A Meteorological Data-Acquisition System for Atmospheric Propagation Studies

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Abstract—Instrumentation for studying the propagation of near-millimeter waves has been designed and implemented at a 1 mile long test site in Sandusky, OH. Measurement of the atmospheric structure functions and the transverse wind velocity along the propagation path is accomplished with a custom-built meteorological data-acquisition network consisting of six towers linked together with fiber-optic data lines. Each tower is microprocessor controlled and includes a 3-axis anemometer, a Lyman-alpha hydrometer, and a differential temperature probe; with other meteorological parameters obtained at various locations along the path. A modified ISO-OSI reference model is used as the controlling protocol.

I. INTRODUCTION

IT IS WELL KNOWN [1], [2] that the spatial and temporal inhomogeneities in the temperature, humidity, and pressure fields of the atmosphere cause stochastic fluctuations in the complex-valued index of refraction which can result in serious degradation to the propagation of electromagnetic radiation. The requirements for an atmospheric propagation experiment are, thus, a means of measuring the characteristics of the propagating beamwave while simultaneously measuring the relevant (micro)meteorological parameters of the atmosphere. This paper will not address the measurement of the propagation characteristics, but will describe a system which has been implemented for measuring the necessary meteorological parameters.

The meteorological data-acquisition system (MDAS) is a distributed multimicroprocessor network operating in a master/slave relationship with a host computer. MDAS utilizes the concept of minimum hardware implementation with maximum software flexibility to accommodate experimental changes. For MDAS this resulted in the selection of microprocessors with integral data communication features using minimal memory and user defined peripherals. A modified ISO-OSI reference model is used as the controlling protocol [3] (this protocol does not necessarily apply to the applications and data-acquisition protocol). System flexibility is attained by using the host

computer to dynamically reprogram the distributed system; therefore, the logical architecture of the system can be quickly changed to meet new data-acquisition or control requirements with no hardware changes.

The physical layout of MDAS described in this paper is based on a near-millimeter (NMM) wave propagation experiment [4], however, the basic elements of the network are the same for any type of experiment requiring characterization of the atmosphere over specified distances. In the next section, a description of the atmosphere for NMM waves (wavelengths which extend from the millimeter region to the long-wave region of the infrared; i.e., 1 mm to 100 μ) is given. Here, we assume the atmosphere is a clear, nonionized medium characterized by stochastic fluctuations in the complex index of refraction. Section III describes the hardware and software used in the multimicroprocessor network. Detailed schematics of the hardware and the software listings can be found in [5]. The meteorological instrumentation specific to the NMM propagation experiment is discussed in Section IV. Finally, a summary of the main results of the paper appear in Section V.

II. RELATIONSHIP BETWEEN THE METEOROLOGICAL MEASUREMENTS AND ATMOSPHERIC PARAMETERS

In this paper, it is assumed that the atmosphere is characterized by a clear (nonparticle containing), nonionized medium, with a magnetic permeability $\mu = 1$ and a complex stochastic index of refraction $n(r, t)$. The index of refraction model can be written as

$$n(r, t) = n_{OR} + \partial n_R(r, t) + i\big(n_{OI} + \partial n_I(r, t)\big) \quad (1)$$

where n_{OR} and n_{OI} are the mean values of the real and imaginary parts, and $\partial n_R(r, t)$ and $\partial n_I(r, t)$ are the fluctuating real and imaginary parts. The real part of the complex index of refraction is related to the amount of scattering of the propagating beamwave by the atmosphere and the imaginary part indicates the amount of absorption of the beamwave. Also, by definition, $\langle n(r, t) \rangle = n_{OR} + in_{OI}$ and $\langle \partial n_R(r, t) \rangle = \langle \partial n_I(r, t) \rangle = 0$. For clear-air turbulence, it is normally assumed that $\partial n_R(r, t)$ is small (i.e., max $(\partial n_R(r, t)) \approx 10^{-5} n_{OR}$; where $n_{OR} \approx 1$) and that its temporal dependence is given by Taylor's frozen flow hypothesis as $\partial n_R(r, t) \approx \partial n_R(r - V(r)t)$ where $V(r)$ is the vector wind velocity [6].

The refractive index structure constants, C_n^2, which are a measure of the magnitude of the fluctuations in the complex index of refraction, are related to the fundamental atmospheric statistics by [7]

$$C_{n_R}^2(\eta) = A_T^2 \frac{C_T^2(\eta)}{\langle T \rangle^2} + A_Q^2 \frac{C_Q^2(\eta)}{\langle Q \rangle^2} + 2A_T^2 A_Q^2 \frac{C_{TQ}(\eta)}{\langle T \rangle \langle Q \rangle}$$

$$C_{n_I}^2(\eta) = B_T^2 \frac{C_T^2(\eta)}{\langle T \rangle^2} + B_Q^2 \frac{C_Q^2(\eta)}{\langle Q \rangle^2} + 2B_T^2 B_Q^2 \frac{C_{TQ}(\eta)}{\langle T \rangle \langle Q \rangle}$$

$$C_{n_R n_I}(\eta) = A_T B_T \frac{C_T^2(\eta)}{\langle T \rangle^2} + A_Q B_Q \frac{C_Q^2(\eta)}{\langle Q \rangle^2}$$

$$+ (B_T A_Q + A_T B_Q) \frac{C_{TQ}(\eta)}{\langle T \rangle \langle Q \rangle} \qquad (2)$$

where the subscripts R and I denote the real imaginary parts, $\langle T \rangle$ is the absolute temperature, $\langle Q \rangle$ is the absolute humidity, and η gives the position dependence of the structure functions along the length of the propagation. path [8]. In (2), A_T, A_Q, B_T, and B_Q, are wavelength dependent quantities which are calculated from the atmospheric index of refraction and absorption spectra. $C_T^2(\eta)$, $C_Q^2(\eta)$, and $C_{TQ}(\eta)$ can be experimentally determined from

$$C_T^2(\eta) = \frac{\langle [T_1 - T_2]^2 \rangle}{r^{2/3}}$$

$$C_Q^2(\eta) = \frac{\langle [Q_1 - Q_2]^2 \rangle}{r^{2/3}}$$

$$C_{TQ}(\eta) = \frac{\langle [T_1 - T_2][Q_1 - Q_2] \rangle}{r^{2/3}} \qquad (3)$$

where the numerator represents an ensemble average of the difference between two temperature (or humidity) points separated by r and at a distance η from the transmitter. This definition assumes that the Kolmogorov 2/3-law holds true for the temperature (humidity) distribution.

From the above discussion, it can be seen that each meteorological instrumentation tower in MDAS is required to measure the following quantities: differential temperature, differential humidity, absolute temperature, absolute humidity, and vector wind velocity. The temperature and humidity measurements are used with (2) and (3) to determine C_n^2, while the wind velocity is used to determine the temporal dependence of the fluctuations. Other instrumentation which is available at various towers are rainfall rate measurement devices and particle size measurement devices. Measured values can either be summed to obtain a path average of the parameters or can be fit with a smooth curve to obtain the parameters as a function of path length.

III. METEOROLOGICAL NETWORK

The requirements of a meteorological data-acquisition system are that sampling rates must be fast enough to measure turbulence and samples of the atmospheric con-
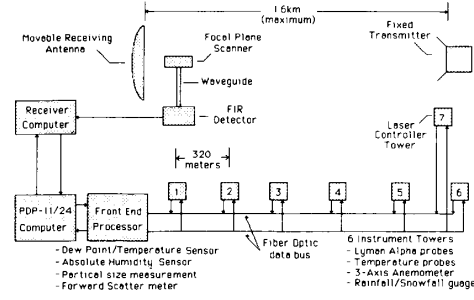

Fig. 1. Block diagram of the experimental site.

ditions must be taken over the entire propagation path. To accomplish this a network of six instrument towers is used. Each tower is microprocessor controlled and networked together by fiber-optic data links to a host PDP-11/24 computer [5].

A. Network Hardware

The meteorological data-acquisition system, shown in Fig. 1, consists of seven instrument towers (one tower is used for monitoring and controlling the transmitter output) interfaced to a host Digital Equipment Corporation PDP-11/24 computer with disk and tape data storage. The PDP-11 is responsible for the overall control of the network, the real time clock, data storage, and interaction with the human operator. A DR11-C bidirectional parallel interface connects the host computer to a dynamically reprogrammable, microprocessor-based front-end communications processor (FEP). This interface handles the communications to and from the towers while two RS-232 serial ports handle communications with the receiver computer. Communications between towers is accomplished using commercial fiber-optic data links which impose some restraints on possible tower interconnection schemes due to their one-way communications nature. In the network described here, two fiber-optic cables are used to carry commands and data to and from the towers and FEP. Each tower actively receives and retransmits all information on the two optical channels with hardware logically determining the towers interconnections. A logical diagram of the possible routing paths at each tower and the FEP is shown in Fig. 2.

Each tower is independently controlled by an Intel 8031 microprocessor which was chosen for its speed (12.0 MHz), on-chip full duplex UART with special ninth-bit mode, and control oriented architecture. The towers also include 2048 bytes of RAM and 4096 bytes of program ROM along with a "snapshot" 8-channel analog-to-digital (A/D) converter (Fig. 3). Each A/D channel is preprocessed by a sample/hold amplifier allowing all channels in the network to be sampled simultaneously. A CONVERSION command causes all sample-hold amplifiers to go into the hold mode until all data conversions are complete. The maximum data-acquisition skew rate permissible between towers for the propagation experi-
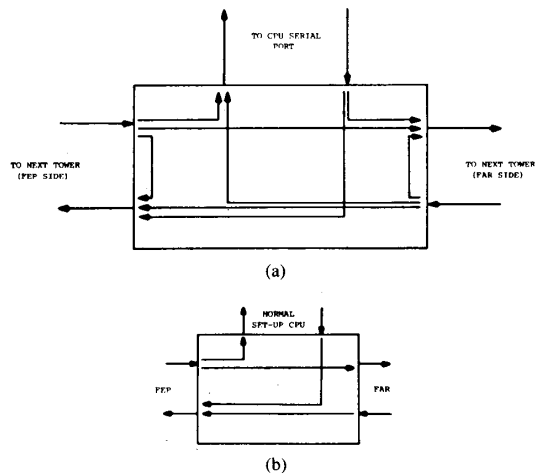
Fig. 2. Possible routing paths at each tower. (a) Tower to tower. (b) FEP to tower.
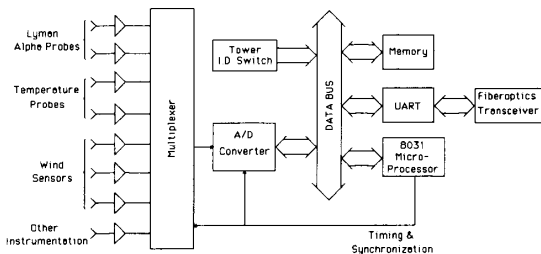

Fig. 3. Block diagram of tower hardware.

Fig. 4. Data-acquisition system logical layer block diagram.

ment is approximately 0.1 ms [7]. In MDAS, a CONVERSION command sent to all towers simultaneously yields an overall maximum latency (due to a combination of transmission delays and skewing of the individual microprocessor clocks) between any two channels on any two towers that is well within the above maximum. The FEP is an 8031 system identical to those in the towers with the addition of extra memory and a parallel 16-bit interface to the host computer.

Maximum system data-acquisition rates are determined by the complexity of the data-acquisition software residing in the individual towers. With the current NMM wave experiment system software, the system is capable of sampling all 48 (6 towers by 8 channels/tower) A/D channels and transmitting the data to the host computer at a maximum sampling rate of 250 Hz. The maximum sampling speed for obtaining data from a single channel on one tower is 6 kHz.

B. Network Software

The basic philosophy behind the data-acquisition network was to design a very flexible system that would allow a wide variety of experiments to be run over a period of many years. Therefore, the software is organized in a modular fashion that permits it to evolve as experiments
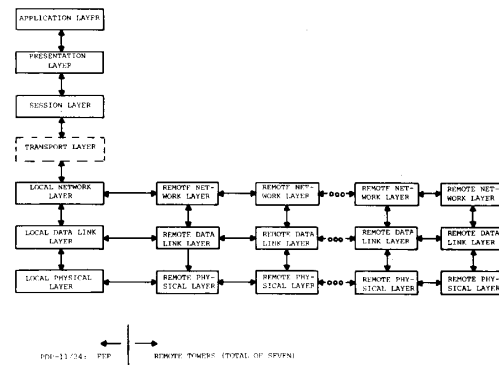
grow and change. A protocol based on the ISO-OSI model given by Tanenbaum [9] provides the modularity needed for tower communications. This model was slightly modified to include the master/slave relationship between the FEP (master) and towers (slaves). The ISO-OSI model for the system contains seven layers of protocol given as (Fig. 4):

1) Application Layer—Responsible for obtaining and transferring necessary files to run the network and collect real-time data via human interface. This layer uses the network protocol and subroutines developed at the network layer for data communications.

2) Presentation Layer—Contains the implementation of frequently used subroutines called by the application layer. These include tower diagnostics and sensor checks, logical reconfiguration of the link, downloading of predefined ''user'' software to individual towers, a RUN LINK command to cause downloaded tower programs to execute, and an ABORT LINK command to return all towers to the network.

3) Session Layer—The lowest user interface into the network. Software executes in the PDP-11 and controls the parallel data communications between the host and the FEP. This layer translates commands from the presentation layer into a appropriate commands to the local network layer and keeps the host computer informed to system status.

4) Transport Layer—The FEP software responsible for control of the subnet, data acquisition and formatting, and encoding commands.

5) Network Layer—It is this layer that significant departures occur from Tanenbaum's model [9]. The local network layer is responsible for decoding network wide commands from the session layer into commands that can be sent to individual towers, as well as all system diagnostics. The remote network layer is responsible for the execution of the received commands within the individual towers.

6) Data Link Layer—Uses the physical layer to provide an error free data path. The ninth bit is added to the data packet to signal a command. By setting this bit high, the FEP is able to interrupt the towers with a command or

leave it low to communicate with a previously selected tower.

7) Physical Layer—This is the hardware level of the communication system, including the fiber-optic data links.

The application layer is the entry point to the software programs which define the actual experiment. The above described control protocol ensures that programs can be downloaded to the towers, started up, and control re-established to the control network at any time. A typical data collection session begins with the user selecting which instruments (A/D channels) are to be used on each tower. This information is encoded into a parameter block, along with the desired sampling rate and separately sent to each tower. A global start command is then transmitted to all towers simultaneously to initiate execution. Data are uploaded from each tower to the FEP and, when the FEP's buffer is full, the PDP-11 is interrupted through the DR11-C so that the host can display and store data on disk and magnetic tape.

IV. Meteorological Instrumentation

The configuration of the meteorological instrumentation for NMM wave propagation measurements is given in Fig. 1. Each tower (Fig. 5) is equipped with differential temperature and humidity probes, 3-axis anemometers and a rainfall/snowfall gauge. Other instrumentation placed at various locations on the site includes an EG&G model 220 ambient and dew point temperature sensor, a polymer humidity sensor (both are used to obtain absolute humidity values), PMS models GBPP-100 and CSASP-100 particle size measurement systems, an EG&G model 207 forward scatter meter, and Lockheed model G01 optical scintillometers. The forward scatter meter combined with the PMS probes provide measurements of particle size over a 0.5–6400-μm particle diameter range and are located at the receiver end of the site. Rainfall is measured with an electrooptic gauge that has a sensitivity of 0.0083 mm and snowfall is measured with a heated 0–500 mm/h gauge with a resistive sensor. The scintillometers are used to verify the assumption of turbulence homogeneity along and across the propagation path.

The differential temperature measurement system is based upon work done at the U.S. Army's Atmospheric Sciences Laboratories with incandescent light bulb filaments [10]. The tungsten filament wires of the light bulbs, when removed from the evacuated glass bulbs, respond to changes in the ambient temperature with a proportional change in resistivity. This change in resistance has a fairly large bandwidth and exhibits sufficient linearity to make these sensors usable for many atmospheric measurements. Differential temperature, equivalent to the ($T_1 - T_2$) term of (3), is measured at each of the towers by placing two of the filament resistors in a bridge configuration. DC offset in the electronics is avoided by pulsing the bridge to provide an ac signal. The ac bridge output is processed by a Precision Monolithics GAP-01 functioning as a phase
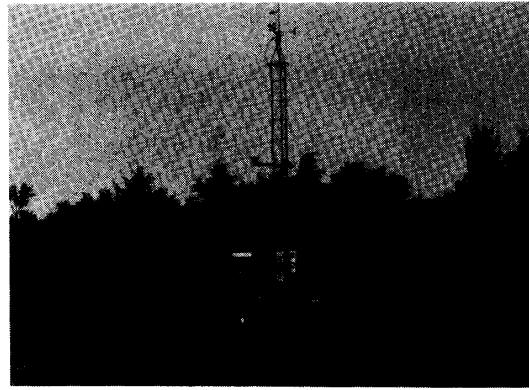

Fig. 5. Photo of tower no. 1 of the meteorological network.

sensitive detector, followed by a two-pole 100-Hz filter for signaling conditioning before the A/D converter. The sensor configuration is located approximately 2 m off the ground with an adjustable spacing between filaments of 100 cm to 1 m [11].

Humidity is measured with a Lyman-Alpha hydrometer similar to that described by Buck [12]. An ultraviolet (UV) source emits at the Lyman-Alpha absorption line of hydrogen and an ionization-type detector measures the source power at a fixed distance from the source. The detected signal is directly related to the absorption of the UV radiation by the hydrogen atoms of water molecules between source and detector. This signal yields a very fast (sub-millisecond) measurement of the absolute water vapor density (humidity) between the source and detector when correctly calibrated.

From an electronic viewpoint the source tube is provided a high-voltage constant current by a current mirror. Because the source tube operates by emission from hydrogen liberated from uranium hydride in the tube by heating an internal filament, the source output is very sensitive to operating temperature changes. To maintain a constant source output, the tube temperature is regulated by a P-I controller. Tube temperature is measured with thermistor sensors embedded in a foam insulation layer surrounding the tube and the temperature is varied by pulsewidth modulation of the tube's filament current. The detector tube, an ionization type device, looks like a high impedance current source. An electrometer chip (Analog Devices AD515K) provides the necessary transconductance gain. Differential humidity measurements are obtained by subtracting and filtering (along with special processing to remove the dc term) the outputs from individually matched Lyman-Alpha hydrometers.

The wind sensors are commercially available three-axis generator-type anemometers [13], employing permanent magnet proportional tachometers. An offset buffer amplifier provides signal conditioning to convert the bipolar voltages generated by the anemometers to a 0- to 5-V signal for the A/D system with 2.5 V representing a zero wind velocity.
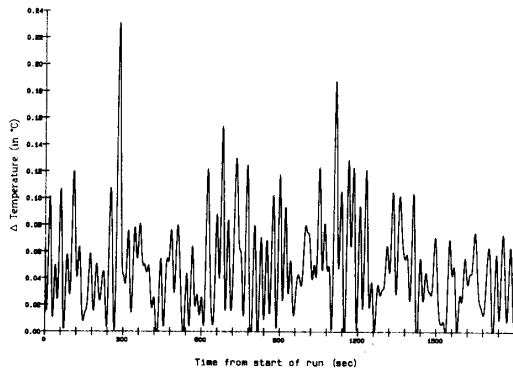
Fig. 6. Typical differential temperature fluctuations (16-in. sensor separation).
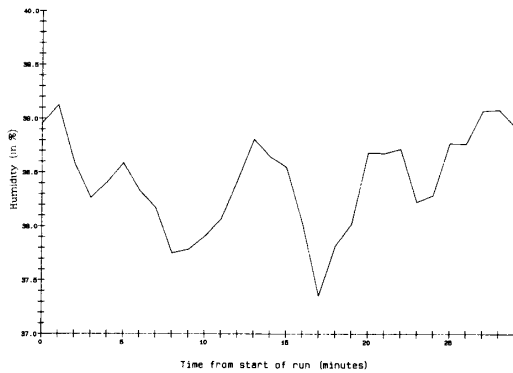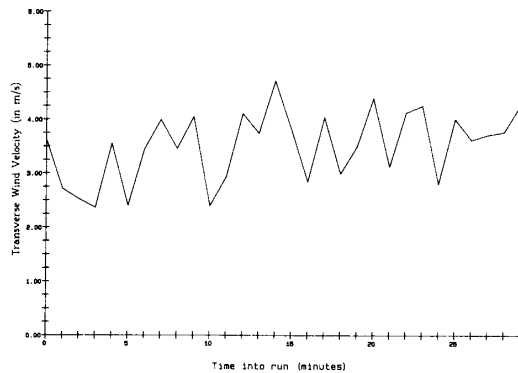

Fig. 7. Typical humidity fluctuations.

Fig. 8. Typical transverse vector wind velocity fluctuations.

Typical differential temperature (40.6-cm probe separation), absolute humidity, and transverse wind velocity data are shown in Figs. 6–8. The value of C_T^2 obtained from the data in Fig. 6 is $4.56 \times 10^{-6}\ °C^2\,m^{-2/3}$. Typical values of the structure constants for NMM wavelengths that have been observed so far show that $C_{n_R}^2$ is on the order of $10^{-11}\ m^{-2/3}$, $C_{n_I}^2$ is on the order of $10^{-17}\ m^{-2/3}$,

and $C_{n_R n_I}$ is 0 to the current system computational accuracy.

V. CONCLUSION

A data-acquisition network has been developed to perform high-speed measurements of meteorological parameters over a one mile test site. The network consists of six instrument towers which are capable of collecting differential temperature, differential humidity, absolute temperature, absolute humidity, vector wind velocity, and rainfall rate at set locations along the site. The towers are interconnected via fiber-optic data links to a dynamically reprogrammable, microprocessor-based FEP which communicates with the host PDP-11/24 computer through a bidirectional parallel interface. A protocol based on the ISO-OSI model provides the flexibility required for tower communications and network control.

The meteorological instrumentation presented here and the propagation measurement system described elsewhere [4] form a complete experiment for investigating the effects of atmospheric turbulence and turbidity on electromagnetic propagation. The variance, temporal spectrum, and mutual coherence function of the propagation beam-wave are computed from both the received electromagnetic radiation and the meteorological parameters of the intervening atmosphere. Correlation of these results will provide a database for modeling near-millimeter wave propagation in terms of measurable meteorological conditions.

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