TIME TRANSFER EXPERIMENTS FOR DCS DIGITAL NETWORK TIMING AND SYNCHRONIZATION

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ABSTRACT

In the planned DCS digital network, the ability to coordinate clocks placed at geographically separated nodes will be of critical importance. Aside from the characteristics of the clocks themselves, medium and link equipment parameters play dominant roles in determining performance for the system. The emphasis in this paper is on troposcatter link parameters and their relationship to network clock synchronization. Following an analysis and discussion of the important physical effects in troposcatter propagation, a description is given of experiments and data acquired during a recent measurement program designed to establish a better understanding of the relevant troposcatter and line-of-sight medium and equipment effects.

INTRODUCTION

A digital transmission network can be visualized in its most elementary form as a collection of nodes interconnected by radio links or cascades of links. Bit streams originating from geographically-separated sources enter the node and typically require multiplexing for retransmission to a common destination node. While incoming data signals may be conveniently buffered to smooth out the path length variations, drift between originating node clocks, if unchecked, will eventually result in buffer depletion or overflow.

In the past few years, various methods of avoiding or minimizing these undesirable phenomena have been proposed, including independent highly stable atomic clocks [1], mutual frequency averaging [2], hierarchical master-slave [3] and self-organizing master-slave [4]. More recently, consideration has been given to the use of network facilities for systemwide transfer of a time reference [5], and theoretical models have been used to predict relationships between time transfer accuracy and link parameters. To satisfy normal communication requirements, relative time synchronization of the nodes is sufficient, i.e., the node clocks need not be phased identically as long as their mutual average frequency offsets are zero. On the other hand, transfer of a time reference throughout a network is equivalent to the requirement that node clocks be synchronized with zero phase offset. The utility of such a scheme will not be elaborated on here except to indicate that substantial link and subsystem resynchronization benefits accrue.

The DCS network involves a large number of links and nodes with various categories of transmission media, including line-of-sight microwave (LOS), troposcatter (TROPO), satellite, and cable. The variety of transmission equipment that is available now, or planned as part of the all-digital network, makes a complete and comprehensive evaluation of system performance difficult; therefore, the emphasis in the experimental work reported on here has been toward a separation of propagation and equipment effects. Furthermore, the scope of the effort was limited to measurement of TROPO and LOS links because of equipment and site availability. Of these two classes of transmission medium, troposcatter involves a greater degree of variability in its parameters, making its characterization and measurement substantially more difficult. Accordingly, a more complete treatment has been given in this paper on the subject of time transfer via TROPO links, as compared with the more widely understood LOS application.

TIME TRANSFER PARAMETERS

Before presenting the detailed experimental configuration and results, a brief review of the parameters controlling system time transfer is in order. Consider, in particular, the transfer of time over a single link, as depicted in Fig. 1. In this example, a troposcatter propagation path is shown but, of course, other transmission media are of direct applicability.

The primary function of the link is the transfer of digital data between the nodes in both directions. At any node, incoming data is clocked into a buffer by clock signals derived from the receiver-demodulator bit tracking loop. This clock signal exhibits fluctuations and drift behavior as a result of transmit clock variations, medium variability, and tracking loop dynamics. In a synchronous network, the received data is later clocked out of the buffer by the node clock and multiplexed or switched with data from other terminated links for retransmission; the primary objective is to coordinate the collection of node clocks so that the buffers do not overflow or deplete. In addition, a timekeeping function for the node clock would involve the desire to meet the above objective with zero phase offset between the node clocks. Time is kept by the clocks at each end of the link in terms of a periodic sequence of time reference pulses (TRP's), which are synchronous with the high rate data clock. If ambiguity issues are ignored in this discussion, it can be simply stated that the time transfer objective is to align the two TRP transmissions. At node B, this is achieved by comparing the arrival time of a pulse transmitted from node A with the locally-generated pulse time, i.e., the node B clock pulse. Time transfer from A to B can then be implemented using this measurement, denoted τ_B, in one of two ways:

(1) Single-ended transfer, where τ_B is viewed as a combination of clock offset, average path/equipment delay, plus a zero mean fluctuating component. That is, if the average delay through the link is known a priori, sufficient averaging of τ_B should yield the clock offset and allow a correction to be made.

(2) Double-ended transfers, where a similar measurement, denoted τ_A, is carried out at node A, and the quantities τ_A and τ_B are exchanged by the two nodes. The difference parameter $\tau_A - \tau_B$, computed at either or both

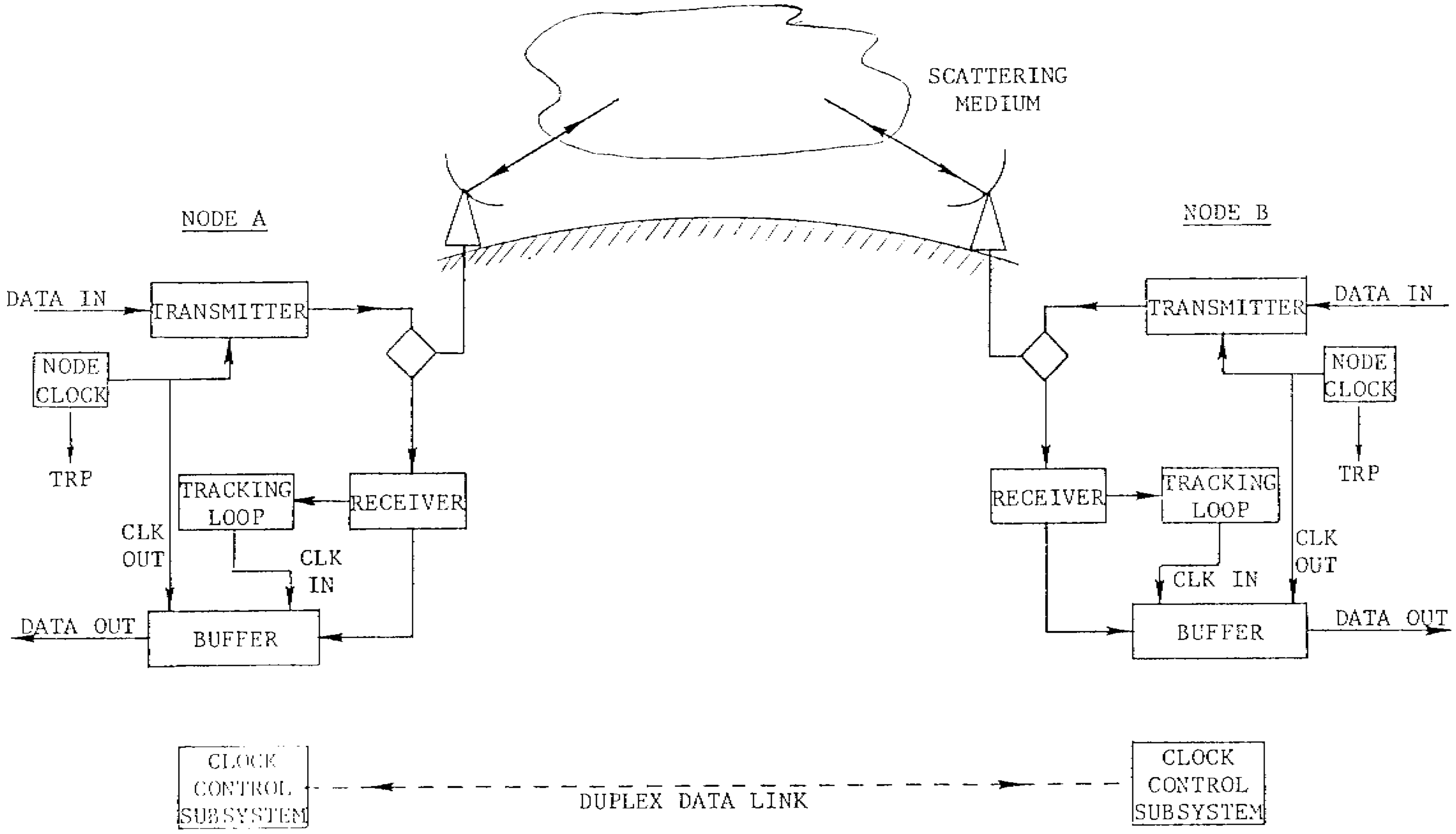

Figure 1 Block Diagram of a Digital Troposcatter Link

ends, is then proportional to the clock offset, provided the transmission time is identical in both directions. To the extent that this is true, $\tau_A - \tau_B$ may be used directly as a clock correction signal.

In both of these situations, the medium and equipment delay variations control the time transfer accuracy. For single-ended systems, variability around a long-term mean, in terms of both magnitude and spectral width, is the essential ingredient. However, the concept of a true known average will be suspect in most operational systems, and the magnitude of residual biases must also be estimated. Double-ended transfer methods depend for their success on similar parameters expressed instead in terms of bidirectional path delay differences; namely, the time structure and magnitude of the difference, along with residual biases which are not accounted for a-priori.

One-way and bidirectional delay parameters have been investigated for TROPO and LOS links at the RADC test facilities during the last year, with measurements carried out over a range of conditions encompassing seasonal, temperature, operating frequency, bit rate, signal level, and diversity angle effects. The temporal behavior of various links has been studied with averaging times ranging from seconds up to 20 minutes, and data records often extending over 3- or 4-day periods.

In the next section, some of the more significant properties of troposcatter links are highlighted. Line-of-sight links need not be described because of their comparatively placid and better-understood properties.

TIME TRANSFER VIA THE TROPOSCATTER MEDIUM

General Troposcatter Link Characteristics

The usual assumptions invoked when deriving theoretical models for troposcatter paths include a linear inhomogeneous weak scattering medium, separating two antennas which are not within line of sight to one another (see Fig. 2). As a result of the weak scattering assumption, a single scattering

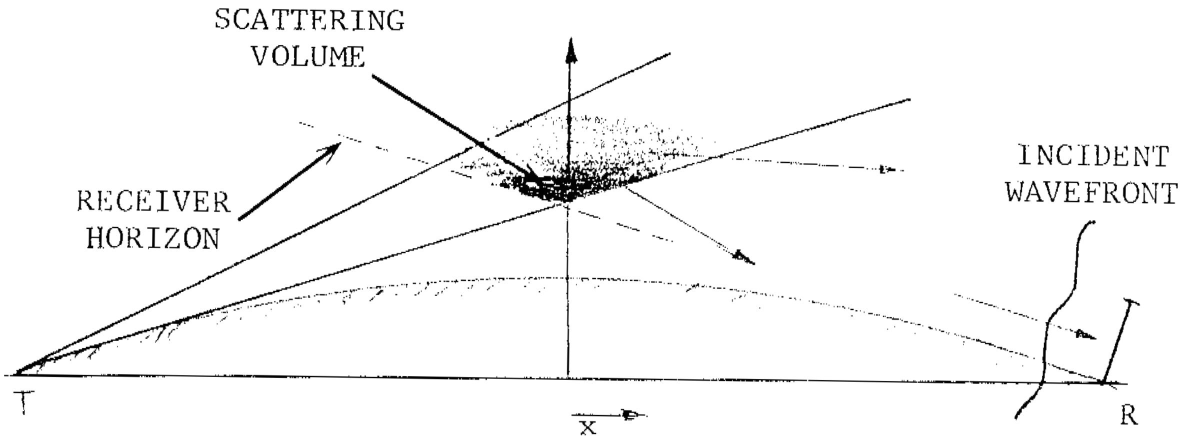

Figure 2 Troposcatter Path Geometry

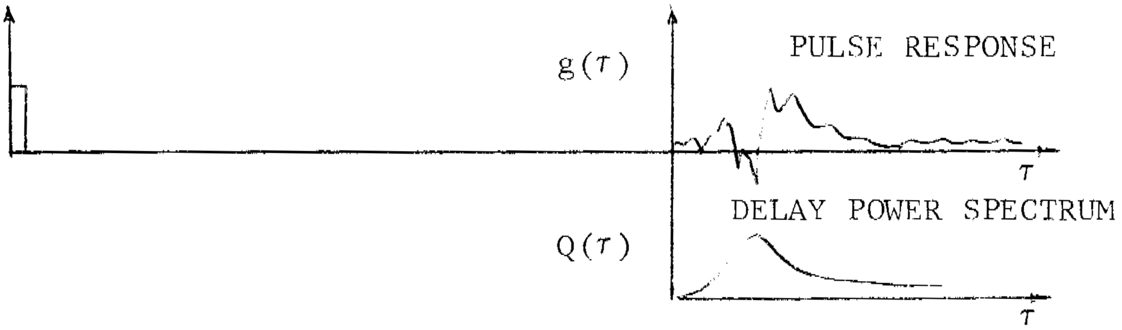

Figure 3 Troposcatter Link Response Characteristics

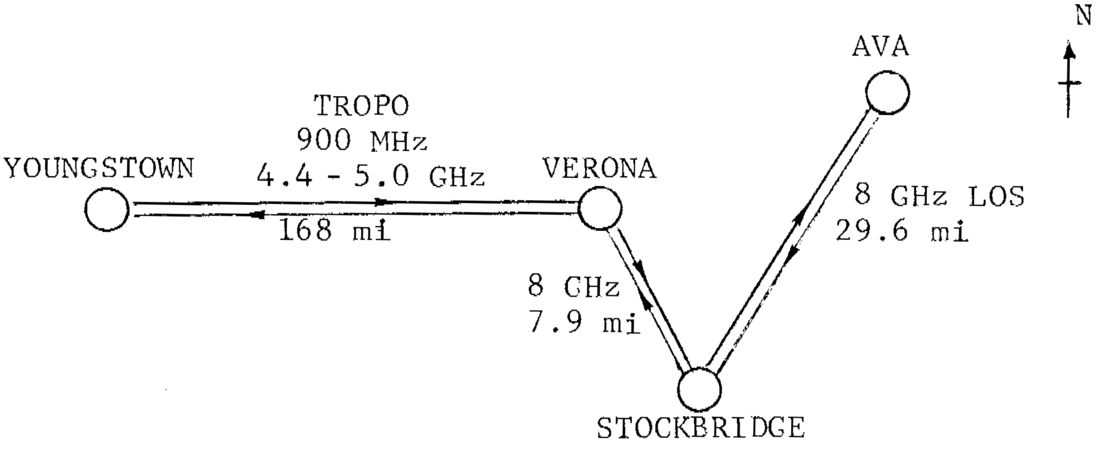

Figure 4 RADC Troposcatter/Line-of-Sight Test Configuration

model is normally used, with the refractivity inhomogeneities causing the scattering attributed to temperature, pressure, and water vapor variations in the atmosphere. The linearity assumptions allow the link to be characterized in terms of its (time-varying) pulse response $g(\tau)$ and, with some further very weak assumptions of the scattering mechanism, the process $g(\tau)$ can be described as a stationary Gaussian process with zero mean and second-order characteristic:

$$E\left\{|g(\tau)|^2\right\} = Q(\tau)$$

where E denotes statistical expectation, and Q is defined as the delay power spectrum [6]. The functions $g(\tau)$ and $Q(\tau)$, which are depicted in Fig. 3, typically extend over several hundred nanoseconds. A more complete statistical description of the received TROPO signal can be formulated, but is not required here.

It is convenient to introduce two different time scales associated with the quantities g and Q. Typically, the pulse response $g(\tau)$ varies rapidly over a period of seconds, depending on wind conditions, link geometry, and frequency of operation. A second time variation is, in effect, a deviation from the stationarity condition normally claimed. Large-scale meteorological influences, typically seasonal or diurnal in nature, give rise to changes in the shape of average characteristics such as $Q(\tau)$. A precise time-scale delineation of the two medium variation classes is not possible, but for measurement purposes the medium is usually considered to be stationary over nominal intervals of 20 minutes.

Time of Arrival Definitions

Even when the time-varying pulse response and its second-order statistic $Q(\tau)$ provide an adequate characterization of the troposcatter medium, there is clearly some difficulty in defining time of arrival for a hypothetical transmitted time reference pulse. An instantaneous arrival time parameter can be defined, for example, in terms of the response leading edge, energy centroid, energy median (early/late), or function maximum, and in sympathy with $g(\tau)$, the parameter will exhibit fluctuations of a short-term nature.

Furthermore, while two similar paths (e.g., forward and return) might have the same profile $Q(\tau)$, their instantaneous arrival time parameters could be quite different. Fortunately, in digital network applications one is normally relieved of the philosophical burden of defining transit time for multipath transmissions by the presence at every link termination of a bit synchronization tracking loop.

Bit synchronization circuits are provided in digital modems to accommodate the timing variations caused by the propagation medium and the timing clock at the transmitter. The function of the sync circuit is generally to smooth out short-term timing jitter present on the received signal so that only the long-term effects are tracked. For troposcatter channels, jitter occurs as a result of the multipath propagation as well as receiver noise. The techniques used vary widely but have the common feature of a continuous channel measurement, either explicitly with the transmission of separable pulses or an imbedded pseudo-noise probing sequence or, implicitly, by means of decision-directed adaptive equalization processing. The derived bit clock, therefore, responds to both short-term and long-term path length changes. An equivalent of the TRP situation is obtained when marked bits in the data stream, such as multiplexer frame patterns, are used as time-of-arrival events.

Virtually all troposcatter modem bit tracking loops have time constants which exceed a few seconds in order to smooth out short-term medium-induced timing fluctuations.

Reciprocity Considerations

One of the important fundamental parameters for a time transfer system is the differential transit time between the two nodes, since any residual difference directly corrupts the clock alignment procedure. One must suppress the immediate desire to invoke the reciprocity theorem, so that some of the more subtle reciprocity issues are at least examined. First consider the conditions under which reciprocity applies. The simplest form of Lorentz's reciprocity theorem [7] states that in a linear medium, a response of a system to a source is unchanged when the source and measurer are interchanged. In the context of a troposcatter path, this can be applied to single antennas placed at nodes A and B. For a current pulse applied to the antenna terminals at A, the response at B, $g_B(\tau)$, will be identical to the response at A, $g_A(\tau)$, for a pulse originating at B. This will not necessarily be true, however, if the antennas are interchanged along with the source. Other factors of interest in a search for potential nonreciprocal effects can be listed as follows:

(1) Transmissions in opposite link directions will generally be on different (albeit close) carrier frequencies.

(2) Space diversity transmission configurations violate the assumptions necessary for application of the reciprocity theorem. Consider the use of a single current source at node A to generate two port outputs, $g_{B1}(\tau)$ and $g_{B2}(\tau)$, at node B. A composite signal, $g_B(\tau)$, is then formed in the diversity combiner. Transmission in the reverse direction (from B to A) normally uses only one of the B node antennas, with reception on two antennas at node A. Generally, there will not be correspondence between the two diversity combined responses $g_A(\tau)$ and $g_B(\tau)$ for the same current pulse transmission.

(3) Even with radios from the same family, differences in tuning and temperature will result in some path delay asymmetry. For example, if receivers are more sensitive to temperature than transmitters, complementary delay/temperature effects will not be exhibited for the two path directions.

With favorable geometry and recourse to some mild assumptions, it is often possible to demonstrate that the paths from A to B, and vice versa, will have the same delay power spectra $Q(\tau)$ if not the same instantaneous impulse response $g(\tau)$. In the experimental program to be described next, the emphasis was on long-term one-way link delay and bidirectional delay asymmetries.

EXPERIMENTAL RESULTS

Link Measurement Configuration

Figure 4 indicates the geographic layout of the sites used in the field test program. The LOS links were set up in a cascade with a loop back from the Ava site to give a total path length of approximately 75 miles. The Ava and Stockbridge sites were normally unattended. Troposcatter propagation experiments were carried out between Verona and Youngstown using frequencies in the vicinity of 1 GHz and 4 GHz.

The equipment set up for the troposcatter experiments is shown in block diagram form in Fig. 5. The atomic clocks shown were calibrated on a weekly basis by means of direct clock comparisons. A synchronized coded sequence transmission was initiated at each end using the 1-pps clock outputs as a trigger. By time-multiplexing the available equipment at each end, round-trip and one-way (Youngstown-Verona) transmissions were made on an 8-second cycle, with two seconds available for each combination. Time of arrival was established by means of centroid calculations of the measured delay power spectra (obtained with correlation techniques), and one-minute averages were printed out, followed by a cumulative 20-minute summary of signal level, fade rate, delay power spectrum, and arrival time at the end of the run.

Equipment Delay Characteristics

A thorough investigation of transit delay was carried out for each piece of equipment used in the experiments, including transmitters/receivers, waveguide runs, modulators/demodulators, and digital instrumentation.

To establish an understanding of the temperature stability of the more significant delay components, combinations of receivers and transmitters were cycled through a range of temperatures. An example of a delay-temperature characteristic is given in Fig. 6. The specified temperature is room temperature, and the three graphs show the delay for loops taken at the power amplifier output and

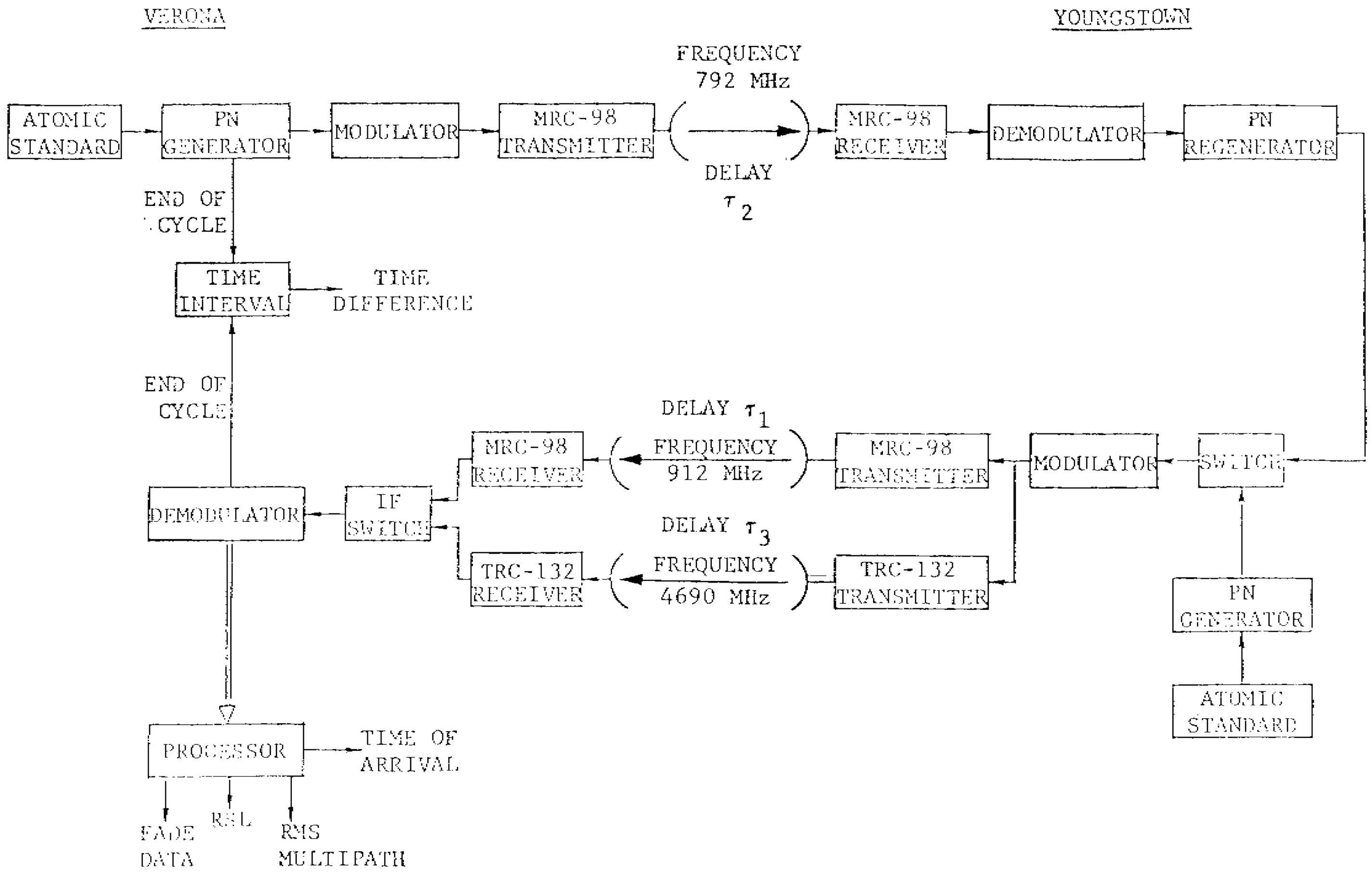

Figure 5 Differential and Absolute Delay Measurement Configuration

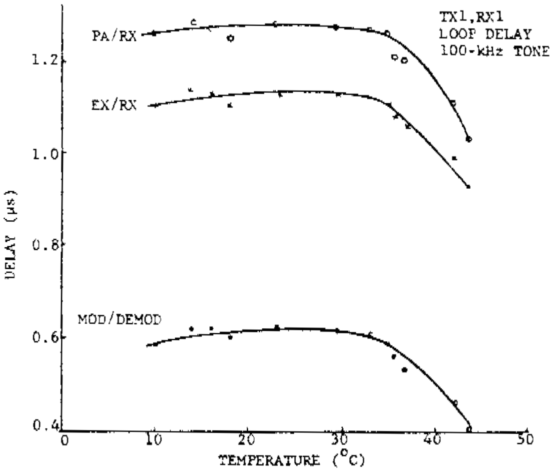

Figure 6 MRC-98 Radio Back-to-Back Delay

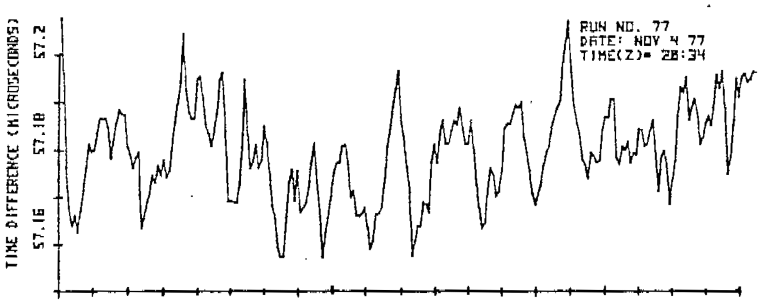

Figure 7 MDTS TROPO Modem Tracking Loop Jitter (3 Mb/s, 4 GHz)

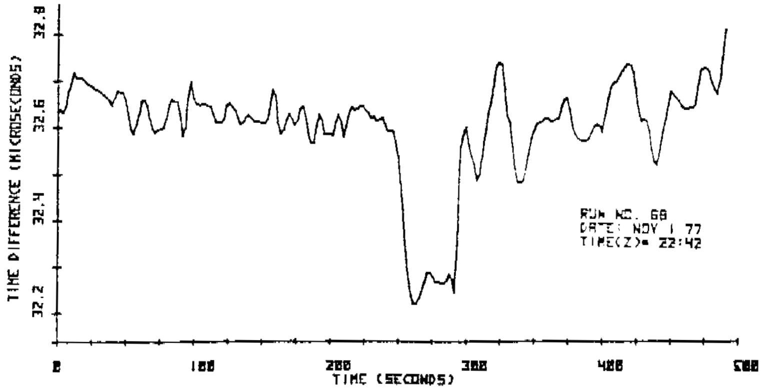

Figure 8 **MDTS** TROPO Modem Tracking Loop Jitter (6 Mb/s, 1 GHz)

exciter output across to the receiver, as well as the FM modulator and demodulator combination alone. These tests were carried out using 100-kHz, 200-kHz, and 500-kHz tone modulation. The results shown in Fig. 6 are for the 100-kHz case indicating the worst temperature sensitivity, most of which occurs in the modulator/demodulator units.

Digital TROPO Modem Jitter Characteristics

Two examples of the clock jitter measured at the output of digital MDTS troposcatter modems on the Verona-Youngstown link are shown in Figs. 7 and 8. Although these digital modems were only available for a brief period at the end of the experimental program, they are more representative of DCS network modems than most of the other equipment used, and are of interest for that reason. Both figures show the time jitter for a cascade of dual-diversity TROPO links equipped with MDTS modems. Figure 7 indicates performance with 3.088-Mb/s modems at 4 GHz, while Fig. 8 is for 6.276-Mb/s modems at 1 GHz. More severe fluctuations can be seen with the latter including a particularly deep excursion corresponding to a momentary loss of sync by the tracking loop.

Troposcatter Path Delay Data

We consider now the one-way and round-trip delay measurements taken with the time-multiplexed configuration illustrated in Fig. 5. The emphasis here is on longer averaging periods, typically 20 minutes, to eliminate the short-term fluctuations, such as those shown in Figs. 7 and 8. Furthermore, all of the equipment delay components have been edited out of the data so that pure path delay is obtained.

The results for a three-day data acquisition period are presented in Fig. 9. Each point plotted represents a 20-minute average of transmit time. A direct comparison between half the round-trip 792/912-MHz path delay and the one-way 912-MHz path delay is shown. Also indicated is the delay variation for one-way transmission on the C-band link. The significant feature in Fig. 9 is the close correspondence between one-way transit time and half round-trip

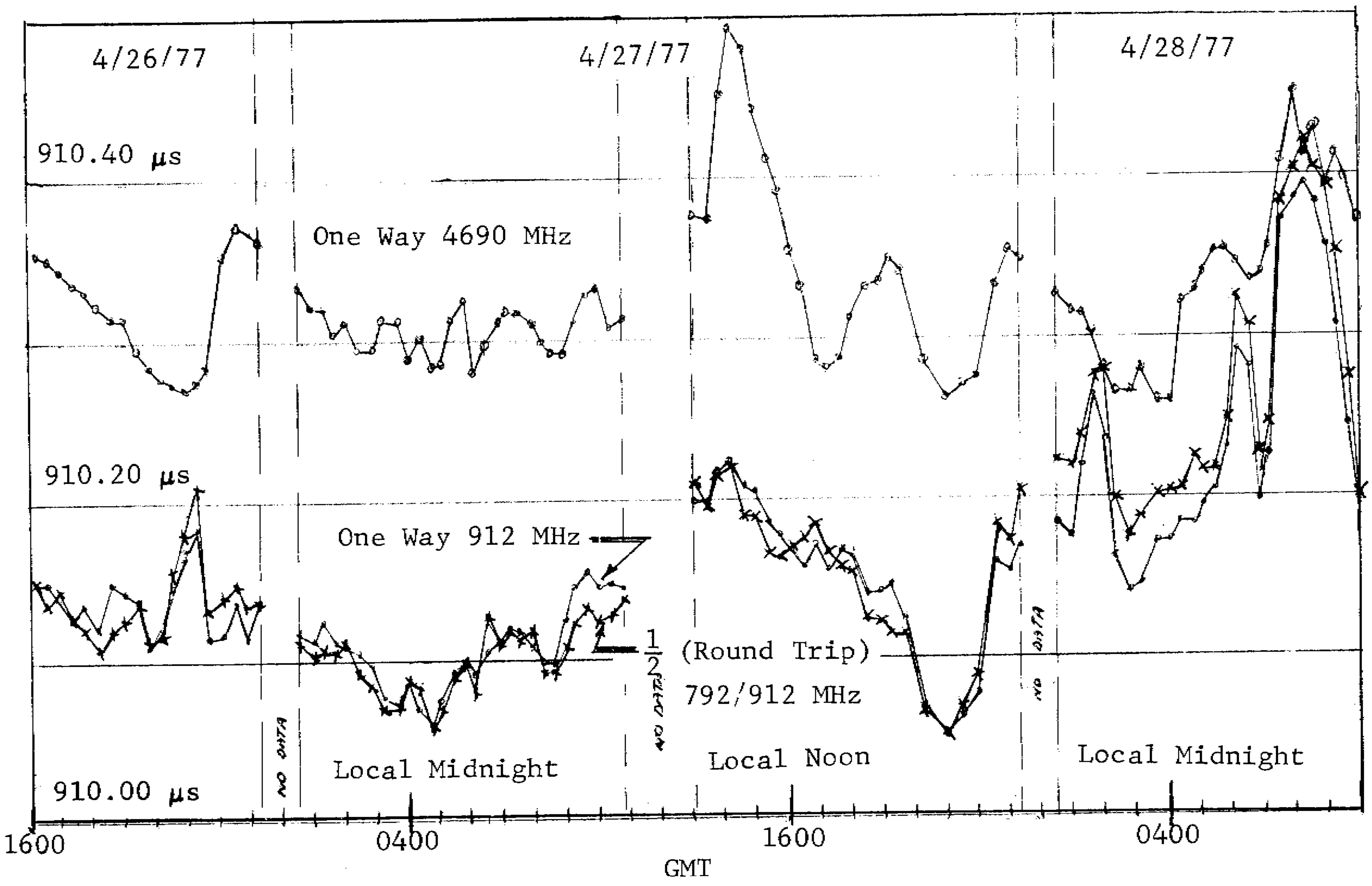

Figure 9 1- and 4-GHz TROPO Path Delay Variation transit time for the low frequency transmissions. On the other hand, the one-way C-band data deviates from the corresponding 900-MHz data with the appearance of a bias on the order of 200 ns as well as a lack of correlation between fluctuations. Looking beyond the bidirectional asymmetry considerations, the time history of absolute delay variation is of interest from the point of view of single-ended time transfer system performance, where a fixed medium delay must be factored into the clock correction procedure, and path length variations contribute directly to clock errors. In addition, required capacity for the data buffers shown in Fig. 1 is weakly related to medium delay variation, but, as can be seen, the magnitude of the fluctuations amounts to a small number of bits at the highest anticipated bit rate.

Because of conflicting coordinate data originally available, the RADC sites were surveyed in July 1977 to re-establish geometric path lengths. Also, some refractive index data is available for correlation with the measured path delay. As a guide, the following delay budget indicates the relative importance of different effects, and provides some insight into the mechanisms inducing path delay fluctuations:

Great Circle Path Verona-Youngstown (1-GHz antennas)	272695 ± 3 meters
Uncorrected Transit Time (using speed of light in a vacuum)	909.612 μs
Correction for Refractivity with $n = 320$ N units	0.291 μs
Correction for Path Length corresponding to Delay Power Spectrum Average relative to the Great Circle Path	~ 0.150 μs
Total Path Delay	910.053 μs

Note that refractivity variations up to 20 N units are common at the test sites, resulting in corresponding delay variations ranging as high as 20 ns. Similarly, refractive index gradients can cause the path length to vary by altering the propagation geometry. The quantitative aspects of this physical effect have yet to be explored.

Line-of-Sight Path Delay

By now it should be apparent that LOS links have relatively mild delay characteristics when compared with TROPO paths. Although several long data acquisition runs were carried out on the 75-mile LOS link cascade, measured transit time was generally confined to a ± 10-ns region about a nominal path. Figure 10 shows a portion of a 4-day run in which a quartz clock was set up to track a master cesium standard at the originating end of the links. The time constant selected in the clock control loop was 100 seconds. The plotted variable is the difference in time between the master and slave clocks. Path length variation on a time scale of less than 100 seconds should, therefore, be averaged out, while long-term path variations will be present.

CONCLUDING REMARKS

The results obtained in this experimental program, including those presented in this paper as being representative, must be used with some caution. It cannot be emphasized too strongly that the range of climatic conditions and equipment configurations involved was quite narrow. However, the results to date do offer quantitative data not previously available to the system designer, and suggest definite guidelines in the development of time transfer techniques to satisfy the DCS network requirements.

ACKNOWLEDGEMENT

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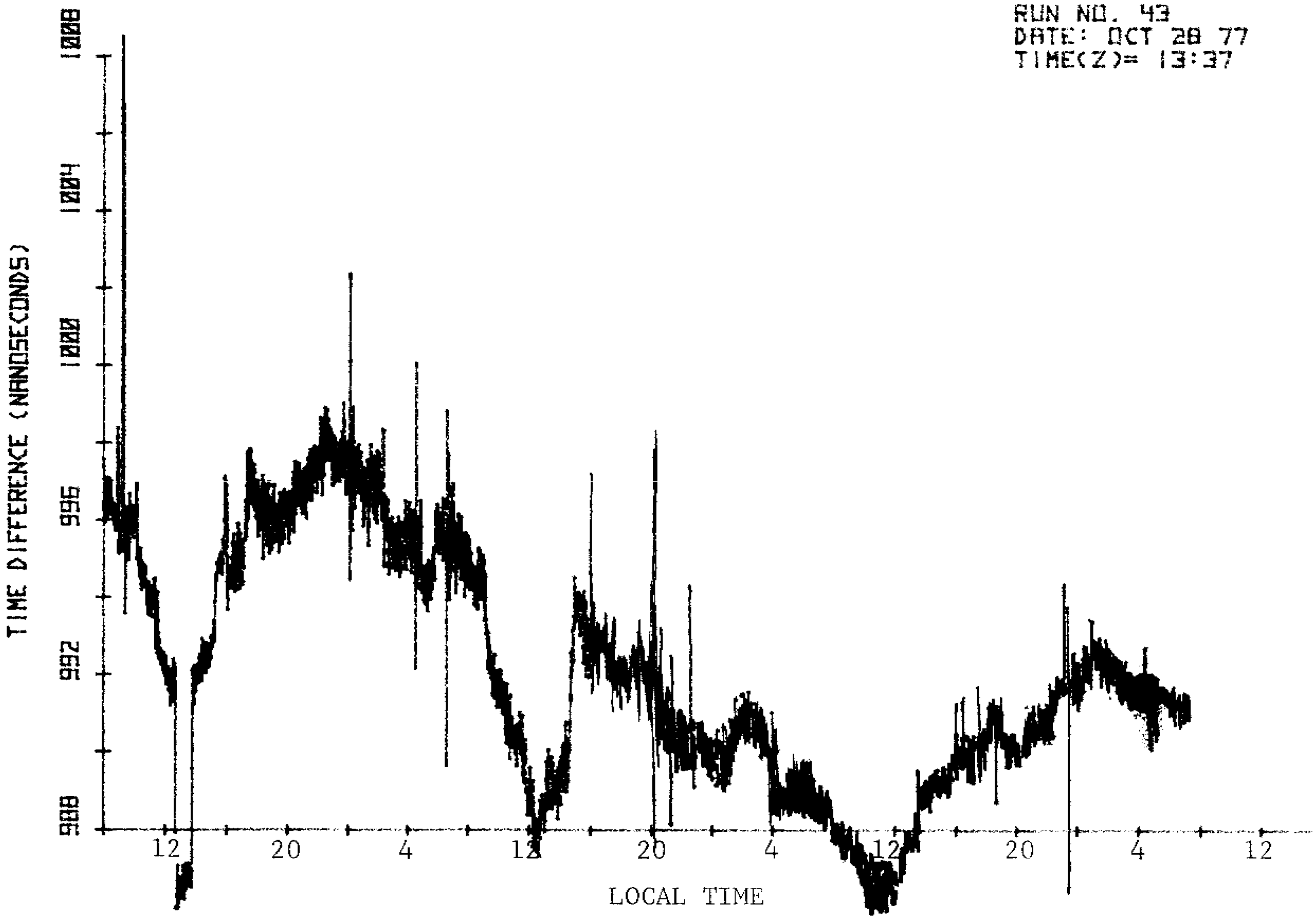

Figure 10 Path Delay Variations for 75-Mile Line-of-Sight Loop

REFERENCES

[1] V. I. Johannes and R. H. McCullough, "Multiplexing of Asynchronous Digital Signals Using Pulse Stuffing With Added Bit Signaling," IEEE Trans. on Comm. Tech., Vol. COM-14, No. 5, October 1966, pp. 562 - 568.

[2] M. W. Williard, "Analysis of a System of Mutually Synchronized Oscillators," IEEE Trans. on Comm. Tech., Vol. COM-18, No. 5, October 1970, pp. 467 - 483.

[3] B. R. Saltzberg and H. M. Zydney, "Network Synchronization," BSTJ, Vol. 54, No. 5, May 1975, pp. 879 - 892.

[4] J. G. Baart, et al., "Network Synchronization and Alarm Remoting in the Data Route," IEEE Trans. on Comm., November 1974, pp. 1873 - 1877.

[5] H. A. Stover, "Time Reference Concept for the Timing and Synchronization of the Digital DCS," DCASEF TC39-73, July 1973.

[6] P. A. Bello, "A Study of the Relationship Between Multipath Distortion and Wavenumber Spectrum of Refractive Index in Radio Links," Proc. IEEE, January 1971, pp. 47 - 75.

[7] R. F. Harrington, Time Harmonic Electromagnetic Fields, McGraw-Hill, New York, 1961, pp. 116 - 120.

QUESTIONS AND ANSWERS

MR. WALL, Jet Propulsion Laboratory:

Do high-flying aircraft have any appreciable effect?

DR. ALEXANDER:

Yes, they certainly do. When we were at the Tropo site, we were, of course, near an air base and the presence of aircraft can be observed by monitoring what is equivalent to that pulse response that I showed. However, we are averaging over 20 minutes in some of that data, and the occurrence of the aircraft is likely to be shortlived. We think it is an insignificant error in our measurements. But they are present, and they do have quite an effect on what you observe in the lab.