Appendix D. DCnet Timekeeping Facilities

In order to help understand the background of the experiment and measurement program described in this report and to calibrate the reliability of its conclusions, it may be helpful to describe the major components of the laboratory equipment, computing resources and networking facilities available to the various projects in timekeeping analysis and measurement. The laboratory is probably best known among our collaborators, perhaps with a little whimsy, as "Time Central."

The experiments and measurements reported in this report and elsewhere require timekeeping precisions to a very high order. Since one of the goals is to determine the performance envelopes of various radio and satellite receivers, the accuracy and stability expectation of the calibration instruments must be at least as good as the receivers. In general, this requires specially instrumented computer workstations, together with laboratory equipment such as oscilloscopes, frequency/event counters and precision frequency and time sources. Most of this equipment is available as the normal complement of a university research laboratory. In following sections the DCnet timekeeping facilities is described, with emphasis on those features not likely to exist in most computer and network laboratories.

D.1. Computer and Network Facilities

For measurements made in the wide-area Internet system, it is necessary to have intimate connections to campus nets, regional nets, research nets and the national backbones. We have built a dedicated research testbed network of workstations, routers and special-purpose servers designed just for this purpose. The research network, called DCnet, is assigned the Internet network number 128.4 and, as a network, dates back to the very early days of the Internet. There are three main subnets of this network, an Ethernet (128.4.1) connecting all on-campus workstations and servers, a FDDI net (128.4.5) connecting DCnet servers and other department servers, plus three high performance workstations used for time-related research, and an Ethernet (128.4.2) (called the "backroom") at a remote site used for program development and testing.

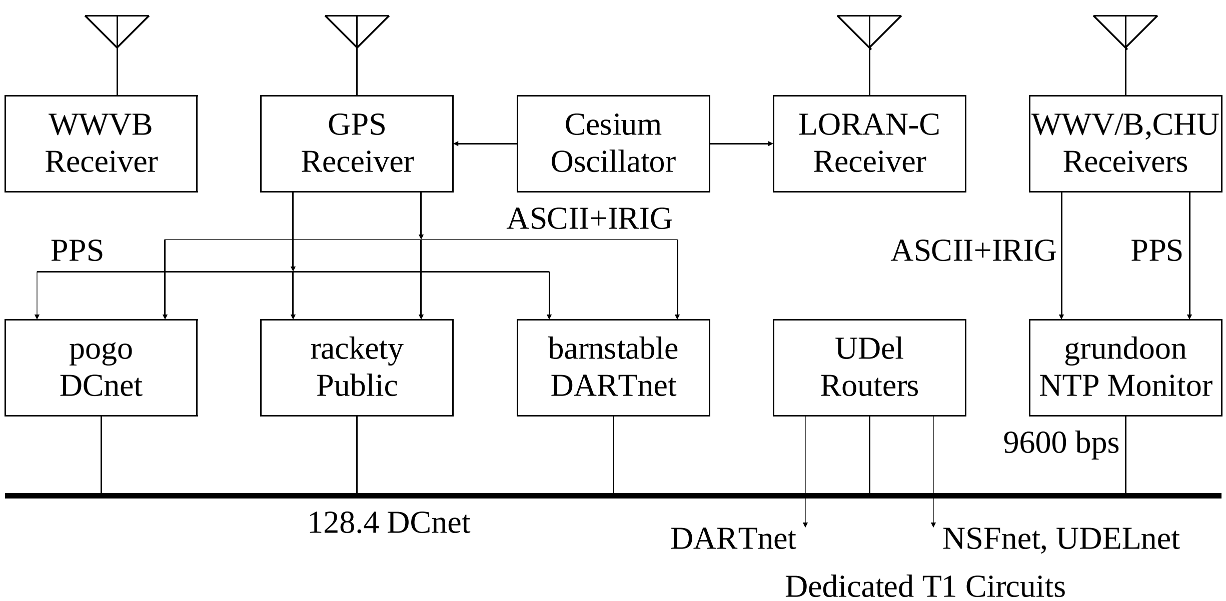

Figure 24. DCnet Timekeeping Facilities

Figure 24 shows a a portion of the DCnet internet configuration, which presently includes 21 workstations, routers and special-purpose servers of various types. DCnet is connected to the campus network UDELnet by an Ethernet router, to the NSFnet national backbone node at College Park, MD, by a dedicated Ethernet router and 1.544-mbps T1 leased circuit, and to the DARTnet national research network by a dedicated Ethernet router and 1.544-mbps T1 leased circuit to Washington, DC. The campus and backroom site are connected by a pair of dedicated routers, a 9600-bps leased circuit and a 9600-bps dial-up modem line.

The DCnet workstations and servers have collectively about 500 MB of main storage and 10 GB of disk storage. These include nine Sun Microsystems SPARCstations, two Digital Equipment DECstation 5000/240, one Digital Equipment 3000/400 AXP Alpha, four Cisco Systems internet routers and four IBM-compatible PCs. Four workstations are equipped with CD-ROMs, two with 250-MB cartridge tape drives, two with 1-GB DAT tape drives and one with a DECtape drive. Almost all of the personal workstations are equipped with audio teleconferencing facilities and three are equipped with video teleconferencing facilities and cameras. Besides proving highly useful for ordinary collaborative discourse, these facilities make an excellent testbed for experiments involving multimedia synchronization, flow management and routing algorithms.

There are two dedicated file servers, one for the campus subnet (pogo), the other for the backroom subnet (grundoon). Each of these is also an NTP primary time server with clients on DCnet and elsewhere. One of the routers (barnstable) is also an NTP primary time server dedicated to DARTnet clients. Two of the Cisco Systems routers (churchy and brunce - not shown) are also NTP secondary (stratum-2) time servers with an experimental NTP Version 3 implementation. In addition, there are two DCnet dedicated NTP primary public time servers (rackety and churchy - churchy not shown) and a UDELnet NTP secondary public time server (louie - not shown), each of which presently have over 250 clients.

All workstations, file servers and all but two of the routers run NTP Version 3 with subsets of each other and the various time servers on DCnet, UDELnet, DARTnet and the NSFnet backbone nodes. Some of the primary servers run NTP Version 3 with opposite numbers in the U.S., Europe, Australia and elsewhere in the world. One of the secondary servers is connected by dial-up modem to National Institute of Science and Technology (NIST) laboratories in Boulder, CO, for timekeeping experiments using NTP and NIST protocols. Some NTP public time servers use DES-encrypted authentication, while others use MD5-encrypted authentication, as described in the NTP specification RFC-1305. Most of the private time servers and personal workstations do not currently use authentication.

D.2. DCnet Master Clock

For the experiments and measurements described elsewhere in this report, it is necessary for the DCnet master clock to maintain extremely stable local time and frequency sources. The primary laboratory frequency standard is a Hewlett-Packard 5061A cesium oscillator, which generates a number of signals used to calibrate other laboratory equipment, and in addition a pulse-per-second (PPS) signal used as a reference for similar signals generated by various radio and satellite receivers. While a cesium oscillator is one of the most stable frequency sources known, it is not inherently synchronized to national time standards and must be periodically recalibrated, either by physically moving it to a national standards laboratory or by means of a precision radio or satellite service. Both methods are used in order to insure accurate and reliable calibration. A specially equipped van with 110-V AC power inverter is available to transport the device to the U.S. Naval Observatory in Washington, D.C., for periodic recalibration.

The working time and frequency laboratory standards are derived from an ensemble of radio and satellite receivers. There are two Global Positioning Service (GPS) receivers, one of which, an Austron 2201A, is configured for precision time and frequency measurements and continuously compared with the cesium oscillator. It is the primary timing source used by all primary time servers on the DCnet campus subnet and furnishes three types of signals: an interactive serial ASCII data stream which provides coarse time and copious housekeeping data, a PPS signal, which provides precision synchronization via a serial port, and an IRIG signal, which provides precision synchronization via the audio port of some workstations, as described in the main body of this report and Appendix A. The other GPS receiver, a Bancomm Tymserve 2000, can also be used as backup, but this requires manual switching. For backup purposes, a Spectracom 8170 WWVB receiver is available. Some time servers listen to it on a continuous basis and switch to it only if the NTP algorithms detect a primary receiver fault.

In its present state of operational readiness, the accuracy of the GPS system is intentionally degraded by its military operators. However, technology has been developed so that this degradation can be largely overcome. The Austron GPS receiver is equipped with a subsidiary receiver for the LORAN-C radionavigation system and uses those signals to reduce jitter and wander of the GPS signal. There are two other LORAN-C receivers for calibration and backup service, one an Austron 2000C-1 LORAN-C receiver of the same type as used by the Coast Guard to monitor the transmitters, and the other a laboratory-constructed unit for general utility use [MIL92b]. The antenna farm for the GPS, WWVB and LORAN-C receivers is located atop a nearby utility building.

The backroom site is 2.6 km from campus and located in a suburban area away from most sources of radio interference. It includes a Sun Microsystems SPARCstation workstation, two IBM-compatible PCs, a Cisco Systems internet router and an historically interesting development machine called the Fuzzball [MIL88]. There are four receivers used with this equipment, a Spectracom Netclock/2 WWVB receiver, two PST/Traconex 1010 WWV/WWVH receivers, a laboratory-constructed receiver for the Canadian CHU time service, and a laboratory-constructed LORAN-C receiver, together with a respectable antenna farm. This site is equipped with several computer-controlled, general-purpose HF, VHF and UHF receivers and demodulators for most radio standard timekeeping services used in the world. The primary timing source used at the backroom site is the IRIG signal of the WWVB receiver, while the WWV/WWVH and CHU receivers serve as hot-standby backups in that order and are automatically switched in as required.

D.3. Data Collection Facilities

In order to conduct experiments and routine timekeeping surveillance operations, it is necessary to have tools that can reach over the network and retrieve data internal to a remote timekeeping system, as well as monitor and record routine operations for later review and analysis. There are two programs of the NTP Version 3 distribution which allow remote monitoring and control of NTP servers and clients, one conforming to the NTP control and monitoring protocol specified in RFC-1305 (ntpq) and the other using a nonstandard protocol designed especially for debugging and experiment control (xntpdc). These programs, which are ordinarily used in a real-time interactive mode, can display all the state variables specified in RFC-1305 and, in addition, private variables used in the Version 3 implementation. The operations of these programs are described in the NTP Version 3 distribution and will not be detailed further here.

The NTP Version 2 distribution includes a comprehensive facility with which various data produced by the protocol can be captured to a set of files for subsequent review and analysis. Most DCnet primary time servers and some secondary time servers use this facility to monitor operations on a continuous basis in order to watch for anomalous behavior and as a retrospective reference while experiments are in progress. Other servers and clients are monitored during experiments as required. The data are captured by the NTP Version 3 daemon and logged to various files on the local file system. Each line of data written includes the (modified) Julian day, together with seconds of the day. There are three types of data collected, each in a separate file:

Loop Statistics (loopstats)

These data are produced by the local clock algorithm and consist of the time offset, frequency offset and time constant of the phase-lock loop (PLL). The time offset and time constant are determined at the time of the update. The frequency offset is calculated by the PLL. One line of data are written to the loopstats file for each local clock update. Following is a sample of the loopstats data for a primary server synchronized to a WWVB receiver via the IRIG audio decoder. Each line begins with the MJD day and seconds of the day, and continues with the time offset in seconds, frequency offset in ppm and time constant in powers of two.

```
49273 14878.802 0.000065 46.6918 0
```

Peer Statistics (peerstats)

These data are produced by the clock filter algorithm and consist of the peer Internet address, status word, offset, delay and dispersion. These quantities are defined in the NTP Version 3 specification RFC-1305. One line of data is written to the peerstats file for each valid update received from the peer. Following is a sample of the peerstats data for a DARTnet client of a primary server. It begins with the MJD day, seconds of the day and internet address, and continues with a two-octet status code in hex, and the offset, delay and dispersion, all in seconds.

```
49273 14389.125 140.173.96.1 9454 0.000737 0.08868 0.00093
```

Clock Statistics (clockstats)

These data are produced by the various clock drivers for specific receivers supported by the NTP Version 3 distribution. Most drivers can produce a report showing receiver identifier, status, last timecode received and related housekeeping information. For some of the more full-featured devices, such as the Austron 2201A GPS receiver, this amounts to a good deal of information, including GPS status, LORAN status and comparisons between receiver time and external devices, such as a cesium oscillator or LORAN-C receiver. One line of data is written to the clockstats file for each valid update received from the clock. Following is a sample of the clockstats data for a Spectracom 8170 WWVB receiver. It begins with the MJD day, seconds of the day and clock identifier, and ends with the ASCII timecode as received from the clock. Certain character positions are used to indicate, among other things, how long the receiver has gone without adequate received signal level.

```
49272 47.811 127.127.4.1   93 285 00:00:31.794  D
```

The types of data collected for each time server are specified in the daemon configuration file. A separate set of data files is recorded beginning each UTC day and identified by date in the file name. Once each day a special job is run which scans the files collected the previous day and appends summary data to a set of archive files. The archive files furnish a historical record which serves as proof-of-performance of the entire timekeeping system.

For example, following is a summary entry for the clockstats file of 10 October 1993 for the WWVB receiver mentioned previously. There were 5339 samples processed on that day, of which none (? 0) were processed while the receiver was unsynchronized. Of the samples processed, 712 had errors higher than 1 ms and 909 had errors higher than 10 ms. There were no samples with higher errors. The entry consists of two lines, a header derived from the day-file name followed by the summary data itself.

```
clockstats.19930910
wwvb 5339, ? 0, 1 712, 10 909, 100 0, 500 0
```

An entry like this is appended to the clock_summary archive file for each radio clock each day.

Another example is a pair of summary entries for the loopstats file of 10 and 11 October 1993, as indicated in the headers preceding each entry. These entries involve a primary server synchronized to the WWVB receiver mentioned previously. The entry for each day shows the number of samples processed, mean time offset+/-maximum absolute deviation, and RMS error over the day in microseconds. This is followed by the mean frequency offset+/-maximum absolute deviation, and RMS error over the day in ppm. On the first day, operations were nominal; however, here was a power interruption on the second day which disrupted timekeeping service for some minutes following the interruption. The latter entry clearly reveals the disruption.

```
loopstats.19931010
loop 5384, 66+/-205.5, rms 33.1, freq 45.59+/-0.287, rms 0.173
loopstats.19931011
loop 5303, 38532+/-67112.0, rms 7943.0, freq 57.50+/-26.857, rms 8.312
```

A final example shows a summary entry for the peerstats file involving an NSFnet backbone router client of a DCnet primary server. This is one (slightly edited) line of a multi-line table which contains an entry for each persistent-state client of the server found during the day. The Internet address of the client is shown first, followed by the number of samples during the day and the mean, RMS and maximum time offset, in milliseconds. This is followed by the mean roundtrip delay, maximum synchronization distance and maximum dispersion, in milliseconds. The relatively large values for latter two numbers show that the daemon was restarted at least once during the day.

```
140.222.136.1  37  -0.788  3.226  7.921  12.666  883.21  110.022
```

In addition to the summary data described above, a set of archival data files are maintained for the DCnet master clock, including continuous comparisons between the cesium oscillator, GPS receiver and LORAN-C receiver. In addition, housekeeping data are collected on a continuous basis from all radio receivers at both the campus and backroom sites. In the case of the Austron GPS receiver, additional data on satellite visibility, GPS and LORAN-C stationkeeping status, internal time/frequency loops and receiver master clock are recorded. These data are used to establish retrospective proof of performance and to signal alarm conditions due to GPS or LORAN-C system problems, receiver performance deficiencies and various configuration and procedure errors. These data have in fact detected previously unsuspected problems in the receiver design which were subsequently corrected by the manufacturer.

D.4. Proof of Performance

Elsewhere in this report is an extended discussion on accuracy and stability of the local timekeeping system relative to the signals generated by a radio clock or cesium oscillator. In this section the discussion is concerned about the accuracy and stability of these sources. This issue is of some concern, since the accuracy regimes of interest exceed the specifications of many radio clocks. For instance, most radio clocks which deliver a timecode in serial ASCII format display time only to the millisecond; however, as we have seen, the accuracies achievable using PPS or IRIG signals can be in the low tens of microseconds. What remains is to assess the accuracy of the sources and the validity of the claims.

Of those precision frequency sources available commercially, the cesium oscillator is considered the most stable. This device has a stability in the order of 10^{-12}, or six orders of magnitude better than the uncompensated quartz oscillator used in typical workstations. However, different cesium oscillators do not necessarily run at the same precise frequency; there is usually a small difference between them. Ordinarily, these differences are mitigated by international agreement to form the International Atomic Time (TAI) timescale. Therefore, a cesium oscillator, while highly useful to calibrate short term effects such as jitter and wander, needs to be disciplined relative to TAI in order to provide long term frequency guidance.

The Global Positioning System (GPS) is intended primarily as a precision navigation and positioning system for use by the U.S. military; however, it has been found many uses in the civil sector for navigation, surveying and scientific applications, especially since the price of GPS receivers has plummeted in recent years. However, since precision navigation requires precision time in order to calibrate propagation distances, a byproduct of precision navigation is precision time.

In one sense GPS is considered too good; that is, the military believes the system may give an adversary a considerable advantage, especially for guided munitions. Therefore, the signal is intentionally degraded using cryptographic codes known only to designated user communities. This feature, called Selective Availability (SA) was originally intended to degrade GPS timing accuracies to those comparable with LORAN-C, about 0.25 nautical mile or about 1.6 µs. As evident from the DCnet archives and U.S. Naval Observatory weekly reports, the timing accuracies achievable with LORAN-C and GPS even with SA have been much improved. In LORAN-C, this has been achieved with much improved stationkeeping; while with GPS, this has been due primarily to improvements in receiver algorithms.

An obvious way to improve the accuracy of GPS is using very long averaging times; however, there are only a few oscillators stable enough to make this effective, including cesium and rubidium oscillators and various types of masers. For most applications these devices are prohibitively expensive. There is another, much less expensive way using the LORAN-C radionavigation system to discipline the short-term frequency of the master clock, while leaving GPS to discipline its long-term frequency. The LORAN-C transmitters are currently maintained to a high degree of precision, usually better than 200 ns, according to daily measurements published by the U.S. Naval Observatory. As discussed in a prior report [MIL92b], a LORAN-C receiver is relatively inexpensive and can be integrated with a counter-timer interface for use with conventional workstations.

For the above reasons, the primary time and frequency source for DCnet master clock was chosen as the Austron 2201A GPS receiver configured with several options which provide various test frequencies, a PPS signal, IRIG signal and serial ASCII timecode. This receiver is equipped with

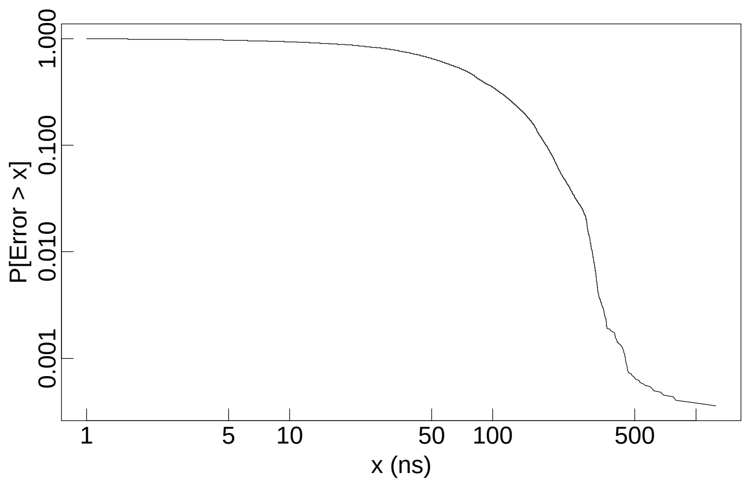

Figure 25. Probability Distribution of GPS Receiver Errors

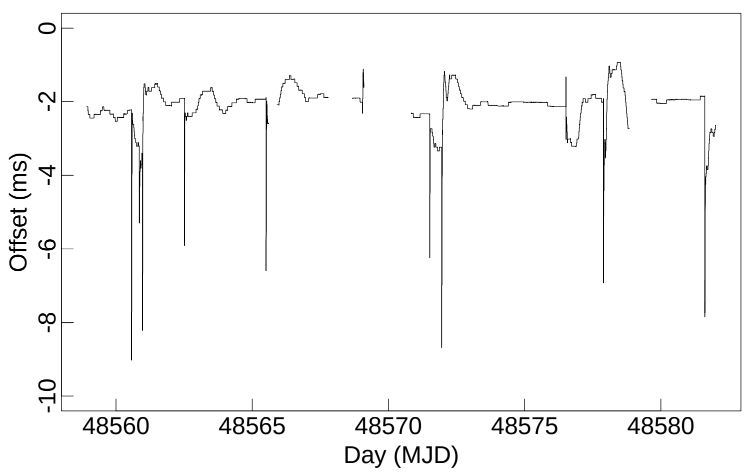

Figure 26. Time Offsets of WWVB Receiver

an internal LORAN-C receiver which largely removes the effect of SA and improves the accuracy to usually better than 200 ns, especially if few or no satellites are in view. The archival record over a 60-day period shows that, under typical conditions, the maximum absolute error of the receiver relative to the cesium clock over one day is less than 200 ns. On the other hand, the archival record shows that the maximum absolute differences of the receiver ensemble time relative to the (weighted) GPS and LORAN-C times rarely exceed 100 ns, with RMS differences in the order of 30-60 ns. These differences are comparable with those published by the U.S. Naval Observatory for the GPS constellation [USNO].

Figure 25 shows the cumulative probability distribution of GPS receiver ensemble time error relative to the cesium oscillator over 60 days and almost 65,000 samples. During most days of this period, the absolute errors and RMS errors were nominal, as described in the preceding paragraph; however, there were some days where, due to equipment repair and maintenance, system reconfiguration, etc., the errors exceeded the nominals. Including these effects, a statement of absolute confidence would have to be limited to an absolute accuracy of 400-500 ns, with a few outlyers even above this.

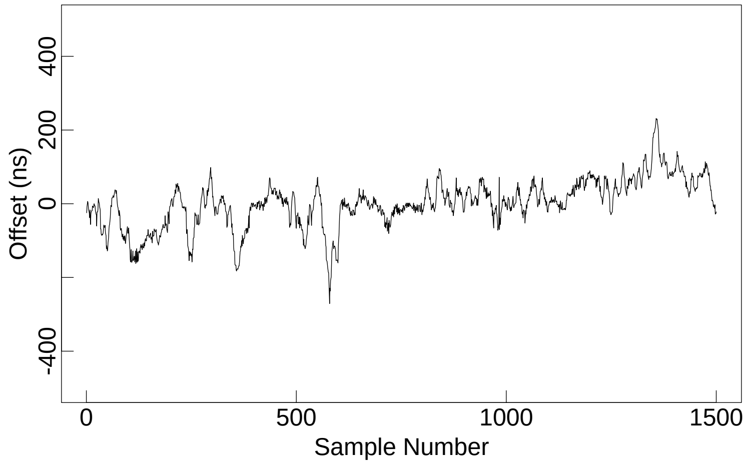

Figure 27. Time Offsets of LORAN-C Receiver

The DCnet master clock includes two backups, one an Austron 2000 LORAN-C receiver, the other a Spectracom 8170 WWVB receiver. The WWVB receiver is operated in a hot-standby mode and is automatically switched in if the Austron GPS receiver fails. Its performance is far inferior to the GPS receiver and, in addition, the WWVB receiver often loses signal for varying periods during the day while the internal receiver oscillator wanders to and fro. To date it has not been possible to resolve the difficulty, which is believed due to the low signal levels in this part of the country, possibly exacerbated by locally generated interfering signals. For these reasons, the readings of the WWVB clock cannot be relied upon to less than a few milliseconds. Figure 26 shows a typical interval of about 20 days where the receiver lost signal (interrupted trace) and exhibited bumps and grinds while the frequency had to be relearned after an outage.

The LORAN-C receiver is normally used only to check the health of the other receivers and in stability measurements with laboratory equipment. Figure 27 shows a comparison between the PPS signal produced by this receiver and the GPS receiver over a period of about a day. The differences shown are consistent with the differences measured between the cesium oscillator and GPS receiver, leading to the suspicion that the limits in accuracy with measurements like this may be due to the measurement system itself, rather than the characteristics of the timing signals being measured. In any case, these data lend confidence to the claim that the DCnet master clock can reliably resolve the tick to within a few hundred nanoseconds on just about any occasion.