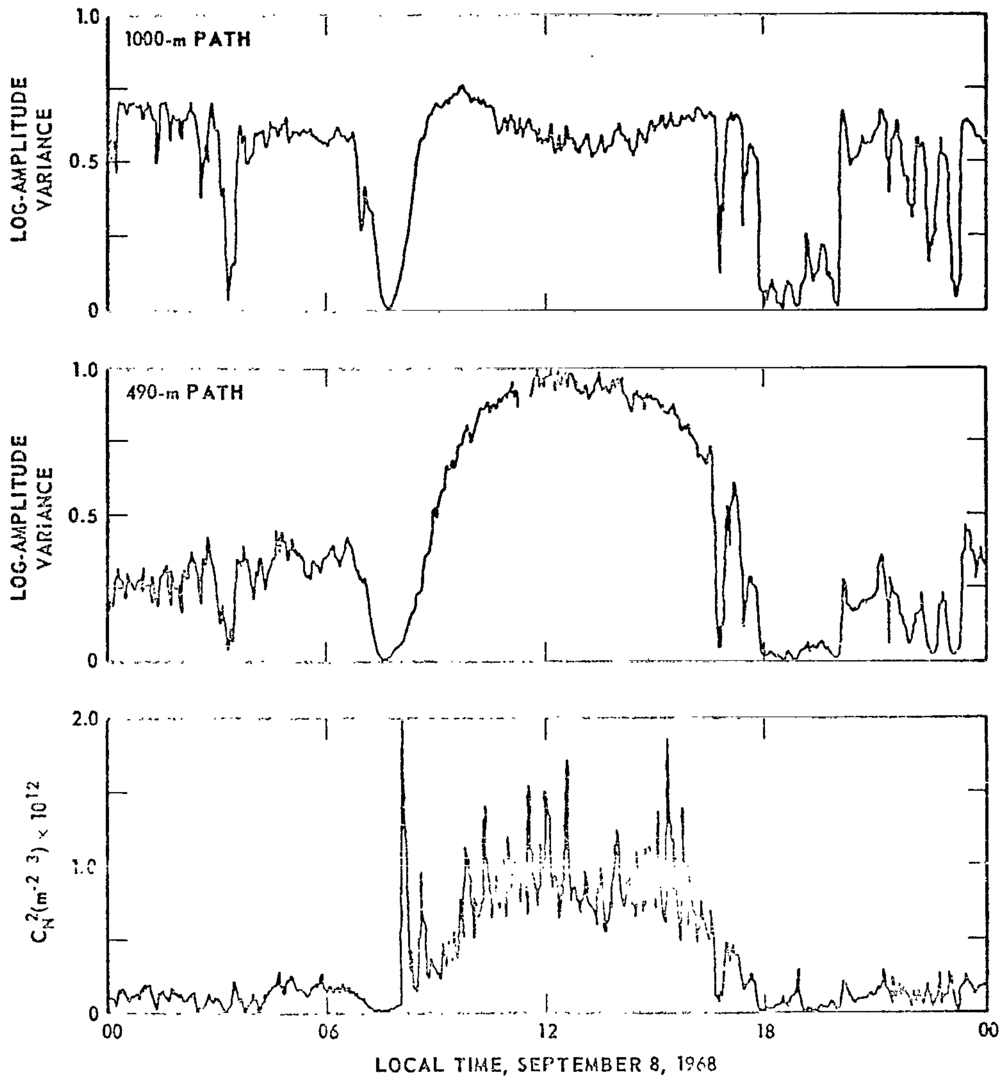

Figure 12–Computer-generated time-series plots of 1-minute summaries of propagation data produced by analog preprocessers.

ESSA personnel will undertake the interpretation of the propagation data, and will work with NASA personnel to compare the propagation data with bit error rates suffered by the communications link under similar atmospheric conditions. It is anticipated that a number of reports of results will be suitable for publication in the open scientific literature. Such papers will be prepared by ESSA personnel in joint authorship, as appropriate, with contributing NASA personnel.

The 1-minute summaries and high-speed data will be made available in digital form, as desired, to an appropriate data center within 12 calendar months from the observing date.

Experiment Plan and Schedule

Design and construction of the ESSA portion of the infrared interferometer must begin during the latter half of calendar year 1970, in order to permit adequate time for a complete checkout with actual optical signals on ground-to-ground paths during the Summer of 1971.

The stellar monitor should be made available to ESSA before January 1971, so that it can be integrated with the ESSA-furnished data-logging system and be checked out with actual field use during the summer of 1971.

The temperature-sensor equipment will be constructed by ESSA during the first half of calendar year 1971.

An attempt will be made to maximize the scientific output of the project by avoiding either of two extremes in the data-gathering schedule. Too much data, especially that requiring digitizing at kilobit rate and subsequent computer analysis, can cause the project to bog down in details of analysis and prevent adequate interpretation. On the other hand, too little data can be misleading in atmospheric research because of the severe nonstationarity of atmospheric processes. It is our opinion that most of the data gathering should be done in the presence of our own professional scientific personnel, namely, those who will be responsible for subsequent interpretation. It is also important that analysis and interpretation proceed contemporaneously with data gathering and not be deferred until the data gathering is nearly complete. These considerations lead us to propose the following observing plan.

We assume that the satellites will be available at approximately 90 degrees West longitude from November 1972 to July 1973. We also assume that during August 1973 the ATS-F satellite will drift slowly eastward and be available for optical propagation measurements at a constantly increasing zenith angle. If the schedule changes, the plan will have to be revised, but the general pattern of observing periods should remain valid.

Observations of ATS-F will commence at Goldstone, California, in November 1972 and continue until about April 1973. During this period we plan to schedule one observing session each month. Each session will last about 5 days and involve as many uninterrupted data runs as the satellite schedule can accommodate. Each data run should be as long as possible; at least 6 hours, it is hoped. The runs should be scheduled so as not to occur all at the same time of day.

Since analysis and interpretation will be proceeding concurrently with data gathering, it is anticipated that the project, including submission of all publications and reports to the editor or printer and including the transmission of all data to the ATS Project, will be complete within 12 months after the termination of data gathering.

GSFC/ESSA Interface

Dual Receiver Interferometer.—GSFC will supply the optical system, the mount, the shelter, the local oscillator, and the detectors. The system will be checked out to assure that system noise (caused by vibration and other motions of the mount, instabilities in the local oscillator, or inefficiencies in the detectors) is well below the level of peak atmospheric effects, in both intensity and phase. The output from this portion of the system will be a pair of electrical signals at 20 MHz (or another frequency acceptable to GSFC and ESSA), carrying both the amplitude and the relative phase information of the infrared beams incident on the two input mirrors of the interferometer. ESSA will supply the equipment required to heterodyne the 20-MHz signals down to approximately 10 kHz, detect their amplitudes, measure their relative phases, and obtain appropriate statistical measures of these quantities, averaged over 1-minute periods. This ESSA-furnished equipment is sketched in Figure 9.

Meteorological Sensors.—Standard sensors (for temperature, barometric pressure, wind speed and direction, and relative humidity) will be supplied by the ground-station contractor. High-speed temperature sensors, whose output signal is proportional to the temperature structure function with a 1-minute time constant, will be supplied by ESSA. A high-speed temperature sensor will be supplied by ESSA, as required, attached to a light aircraft and completed with necessary recording equipment for the measurement of temperature structure function to heights of 4 km above the ground.

Stellar Monitor.—GSFC will supply the Stellar Image Monitor (Reference 15) but excluding the digital recording equipment. ESSA will supply and attach analog preprocessing equipment to provide 1-minute summaries of each channel.

Data-Logging Equipment.—ESSA will furnish analog-to-digital conversion equipment and a multiplexer, together with necessary control circuitry and recording equipment, to permit the recording of about 12 channels of data, once per minute, on punched paper tape or digital magnetic tape. This equipment will satisfy most of the data-logging requirements of the propagation experiments. Occasional requirements for FM analog magnetic tape recordings will be met either by tape recorders available at the NASA sites or by an ESSA recorder temporarily diverted from other work. It is not considered necessary to purchase a dedicated recorder for this application.

Observations.—Propagation measurements (excluding tests of the communications link) will be made by ESSA personnel during the observing session, about 5 days each month.

Temperature sensor measurements will be made by ESSA personnel during propagation-experiment observing sessions. It is recommended that such measurements be added to the routine of duties for the NASA (or contractor) personnel who will be observing the communications link performance at Goldstone.

Data Analysis.—ESSA will undertake the analysis and interpretation of the propagation data.

PART II: GSFC OPTICAL RESEARCH FACILITY GROUND STATION

Experiment Objectives

It is the objective of this experiment to investigate the effects of atmospheric turbulence upon the signal-to-noise ratio of a coherent laser communications link at 10.6 micrometers. In particular, measurements of phase structure function, log-amplitude structure function, and wave structure function will be made. Frequency spectra and probability distributions will also be developed for the above functions. Tests will be made with time of day, weather, and season as variable parameters.

In addition to the objectives described in Part I, the GSFC station will employ a large-aperture high-gain transmitter/receiver telescope to measure the ability of high-gain antennas to overcome severe atmospheric conditions. The additional objectives of this part of the experiment are as follows:

(1) To measure the cloud-penetration capability of 10.6-micrometer coherent propagation links.

(2) To measure the signal-to-noise ratio in the presence of severe atmospheric conditions such as heavy cloud overcast, rain, fog, etc.

(3) To measure the maximum S/N ratio possible under good atmospheric conditions.

(4) To analyze the effects of aperture averaging upon the S/N ratio.

Dual-aperture interferometer measurements similar to those made at Goldstone, California, will also be made at GSFC to evaluate the effects of the climate upon phase and log-amplitude structure functions. The data derived from these two near-simultaneous experiments can be compared for later use in evaluating transmitter/receiver site locations.

The experiment will employ a coherent 10.6-micrometer ground-based laser transmitter/receiver system based at the GSFC Optical Research Facility (Greenbelt, Maryland) in conjunction with the ATS-F LCE flight equipment to perform space-to-earth propagation link analysis. The tests will be performed during the first 9 months after the ATS-F launch and will be compared with similar tests performed at the ATS Goldstone site for evidence of climatological influence upon the propagation of coherent radiation. During the performance of the experiment, microthermal measurements of the vertical profile of the refractive-index structure constant (C_N^2) will be made using radiosondes, and/or instrumented aircraft. These profiles will be used in an effort to correlate observed communication-link performance with the prevailing theories of optical propagation postulated by Tatarski, Kolmogorov, Fried, and others.

The experiment results will further be compared with a series of other propagation experiments performed at GSFC, and with the extensive background of material available in the literature.

Because of the large amounts of data which will be recorded and the statistical nature of atmospheric turbulence, we believe the results can best be analyzed by digital computer. Under previous atmospheric test programs, GSFC has developed a large percentage of the necessary programing. This present program library will be augmented as necessary to encompass the expanded requirements of the LCE.

Because of the nature of the synchronous orbit and the availability of a controlled coherent 10.6-micrometer source aboard the satellite, the experiment provides a unique opportunity to measure nearly all of the atmospheric-turbulence parameters affecting laser communication. Because this opportunity cannot be duplicated without great expense, it will be exploited to the fullest measure to solve as many problems as possible.

Measurements to be Made

The experiment, for the purpose of operational convenience, will be set up to operate in two basic modes. The first mode, which we call the large-aperture mode, will employ a 76-cm-aperture transmitter/receiver system to measure the ability of a 10.6-micrometer coherent communication link to "punch through" severe atmospheric conditions such as fog, cloud cover, severe turbulence, rain, etc. Radiation from this transmitter will utilize the extremely high antenna gains possible with large apertures, to compensate for the losses due to the atmosphere. This mode will be employed whenever weather conditions preclude operation in the second mode. The second mode, called the dual-aperture mode, will employ a Michelson stellar interferometer system mounted in front of the 76-cm aperture. The interferometer will be designed to measure phase and log-amplitude structure function for separations from approximately 30 cm to 3 m. The maximum separation of the measurement points is less than that to be used in the Goldstone experiments, because atmospheric turbulence is stronger in the east; therefore, the coherence aperture is expected to be considerably smaller. Each of the two sampling apertures, whose separation will be continuously adjustable out to maximum separation, will have an aperture of approximately 15 cm and will employ an iris to allow the aperture to be reduced to zero as desired. The remainder of the area of the 76-cm aperture not obscured by the interferometer will be employed to function as the transmitter aperture for the ground laser beacon.

The dual-aperture mode will be used in normal operation; the large-aperture mode will be used only when weather conditions require greater antenna gain or when this mode is requested by the LCE Principal Investigator.

Equipment

The proposed ground system for this experiment will rely heavily on equipment developed for previous GSFC atmospheric propagation experiments. The major item to be used is the Atmospheric Laser (ATLAS) transmitter/receiver system developed under the Vertical Profile of Refractive Index Structure Constant. This system, shown in Figure 13, consists of a 76-cm-aperture telescope mounted on an altazimuth tracking mount. It is equipped with a six-mirror Coude focus, which places the focal plane in a convenient stationary position within the laser van located adjacent to the telescope. Inside the laser van, all laser transmitter/receiver equipment can be setup in a convenient stable laboratory environment, A vibrationally isolated granite table (not at present part of the system) will be setup inside the trailer and supported via piers to a concrete pad below the trailer. Holes in the trailer floor will prevent mechanical

Figure 13–ATLAS tracking system.

connection between the table and trailer, and a separate concrete pad will be used to support the trailer. Suitable flexible seals will be used around the piers to prevent air leakage between the trailer interior and the surrounding environment. A double Brewster-angle exit window with a vacuum between the windows will provide a means of coupling laser beams in and out of the trailer without the severe atmospheric boiling that normally occurs at windows. Experience gained over many years has shown that, as the complexity of an experiment increases, operator access, flexibility, and control of environmental conditions decrease. These parameters play an important part in the success of the experiments; therefore, we have designed the system to obtain these desired qualities. Figure 14 shows the Geodetic Orbiting Satellite (GEOS) laser tracking system, a telescope of similar design which has been highly successful in both pulsed-ruby and continuous-wave argon-laser tracking experiments.

The second trailer shown in Figure 13 contains the servo system for the telescope, a digital computer for controlling the mount, timing systems, multichannel data-recording facilities, data-display devices, and other equipment necessary for running the telescope and analyzing laser propagation data.

The entire system is highly mobile, and can easily be moved to alternate sites if required.

The large-aperture mode operates in the following manner. The 20-W CO_2 laser beacon is turned on (Figure 15) and pointed at the ATS-F satellite with the two-axis IMC in its inactive position. The telescope servo system is used as the course-positioning system, with the laser beacon diverged to the extent necessary to cover the uncertainty in satellite position. The satellite is then commanded to search and acquire the beacon. After acquisition, the two-axis IMC is activated for vernier control of the beacon; beacon divergence is narrowed, the satellite transmitter being used as an autotract target source.

Figure 14–GEOS laser tracking system.

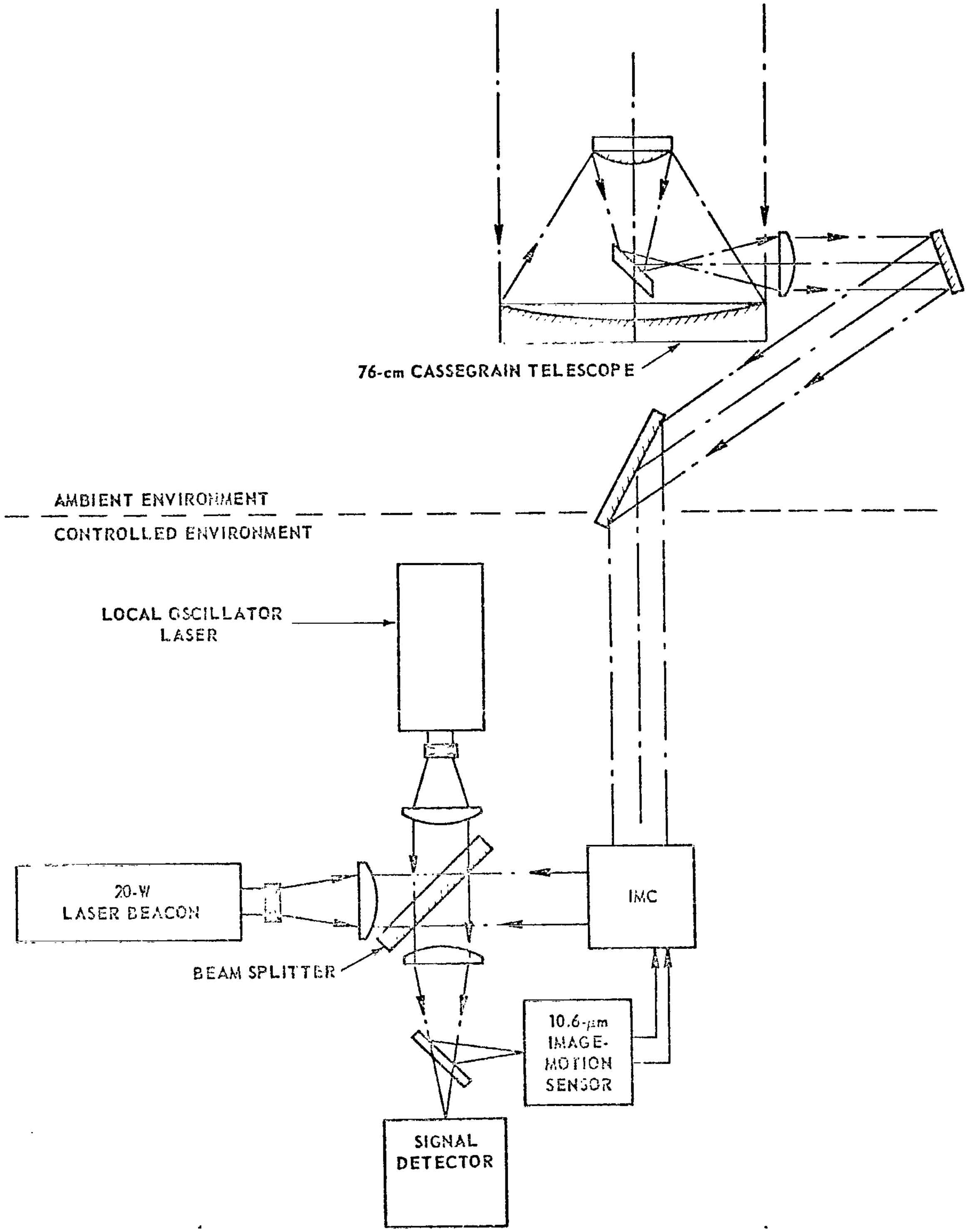

Figure 15–Large-aperture mode, schematic.

Measurements of the signal-to-noise ratio are made with a second mixer separate from the star tracker, to isolate servo-system operation from data-recording functions. After heterodyning with the LO in the optical mixer, the output (20 MHz) is converted to a second IF (10 kHz) and then recorded on magnetic tape for later analysis.

The dual-aperture mode (Figure 16) operates in a similar manner, except that two channels of received signal, one from each of the two interferometer arms, are processed. A common local oscillator is used for the mixing operations to prevent LO phase perturbations from influencing the data. The second IF outputs (10 kHz) of the two channels are recorded directly on a multichannel tape recorder. In addition, the 10-kHz outputs are fed into a phase compensator; its output is also recorded.

Data from each of the two modes will be recorded on a multichannel tape recorder with AM and FM modules to handle both the 10-kHz intermediate frequency and the base-band phase-comparator outputs. In addition, data on the transmitter/receiver operational parameters, weather conditions, and visible scintillation will be recorded for use in comparing and analyzing the data. The analog tapes will be converted to digital tapes and processed by digital computer to give the final results.

Vibration is a possible source of phase error in the dual-aperture mode. In order to prevent any possibility of error in the results due to vibration in the receiver system, an error-monitoring system will be incorporated in the stellar-interferometer arms. Two cube corners mounted on the final mirrors of the

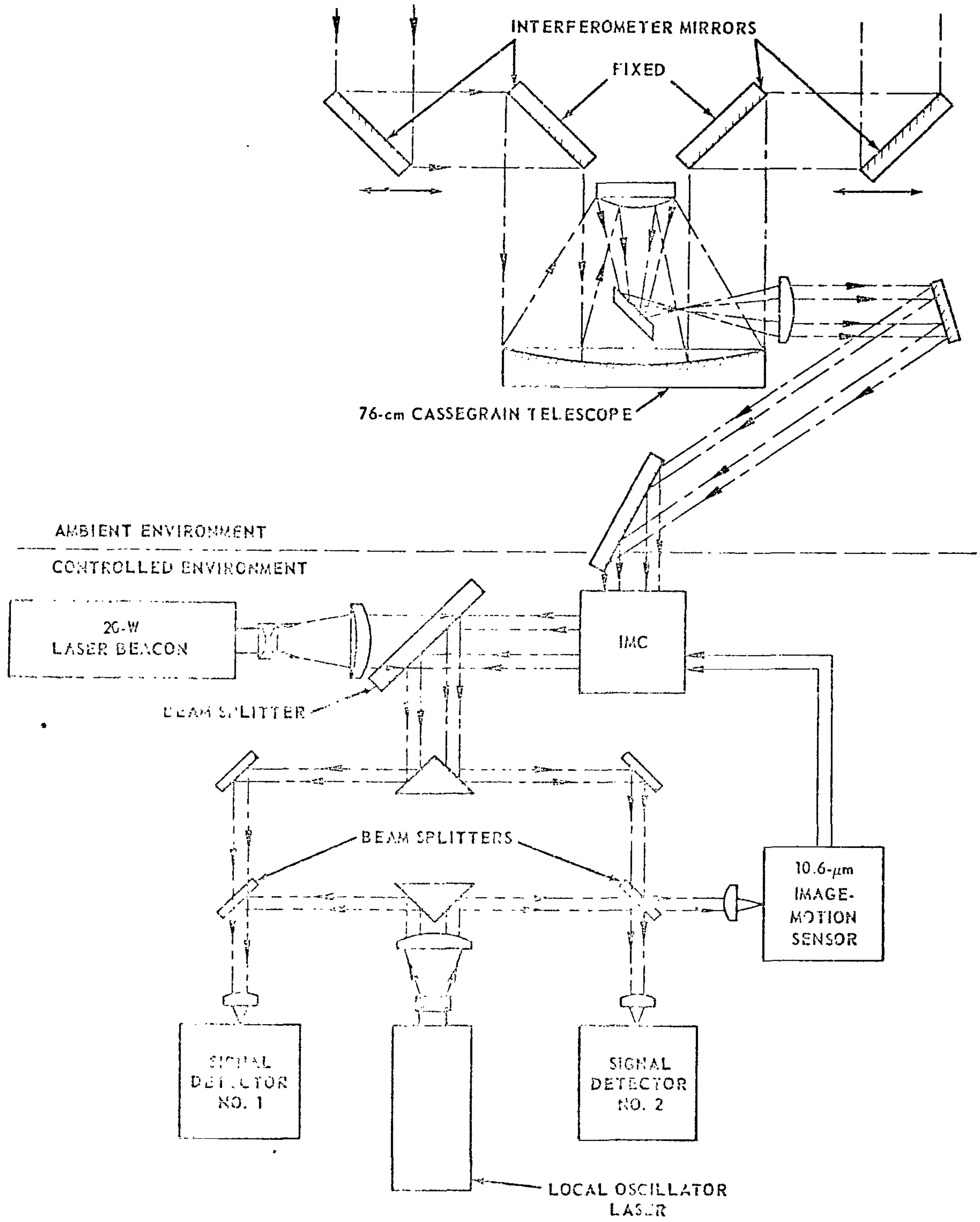

Figure 16–Dual-aperture mode, schematic.

interferometer will retrodirect a small portion of the transmitted radiation back to a noncoherent detector in the Coude focal plane which will monitor the phase difference between the arms by measuring intensity. A divider circuit in the detector output will divide the signal by the laser transmitter output to prevent transmitter output fluctuation from causing phase-error indications. Phase errors detected by this system will be subtracted from the phase errors seen by the entire system. This relatively simple system consisting of two cube corners, a piezoelectric translator, and several small electronic circuits completely eliminates any possibility of errors caused by vibrations or thermal effects in the transmitter optics and eliminates the need for the massive, expansive, and cumbersome vibration-isolation devices that would otherwise be needed.

Experiment Plan

The ATLAS transmitter/receiver system is now nearing completion at GSFC. All major items of this system have been designed and are being assembled. During the summer of 1970, this system will become operational, performing a series of balloon-borne atmospheric propagation studies in the visible spectrum and at 10.6 micrometers. The system will continue atmospheric-propagation experiments during 1971 and the first half of 1972. It should, therefore, be a highly reliable, well tested system by the time of the ATS-F launch. In July 1972 the ATLAS system will be set up at GSFC for the ATS-F LCE. Measurements of phase and log-amplitude statistics will be made over a horizontal path using reflections from 10.6-micrometer cube corners mounted on towers several kilometers from the transmitter/receiver station. Data taken from horizontal measurements will be used to calibrate the system, train personnel, and perfect data-reduction procedures. Because of the flexibility of the Coude focus, a complete checkout of the system can be made on ground targets; the system can then be quickly pointed at the satellite without any recalibration. Horizontal range checkout of the system will be a routine operational procedure carried out before each data-recording period.

Procurement, design, and testing of all components required for the LCE will begin during the second half of calendar year 1970 and proceed throughout 1971 and the first half of 1972. This work will be coordinated with the balloon-borne 10.6-micrometer laser-propagation measurements made during 1970 and 1971, and the lessons learned from these experiments will be incorporated in the design of the LCE.

We believe that a period of prelaunch checkout of the system over a horizontal range is essential to ensure that it is completely debugged and ready to operate reliably. Therefore, final assembly of the system will begin in July 1972. Because most of the system will already be operational, assembly should not require more than 2 months; this will leave approximately 2 months for test and checkout before satellite launch. Components of the system, of course, will be assembled and tested before July 1972.

In order to characterize the vertical profile of the refractive-index structure constant (C_N^2) GSFC has under development an inexpensive radiosonde modified to measure (C_N^2) in addition to its normal measurements of pressure, temperature, and relative humidity. The value of C_N^2 is derived from high-speed temperature sensors mounted on the sonde, plus barometer-pressure and temperature data. The radiosonde is being developed as a simple way to obtain turbulence profiles of the atmosphere at altitudes inaccessible to instrumental aircraft.

Prior to each of the data-collection sessions, one of these radiosondes will be released to profile the atmosphere. From each flight, a profile of C_N^2, C_T^2 barometeric pressure, relative humidity, wind speed, and mean temperature will be obtained to an altitude of approximately 30 km. Estimates of C_N^2 from measurements by Hufnagel and Stanley indicate that measurements up to at least 20 km are required for a good characterization of the atmosphere. Radiosondes modified to make C_T^2 measurements cost approximately $2000 per sonde. In order to reduce the sonde cost an attempt will be made to recover the sondes. Assuming a 50-percent recovery rate, this would mean a cost of about $1000 per flight. This cost is considerably less than the cost of the high-altitude aircraft necessary to measure C_N^2. However, low-altitude aircraft suitable for measurements up to 5 km would be economical and useful. Our plans call for a mixture of radiosonde and low-altitude flights to characterize the atmosphere. Radiosondes would be used mostly for dual-aperture-mode measurements under clear weather conditions, while low-altitude aircraft would be used under overcast conditions with the large-aperture mode to measure cloud density for the bulk of the cloud cover (which usually is at low altitude). In addition to the radiosonde/aircraft measurements, ground-based telescopes at GSFC will be used to monitor stellar scintillation and dancing in the visible region for comparison with 10.6-micrometer propagation data.

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