

RELATIONSHIPS BETWEEN U.S. NAVAL OBSERVATORY, LORAN-C  
and  
THE DEFENSE SATELLITE COMMUNICATION SYSTEM

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ABSTRACT

Department of Defense (DoD) Directive 5160.51 of 31 August 1971 states that "All DoD components ... refer time and time interval to the standards established by the (U.S. Naval) Observatory." To obtain the required traceability, the most widely used system for time dissemination has been the navigational system of the U.S. Coast Guard - Loran-C. When the only chain available for timing was the East Coast chain, monitored by the Observatory, there was no problem in publishing comparisons of that chain to the U.S. Naval Observatory's Master Clock (USNO MC) with a fair degree of reliability. By 1981, however, thirteen chains, covering a substantial portion of the Northern Hemisphere, were in use. The question of how the time comparisons were to be obtained, the chains calibrated, and the results published for chains not directly monitored by USNO then arose.

During this same period, the number of links permitting time transfers point-to-point over the Defense Satellite Communication System (DSCS) were being expanded. In addition, at some selected sites, Loran-C monitoring equipment was installed. It was now possible to have values of USNO MC - DSCS Monitoring Site and thus to be able to determine USNO MC minus Loran-C.

This paper addresses, in general terms, the methods used in forming time scales for distant sites monitoring Loran-C. Particular emphasis will be given to the time transfers obtained via the DSCS and on how the data provided by this system is used to calibrate these remote time scales. The errors involved will be discussed.

INTRODUCTION: Closely related to the U.S. Naval Observatory's (NAVOBSY) basic mission of providing astronomical and time data to all "who avail themselves thereof" are the additional functions imposed by DoD Directive 5160.51 of 31 August 1971. The imposition of these functions required (1) an upgrading of the Master Clock system, (2) improvement in distribution services and (3) an expanded means of maintaining traceability to USNO MC.

The upgrading included such items as purchase of additional cesium clocks, improved Data Acquisition and Control (DAC) systems - an IBM Series 1 and a Hewlett-Packard 1000 - installation of better environmental chambers and improved algorithms for the formation of the USNO MC time scale. To improve the distribution services, an increased number of Time Service Announcements were made available. More than 1000 pieces of mail are now distributed weekly. This mail service is supplemented by telephone voice announcements and more recently (albeit on an experimental basis) by the Digital Data Access System (1,2). Traceability to the USNO MC, for the greatest number of users, is still provided by the Loran-C system maintained by the U.S. Coast Guard. During the period 1967-1981, NAVOBSY expanded the Loran-C timing information it provided to the user community. From providing data only for the East Coast chain, monitored at NAVOBSY, the differences between USNO MC and thirteen Loran-C chains are now routinely published. The body of this paper will deal with how these daily relationships are determined (in particular for the distant chains) and how these relationships are calibrated.

NAVOBSY MONITORING SITE: Presently NAVOBSY monitors four Loran-C chains. These chains are the Northeast USA (9960), the Southeast USA (7980), the Great Lakes (8970) and the East Coast of Canada (5930). The daily times of reception from several receivers for each of the four chains are collected, the delays subtracted, and the values averaged by the HP1000 DAC: This information is then published. By using these data and measurements from monitoring sites (Table 1) which contribute to the NAVOBSY data base, relationships between USNO MC and more distant chains are determined and published. For example, the U.S. Coast Guard station at Cape Race, Newfoundland provides the daily difference between the East Coast of Canada (5930) and the North Atlantic (7930) chains. By a simple calculation, then, of  $USNO\ MC - LC/5930$  plus  $LC/5930 - LC/7930$  one obtains  $USNO\ MC - LC/7930$ . This procedure continues for other eastern chains.

A difficulty arises in this 'linking' - seasonal effects as large as one microsecond have been seen in propagation path delays at NAVOBSY. These effects will be reflected in Loran-C data where 'linking' is used. Some recent analyses by Monger (3) of the U.S. Naval Observatory Time Service Substation (NOTSS) confirmed the earlier propagation studies by Charron (4). In Figure 1 the differences  $USNO\ MC - NOTSS$  via the Southeast USA chain are plotted. It appears that the NOTSS time scale changed in fre-

quency with respect to USNO MC. This change, however, is deceptive - it is not a change in the NOTSS time scale (which was calibrated through portable clock visits during this period) but instead is due to a change in the propagation path delay between NAVOBSY and Carolina Beach, NC, a transmitting station of the 7980 chain.

PRECISE TIME REFERENCE STATION (PTRS), according to Ref. 5, "by agreement, maintains at least one atomic clock coordinated with the NAVOBSY Master Clock; is linked to the NAVOBSY via portable clock and at least one other high precision time transfer technique; can transfer time with a precision of 100 nanoseconds...". These stations, having been established for their own organizational requirements, are all independent of one another and of NAVOBSY. Only by agreement do they transmit data to NAVOBSY. Even though NAVOBSY has no official control of the operation of these stations, the data received from them provides another method of providing comparisons between USNO MC and a Loran-C chain. NAVOBSY adopts the daily values of USNO MC - PTRS (as determined by the PTRS) and its monitored Loran-C data. This is what is done for the West Coast USA (9940) and the West Coast of Canada (5990). Frequent portable clock visits are the means used to calibrate the PTRS, and thus these Loran-C chains. That portable clock visits alone are insufficient for calibration may be seen in the fact that discontinuities as small as 0.3 microsecond and as large as 1.5 microseconds have been reported in the Time Service Announcements Series 4. The discontinuities or jumps seen in Figure 2 are not due to changes or discontinuities at the Loran-C station but are due to undetected frequency changes in the PTRS time scale. Since both chains are dependent upon the same PTRS, any error in the calculation at the PTRS will be seen as discontinuities in both chains. In developing the method of remote time scale determination of Loran-C, a comparison of the values as calculated at the PTRS (and then published by NAVOBSY) and those values obtained using the remote time scale were examined (Figure 3). As can be seen in this plot, each jump that occurred in the Series 4 data brought the values of USNO MC - LC/9940 (as published) into agreement with those obtained using the time scale method.

REMOTE TIME SCALES: Farther west, greater difficulties are encountered in determining daily values of USNO MC - Loran-C chains, namely, the Central Pacific (4990), the Gulf of Alaska (7960), the Northern Pacific (9990) and the Northwest Pacific (9970). Dependence upon a PTRS, calibrated through frequent portable clock visits, is not practical. The distance and resulting costs may allow only yearly trips. The method now used to obtain values for these chains - to a greater or lesser degree - consists of forming a time scale for each Loran-C chain using the average of a number of atomic clocks which will be more uniform and stable than any clock contributing to the time scale.

To implement this approach for a particular chain, a search is made of the pertinent data bases (Table 2) to locate the required data which in-

cludes approximately 18 months of daily Loran-C measurements from as many monitoring sites as possible and several portable clock measurements made at the different sites at different times during that period.

From these data, a delay (sum of delays from propagation path, receiver, antenna, etc) is determined for each site. A series of straight lines then gives values of USNO MC - Site for all sites. The measurement, Site - Loran-C, minus appropriate delay are added to the USNO MC - Site values. This allows one to obtain a comparison of USNO MC - Loran-C via each site. These individual values are then averaged to form a MEAN and the difference between the individual values and the MEAN is calculated. As necessary, new series of straight lines are determined so that the individual values of USNO MC - Loran-C agree with the MEAN to within some specified tolerance. Values of USNO MC minus each Site are calculated using the MEAN value of USNO MC - Loran-C. These values must agree with the values obtained by portable clock measurements. In this reiterative process, it is assumed (a) that the cesiums used for measurements are 'free-running', that is, that none are, for example, steered to follow the published values of Loran-C and (b) that cesiums will not spontaneously change, by the same amount, in time and/or frequency simultaneously.

Once a time scale is formed for an individual chain, a great deal of judgement must be exercised in continuing the process. What has changed with respect to what must be decided (rate correlation)? Did a cesium at a particular monitoring site change frequency? Did one or more fail? Were some adjusted, replaced or removed? These are recurring questions and must be dealt with as each new piece of information is received. Current data from more than one site are always needed but seldom obtained. The continued accuracy of the chain is maintained by reliance upon the occasional clock trip and time transfers from DSCS terminals.

DEFENSE SATELLITE COMMUNICATION SYSTEM (DSCS): Thus far, the only means of calibrating the Loran-C chains mentioned has been portable clock visits to some monitoring sites. However, the trips are infrequent, costly and the measurements made are also subject to error. Examples include incorrect identification of site, of cesium/measured reference, of date/time, and/or start/stop pulse. In addition, during the trip, changes of the portable clock in time and/or frequency with respect to USNO MC are not uncommon. In Figure 4, values of USNO MC minus PC1368 as collected by the DAC before and after a portable clock trip are plotted. If an extrapolation of the frequency offset was used in determining USNO MC minus - Site during the trip, an error as large as 0.300 microsecond could have resulted.

A second means of calibration is possible by use of the DSCS. By the mid-1970's, time transfers between earth terminals were being regularly performed. The differences between the cesiums at each terminal, as deter-

mined from the time transfers, were regularly transmitted via teletype to NAVOBSY and became part of a data base. (Reference 6 details the procedures used in processing these data.) Some terminals were either monitoring Loran-C or had a connection via cable/portable clock to a monitoring site (Figure 5). Such was the case at Elmendorf AFB, AK.

Prior to 1979, the Precise Measurement Electronics Laboratory (PMEL) at Elmendorf AFB acted as a PTRS, described earlier, for the Northern Pacific (9990) chain. (Data for the untimed Gulf of Alaska (7960), although monitored by PMEL, was not used by NAVOBSY.) Transmitted to NAVOBSY were (a) the daily measures of the LC/9990 and the LC/7960 chains, (b) the daily intercomparisons of on-site cesiums and (c) the weekly portable clock measurements between PMEL and the satellite terminal (ELM).

At the same time NAVOBSY also received the time transfer data between the Elmendorf (ELM) satellite terminal and the Ft. Detrick, Md (FDS) terminal. One, therefore, had

|   |         |   |      |                           |
|---|---------|---|------|---------------------------|
|   | USNO MC | - | FDS  | via TV line 10            |
| + | FDS     | - | ELM  | via time transfer         |
| - | PMEL    | - | ELM  | via portable clock visits |
|   | USNO MC | - | PMEL | .                         |

By adding the on-site intercomparisons to this value, a relationship between USNO MC and all of the on-site cesiums was obtained.

A time scale, as described earlier, was formed for each PMEL cesium and an averaged value of USNO MC - LC/9990 and USNO MC - LC/7960 was calculated. It was noted that the averaged determination of USNO MC - LC/9990 not only did not agree in time but that the frequency offset differed (Figure 6). It was decided that publication of data for this chain would be suspended temporarily and that a portable clock team knowledgeable in Loran-C operations would visit Elmendorf AFB as soon as possible. The trip was made in December 1978. A thorough examination of sites at PMEL and ELM and also at a NASA site in Fairbanks, AK was made. Delays in the monitoring systems were calibrated. It was found that the Loran-C determinations via the time scale, calibrated by using the weekly DSCS time transfers, were accurate. Since then, the values published in Time Service Announcement Series 4 have been determined in this manner. In addition, the 7960 chain was set on time and publication of USNO MC - LC/7960 began. In Figure 7, the values determined using the time scale are plotted. The DSCS time transfers, used as calibration points, also are seen. The differences between USNO MC and the cesiums at the PMEL, calculated via the remote time scale and a recent portable clock measurement, agreed to within 0.090 microsecond.

The combination of remote time scales and time transfers is a very useful tool. Besides being routinely used in Alaska for the 9990 and 7960 chains, it is also now used for the 9970 chain and to some degree for the 4990 chain.

In determining the feasibility of this method for Loran-C timing and for possible further applications, a time scale also was formed for the 9940 chain. The MEAN, or averaged value, of USNO MC - LC/9940 was used to determine the relationship between NAVOBSY and the National Bureau of Standards (NBS). In Figure 8, values of USNO MC - NBS via (a) 9940 Loran-C time scale, (b) portable clock measurements, (c) DSCS time transfers and (d) Bureau International de l'Heure (BIH) are plotted. It appears that there is some seasonal effect on the order of 0.5 microsecond in the values obtained using the BIH Circular D data.

**CONCLUSIONS:** Each method of determining the relationships between USNO MC and Loran-C and each method of calibrating that relationship is subject to possible error. Dependence upon one data point, whether it be a portable clock measurement, a DSCS time transfer or a Loran-C measurement, can result in erroneous conclusions. In Figure 9, a means of relating Loran-C chains to each other and USNO MC through DSCS terminals and some strategically located monitoring stations (nodal points) can be seen. The expansion and strengthening of the relationships shown can only serve to improve traceability to USNO MC for those users of Loran-C.

More extensive use of remote time scales and greater correlation of the information contained in the data bases make possible:

- 1) Better determinations of USNO MC - Loran-C and thus better world-wide synchronization for those users of Loran-C
- 2) Better determination of time and/or frequency changes in the cesiums at distant sites. It is possible to resolve ambiguities in data. Use of remote time scales provides information necessary to respond quickly to requirements for cesium adjustments at DSCS terminals.
- 3) Improvements in total delay determinations.
- 4) Some monitoring of portable clock behavior in the field.
- 5) Further studies of seasonal and annual terms in propagation path delays.
- 6) Further studies of the relationships between international time scales (USNO, NBS, BIH, etc).

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#### REFERENCES

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2. Winkler, Gernot M.R., "The U.S. Naval Observatory Data Services", Proceedings ISOSO 81, November 1981, New York, New York.
3. Monger, Donald, "NOTSS Clock System", Time Service Memorandum, 10 July 1981
4. Charron, Laura G., Internal Memorandum, 10 September 1978.
5. Operating Procedures Precise Time and Time Interval Equipments, NAVOBSY - TS/PTTI SOP 81.
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TABLE 1

REPRESENTATIVE SAMPLE of MONITORING STATIONS

| <u>7970</u><br><u>NORWEGIAN SEA</u> | <u>7980</u><br><u>SOUTHEAST USA</u> | <u>7990</u><br><u>MEDITERRANEAN SEA</u> |
|-------------------------------------|-------------------------------------|---|
| OP FRANCE                           | NAVOBSY                             | OP FRANCE                               |
| HP SWITZERLAND                      | NOTSS RICHMOND, FL                  | HP SWITZERLAND                          |
| ON SWITZERLAND                      | AGMC NEWARK AFS, OH                 | ON SWITZERLAND                          |
| NPL ENGLAND                         | WHITE SANDS MISSILE                 | IEN ITALY                               |
| RGO ENGLAND                         | RANGE, NM                           | RGO ENGLAND                             |
| NAVSECGRU SCOTLAND                  |                                     | NAVSECGRU ITALY                         |
|                                     |                                     |   |
| <u>8970</u><br><u>GREAT LAKES</u>   | <u>9960</u><br><u>NORTHEAST USA</u> | <u>9990</u><br><u>NORTH PACIFIC</u>     |
| NAVOBSY                             | NAVOBSY                             | PMEL ELMENDORF                          |
|                                     | NOTSS RICHMOND, FL                  | NASA FAIRBANKS                          |
|                                     | AGMC NEWARK AFS, OH                 | SHEMYA AFB, AK                          |
|                                     | NBS BOULDER, CO                     | *DSCS ELMENDORF                         |

\*INDIRECT MEASURE

TABLE 2

U.S. NAVAL OBSERVATORY DATA BASES

|   |   |
|---|---|
| INTERCOMPARISONS OF CESIUM CLOCKS       | NAVOBSY TIME SCALES                                   |
| OMEGA MEASUREMENTS                      | SATELLITE TIMING INFORMATION (DSCS, TRANSIT)          |
| LORAN-C MEASUREMENTS                    | UTC(BIH) - UTC(i)                                     |
| REMOTE TIME SCALES FOR MONITORING SITES | EARTH ORIENTATION PARAMETERS (UT1, POLAR COORDINATES) |
| PORTABLE CLOCK REDUCTIONS               | ASTRONOMICAL OBSERVATIONS                             |



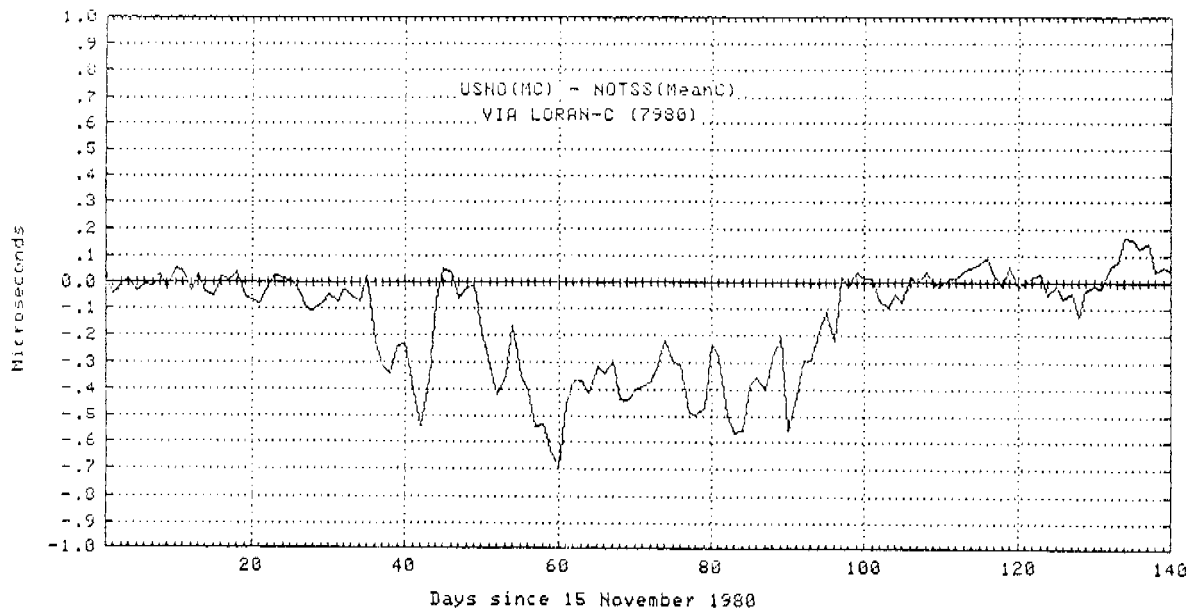


FIGURE 1

COMPARISON OF USNO MC - NOTSS  
via 7980 Loran-C

The change of approximately 0.4 microsecond seen in this figure from Reference 3 is not due to changes in the time scale at NOTSS but, rather, is due to the seasonal effect on the propagation path delay between USNO and the transmitting station of the 7980 chain.

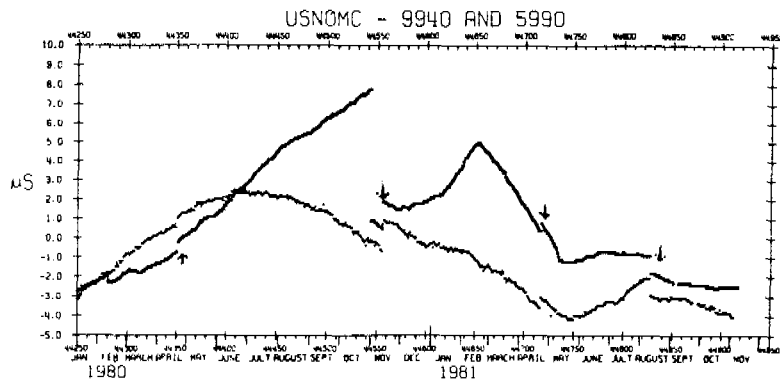


FIGURE 2

These are the published Series 4 values for the 9940 (darker trace) and the 5990 chains. The discontinuities (marked by arrows) seen in both chains occur after portable clock calibrations of the PTRS which determine the values for these chains.

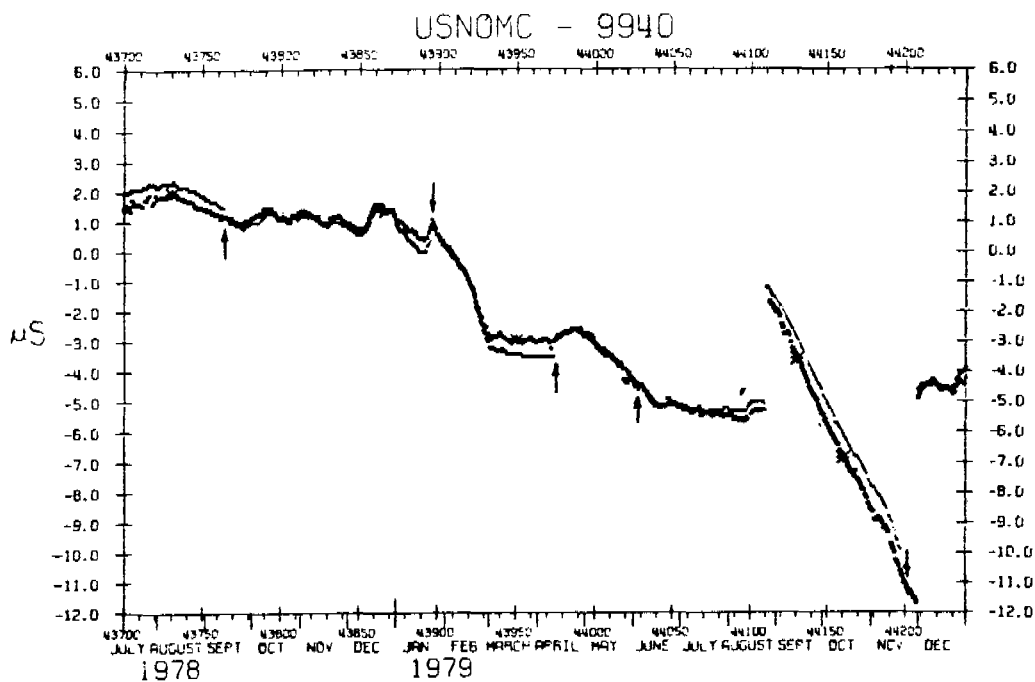


FIGURE 3

The heavy tracing is composed of the averaged values obtained using the time scale reduction method. The second trace consists of the values which were published in Series 4 obtained using the PTRS procedure. The discontinuities, marked with an arrow, are the results of portable clock calibrations at the PTRS. Note that after each discontinuity, the Series 4 values become co-incident with the time scale values.

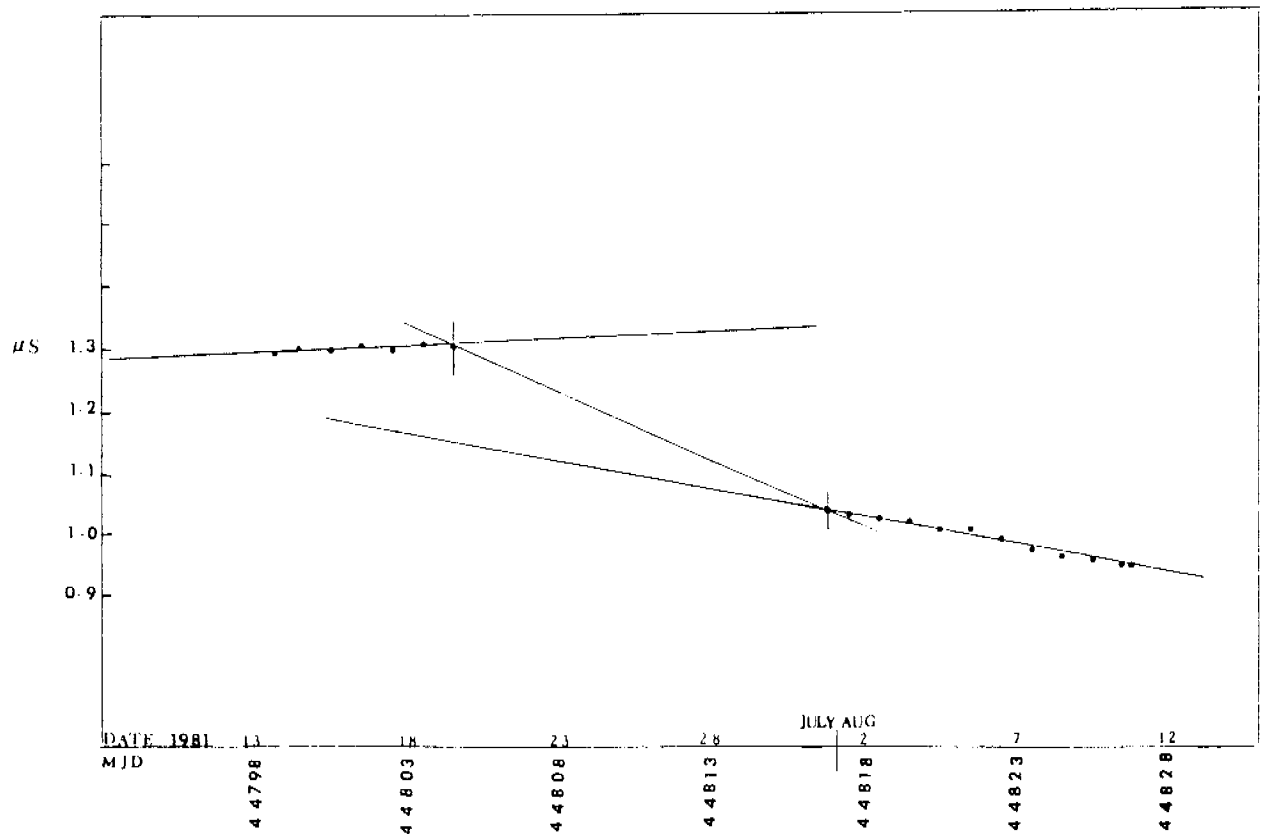
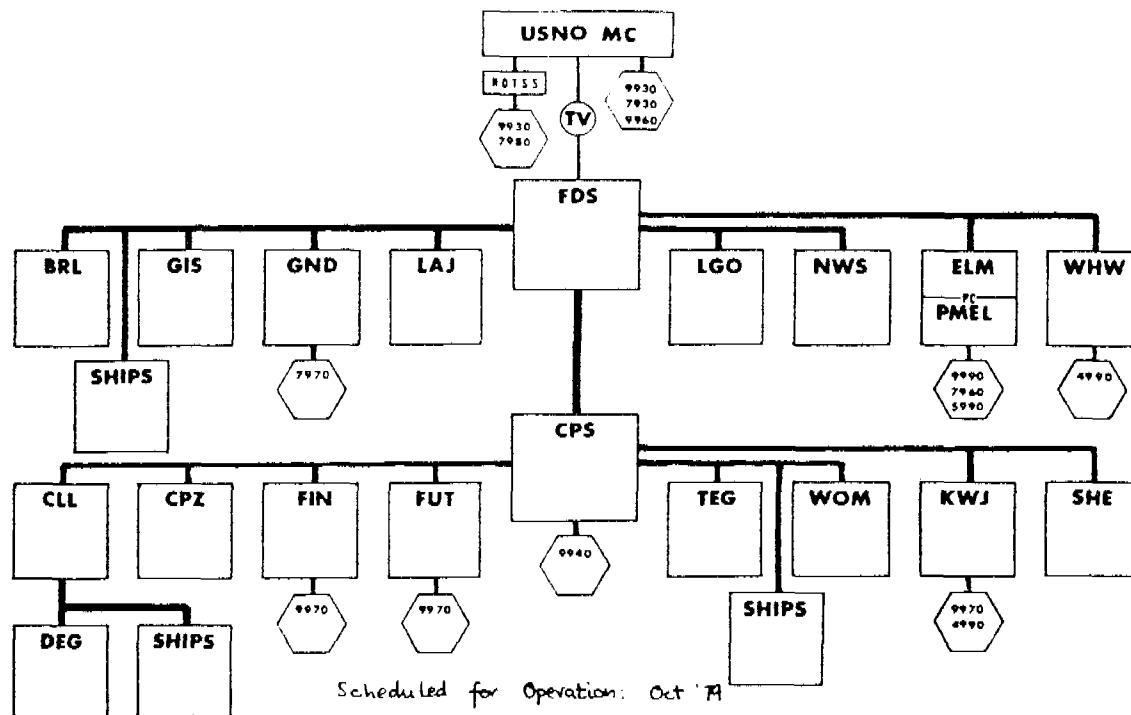


FIGURE 4

COMPARISON: USNO MC - PC1368  
 Trip of 13 July - 10 August 1981

The DAC system collected these data before and after a recent portable clock trip. Time and/or frequency change(s) occurred: such changes are not uncommon.



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FIGURE 5

HIERARCHY OF TIME TRANSFERS PERFORMED BY THE DSCS TERMINALS

|     |                       |     |                        |
|-----|-----------------------|-----|------------------------|
| FDS | FT. DETRICK, MD       | CLL | CLARK AFB, PHILIPPINES |
| BRL | BERLIN, GERMANY       | CPZ | CP ZAMA, JAPAN         |
| GIS | GUANTANAMO BAY, CUBA  | FIN | FINEGAYAN, GUAM        |
| GND | LANDSTUHL, GERMANY    | FUT | FUTEMA, OKINAWA        |
| LAJ | LAJES AFB, AZORES     | TEG | TAEGU, KOREA           |
| LGO | LAGO DI PATRIA, ITALY | WOM | WOMERA, AUSTRALIA      |
| NWS | NORTHWEST, VA         | KWJ | KWAJALEIN, MI          |
| ELM | ELMENDORF AFB, AK     | SHE | SHEMYA, AK             |
| WHW | WAHIAWA, HI           | DEG | DIEGO GARCIA           |
| CPS | CP ROBERTS, CA        |     |                        |

|         |  |
|---------|--|
| USNO MC | U.S. NAVAL OBSERVATORY MASTER CLOCK                          |
| NOTSS   | NAVAL OBSERVATORY TIME SERVICE SUBSTATION, RICHMOND, FL      |
| PMEL    | PRECISE MEASUREMENT ELECTRONIC LABORATORY, ELMENDORF AFB, AK |
| TV      | CHANNEL 5 WTTG WASHINGTON, D.C.                              |
| ◊       | LORAN-C CHAINS   |

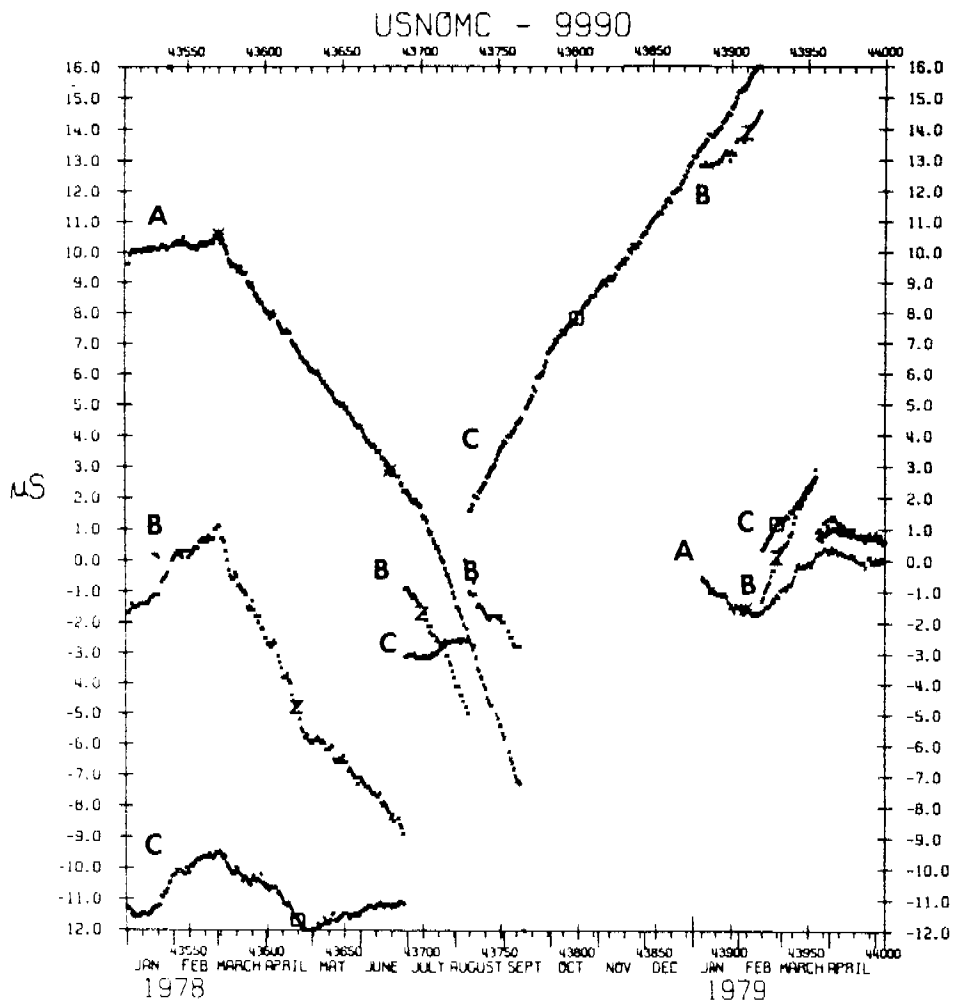


FIGURE 6

The trace labelled, A, is the difference between values determined a PTRS (Trace B) and those obtained from the time scale method (Trace C).

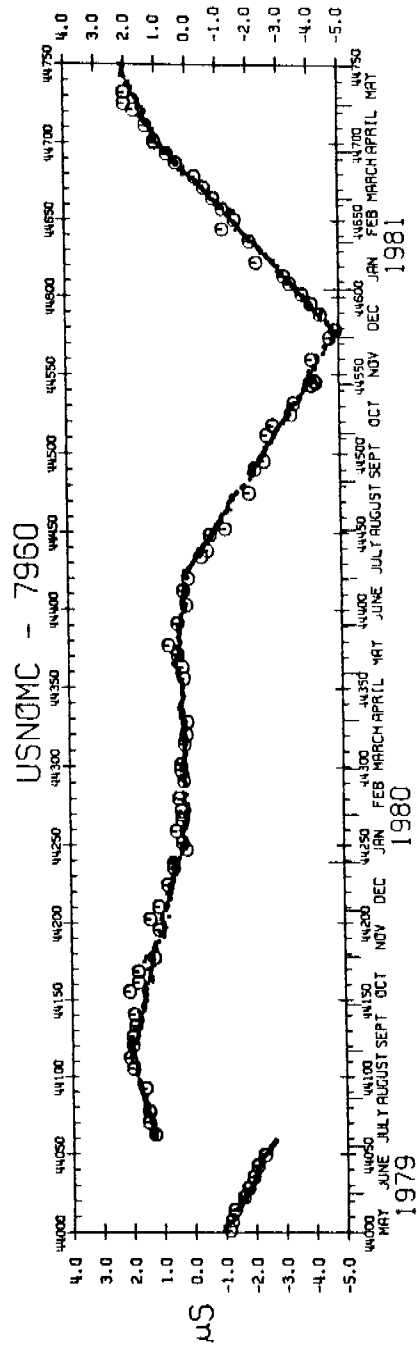


FIGURE 7

After the portable clock calibration discussed in the text, the 7960 chain was set on time and the values published since that time are those determined using the time scale method. The large symbols are calibration points obtained using DSCS time transfers.

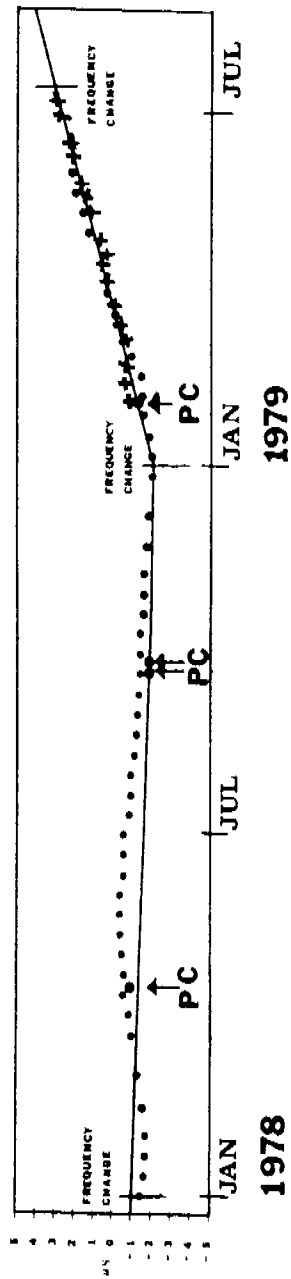


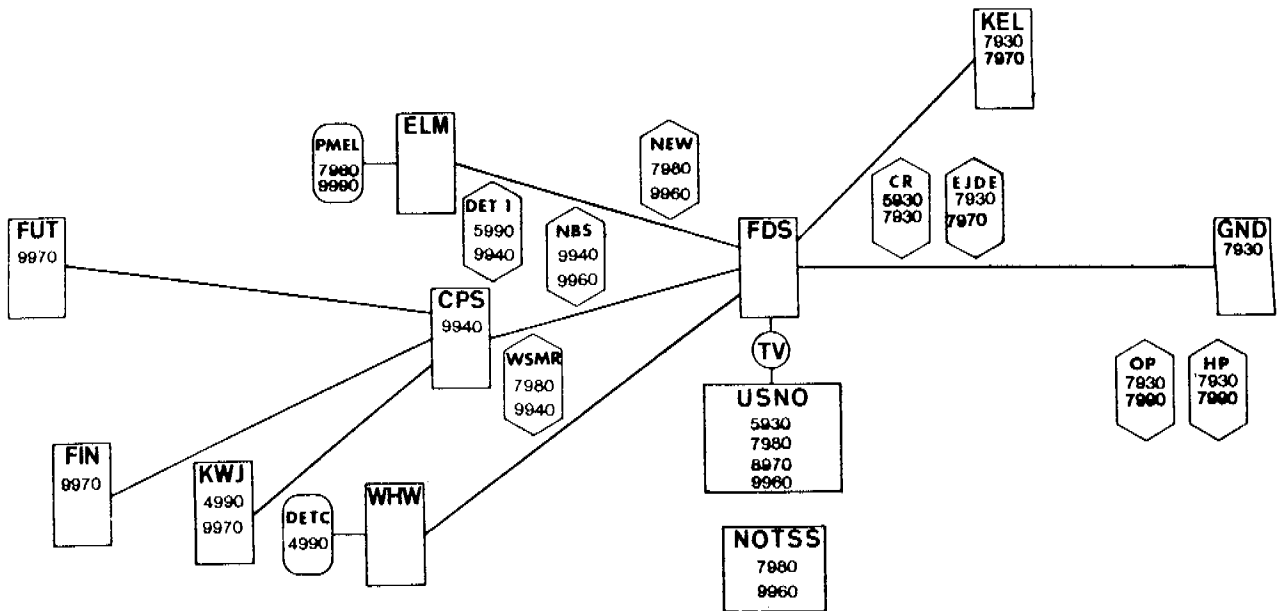
FIGURE 8

USNO MC - NBS

Four methods of determining the relationship USNO MC - NBS have been plotted:

- a) VIA A TIME SCALE - SOLID LINE
- b) VIA PORTABLE CLOCK - INDICATED BY ARROWS
- c) VIA BIH CIRCULAR D - DOTS
- d) VIA DSCS TIME TRANSFER - INDICATED BY + SIGNS

The frequency changes indicated were those made in the NBS time scale.



**RELATIONSHIPS: USNO, LORAN-C, DSCS**

FIGURE 9

**DSCS TERMINALS**

FUT FUTEMA, OKINAWA  
 FIN FINEGAYAN, GUAM  
 KWJ KWAJALEIN, MI  
 WHW WAHIAWA, HI  
 ELM ELMENDORF AFB, CA  
 CPS CP ROBERTS, CA  
 FDS FT. DETRICK, MD  
 KEL KEFLAVIK, ICELAND  
 GND LANDSTUHL, GERMANY

**NODAL POINTS**

DET1 FAIRCHILD AFB, WA  
 WSMR WHITE SANDS MISSILE RANGE, NM  
 NBS NATL BUREAU OF STANDARDS  
 BOULDER, CO  
 NEW AEROSPACE GUIDANCE METROLOGY  
 CENTER, NEWARK AFS, OH  
 CP U.S. COAST GUARD, CAPE RACE,  
 NEWFOUNDLAND  
 EJDE U.S. COAST GUARD, EJDE,  
 FAEROE IS.  
 OP PARIS OBSERVATORY, PARIS,  
 FRANCE  
 HP PTRS - HEWLETT-PACKARD CO.  
 GENEVA, SWITZERLAND

USNO U.S. NAVAL OBSERVATORY, WASHINGTON, D.C.  
 NOTSS NAVAL OBSERVATORY TIME SERVICE SUBSTATION, RICHMOND, FL  
 TV Channel 5, WTTG WASHINGTON, D.C.