REMOTE CLOCK CALIBRATION VIA GPS

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INTRODUCTION

During the summer of 1986, the United States Naval Observatory (USNO) equipped an automotive van as a Mobile Electronic Laboratory for a dual purpose experiment. The equipment consisted of LORAN-C receivers, counters, oscilloscope, two portable cesium clocks and a Global Positioning System (GPS) receiver. The first purpose was to calibrate the propagation delays and timing between USNO and the LORAN-C transmitters at Cape Fear, NC (9960Y), Seneca, NY (9960M) and Caribou, ME (9960W/5930M). The emitted LORAN pulses would be compared to a cesium portable clock as it was systematically moved away from the transmitter. Accurate positions in the vicinity of each transmitter could be obtained from survey markers in the area or determined by the GPS receiver at any desired location. While the GPS receiver was used to obtain positions for the LORAN part of the experiment, it was also used to monitor the performance of the cesium clocks (thus determining their rates).

As a second part of this experiment, the GPS receiver would be used in the same manner as a portable cesium clock at selected field installations to examine the operational feasibility of such an application of GPS receivers. At various sites the GPS receiver and one portable cesium clock were used to obtain measurements against each on-site clock. There were, thus, two independent methods used to determine the difference USNO Master Clock (USNO MC) minus Site Clock. This paper will address the second part of the dual experiment only.

Throughout the experiment, the same Datum Model 9390-5003 GPS single frequency (C/A) time transfer unit was used. Similar to the portable clock method, a calibration was made at USNO (before and after a trip) whereby the antenna of the travelling GPS unit was located near the antenna of the USNO GPS receiver, while each time transfer unit was being driven by the same clock (USNO MC). No special precautions were taken during the trip. For example, visits to field installations were done quickly. No testing involving several days of data collection was done at the field sites. As long as satellites were available , the GPS equipment was set up and broken down as quickly as possible - usually in about two hours. Sometimes data could be collected overnight - but this was not a requirement. When the GPS receiver was used as a replacement for a portable clock, it was intended to duplicate the cesium technique as much as possible. It was hoped that most problems encountered in the use of this technique would arise and possible solutions be determined.

While the experiment included measurements made at approximately a dozen sites, this paper will discuss the measurements obtained at USNO and the Defense Satellite Communication System terminals at Northwest, VA and Ft. Detrick, MD. Further analyses of data from these other locations will provide additional information about the application of a GPS receiver as a replacement for a portable clock.

OBSERVATIONS

Unlike traditional portable clock measures which typically involve a handful of readings made by a counter between two cesiums, GPS suddenly introduces a stream of data and various choices to be made. Such considerations as track mode (automatic vs. common-view) and length of averaging time quickly confront the user.

All measurements in this experiment were made with the Datum time transfer unit synchronized to GPS time. The data obtained consists of Cesium Clock minus Space Vehicle (SV), where Cesium Clock could be either one of the portable clocks carried on the trip or a clock at an installation. Values of USNO MC minus SV obtained at USNO are used with the above differences to determine values of USNO MC minus Cesium Clock.

The "common-view" method of tracking satellites simultaneously by USNO and the remote locations was used in making measurements about 25% of the time - usually while determining rates for the portable clocks in the Mobile Electronic Laboratory. Generally, the GPS receiver was left in an automatic mode to select whichever satellite was best suited geometrically. Indeed, all of the calibration visits to field installations used the automatic mode of satellite selection. If a common-view schedule had been adhered to, most measurements would have been obtained when the satellites were very low on the horizon. Due to the intent of simulating a portable clock trip, there was no requirement to collect data in a controlled situation such as common-view. Even track averaging times ranged from a few minutes to a couple of hours. However, for time calibration purposes at field installations, tracking times were kept to about 20 minutes.

REMOTE SITE TIME TRANSFER RESULTS

Two cesiums were used on the trip to Cape Fear, N.C. which lasted about one week. Portable Clock (PC) 1449 was used as a portable clock and PC 1710 was dedicated to the LORAN experiment. While GPS time transfers were made primarily against PC 1449 , readings were taken occasionally against PC 1710. In addition, counter readings between the two cesiums were taken daily which provided another check on the GPS measures. Figure 1 shows values of USNO MC - PC 1449 obtained at USNO before and after the trip as well as values obtained using GPS during the trip. Agreement with USNO direct measures on either side of the trip and GPS data is very good. Upon return of PC 1449 to USNO, there was a noticeable change in frequency although the PC performed well during the trip.

A similar plot of USNO MC - PC 1710 is shown in Figure 2, but with some additional data. The differences obtained using the GPS receiver as well as the differences obtained by reducing the PC 1449 - PC 1710 measurements to USNO MC are also shown. Both sets of data lie on a plane agreeing with the direct reading made at USNO before and after the trip. An unexplained frequency change and time step occurred in PC 1710 after its return to USNO.

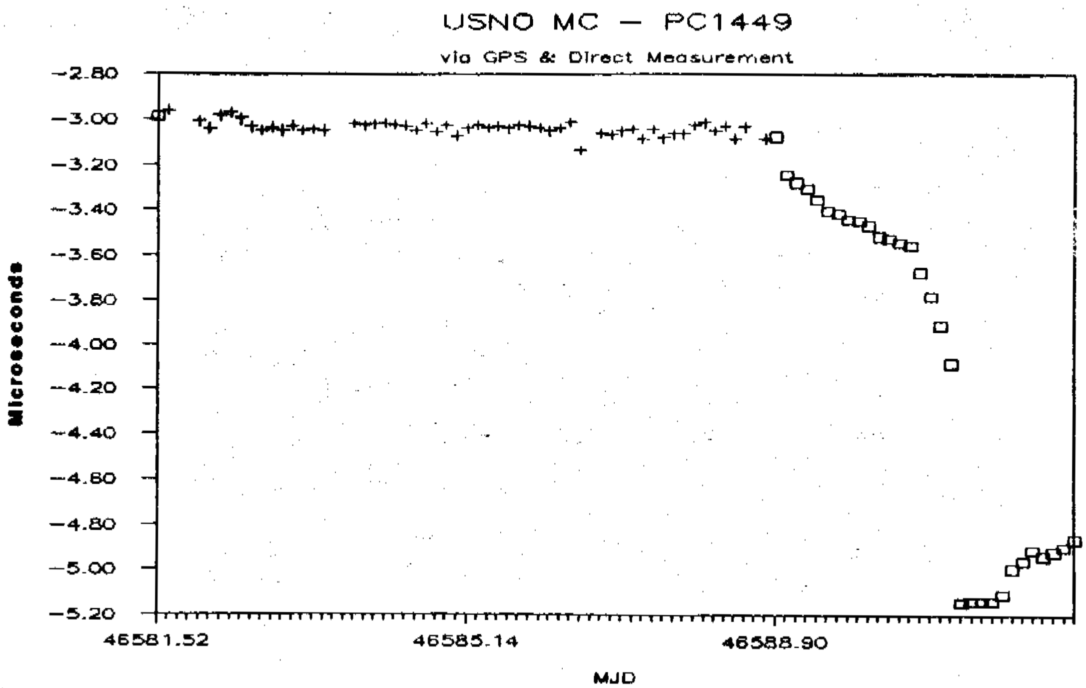

Figure 1— Square symbols indicate the direct measures made of PC 1449 while at USNO before and after the trip. GPS measures made during the trip were used to obtain values of USNO MC — PC 1449 and are shown by the plus symbols.

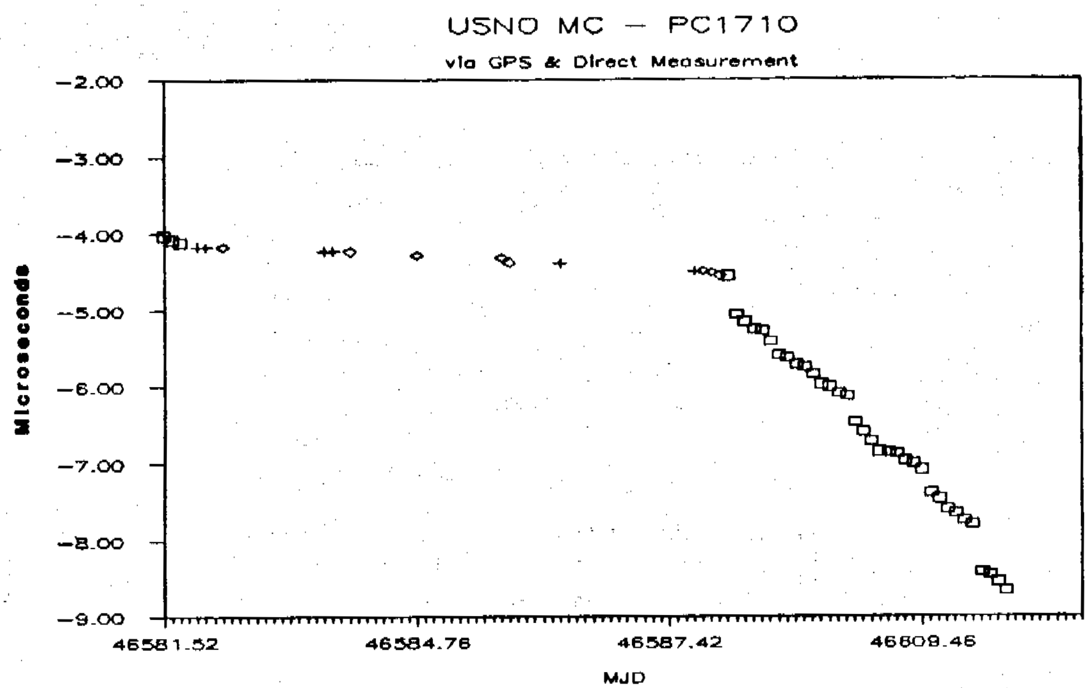

Figure 2 — Square symbols represent measures made at USNO. Plus symbols indicate values obtained using GPS measurements. Measurements of the differences between PC 1449 and PC 1710 were made during this trip. These measurements were used to obtain USNO MC — PC 1710 in the same manner as any other portable clock measurement. These values are represented by the diamond symbols.

Figure 3 is a high resolution plot of Figure 1 covering the trip portion and illustrating the spread in GPS measures. Generally, the scatter appears to be about ± 25 nanoseconds from data obtained. This effect will also be more evident in a later figure which was generated in a much more stable environment. Thus, barring any sudden changes in GPS reference time, a clock at a remote site could be immediately synchronized within 50 nanoseconds of USNO MC if required by local personnel.

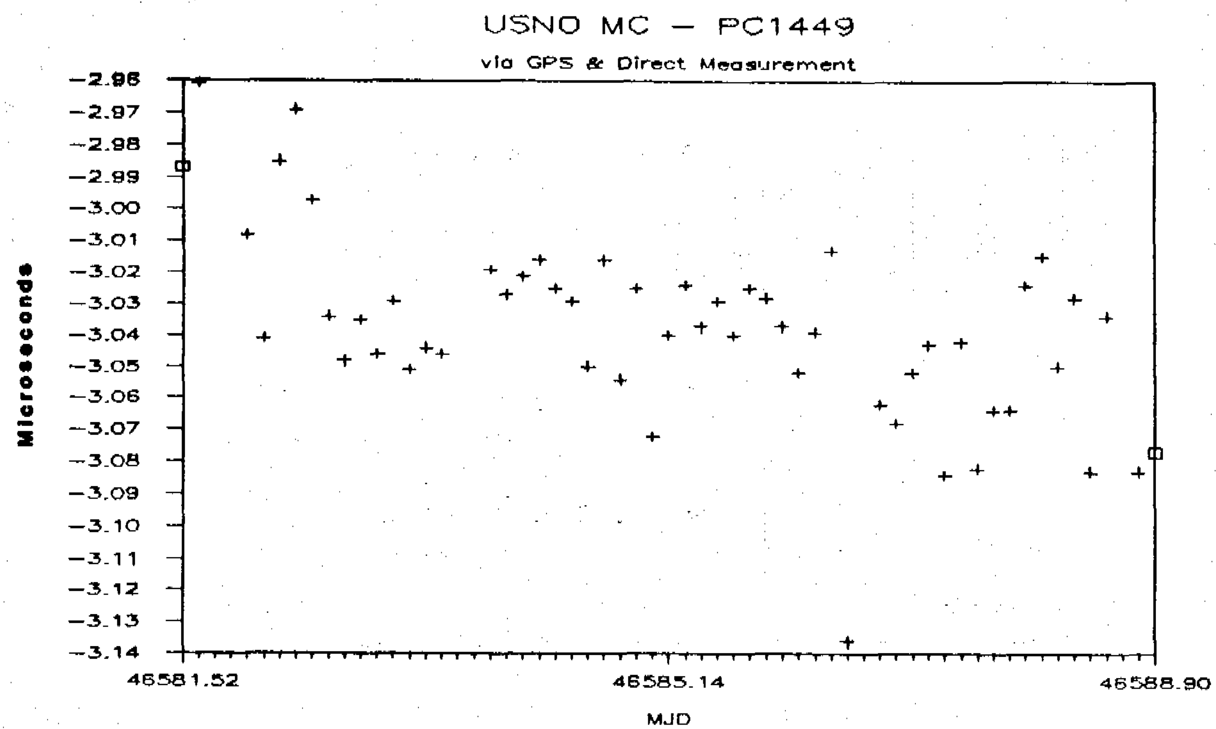

Figure 3 — High resolution plot of a section of figure 1 (while travelling) showing scatter in values of PC 1449 using GPS data. The two square symbols are direct measurements at USNO before and after the trip.

On the last part of the three week trip to Seneca, NY and Caribou, ME, PC 1710 became the only portable cesium clock available in the Mobile Electronic Laboratory due to the failure of the portable cesium designated for GPS field measurements. Figure 4 illustrates the two types of measurements used to obtain values of USNO MC - PC 1710. It can be seen that the performace of PC 1710 was subject to several frequency changes during the trip. In conventional portable clock trip reductions, the frequency offset between the portable clock and USNO MC is determined using the direct measurements made at USNO before and after the trip. Time accumulations are linearly applied to measures made at sites visited during the trip. However, Figure 4 shows that a straight line assumption is not always correct. Indeed, Figures 1, 2, and 4 show very clearly just how some portable cesiums perform during an extended trip when subjected to various types of handling and temperature changes.

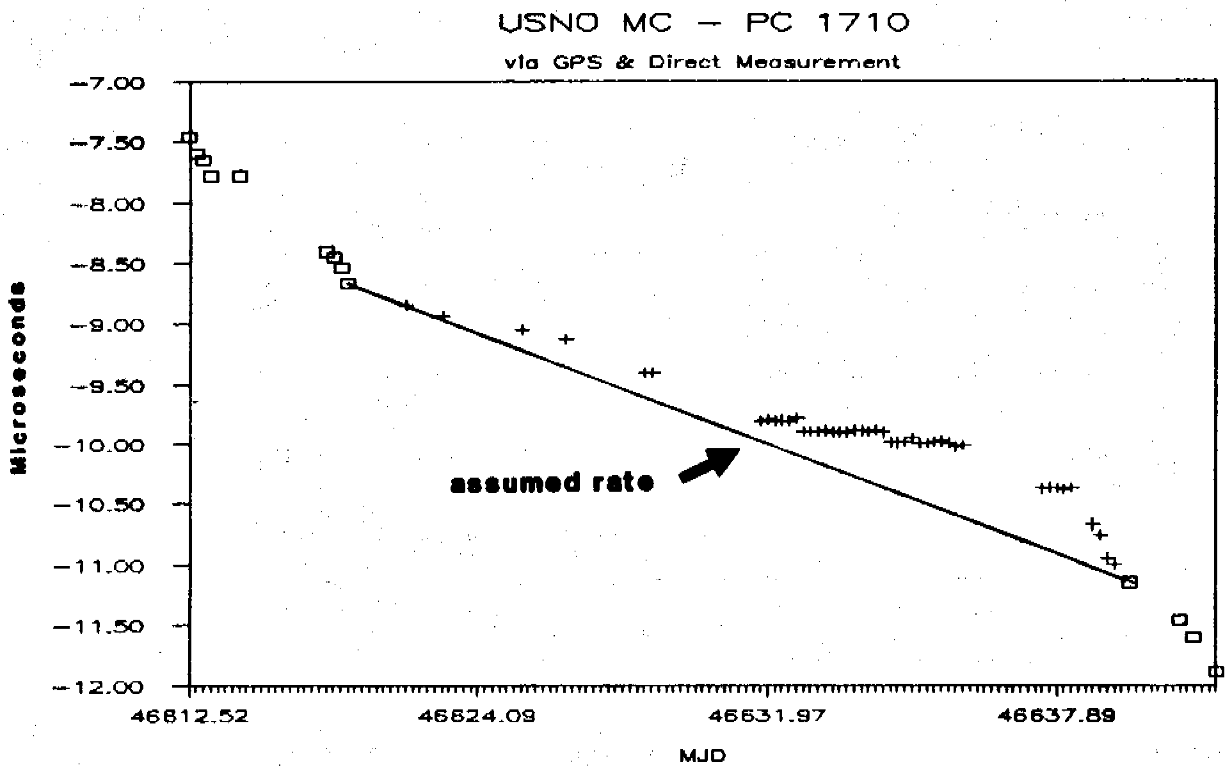

Figure 4 — Several changes in the rate of USNO MC — PC 1710 during the three week trip may be seen in the data represented by the plus symbols. The square symbols represent the differences of USNO MC — PC 1710 made by direct measurement at USNO prior to, and upon completion of, the trip. A straight line drawn between the beginning and ending points illustrate the assumed rate for PC 1710 during the trip.

Table 1 gives a summary of results for the clock comparisons made at Northwest, VA. It should be noted that the column headed PC - GPS shows a spread of approximately ±30 nanoseconds (with most differences substantially smaller) which agrees with the scatter in Figure 3. In addition, the GPS measurements were corrected to USNO MC by using a 3-day smoothed value (published in Time Service Announcement Series 4) for the date in question. This choice was made because of lack of common-view data. Indeed, for clock comparisons when common-view was available, there was no significant difference in the GPS correction when compared to the 3-day smoothed value. As can be seen, the agreement between the values obtained using GPS and PC 1449 at the Northwest station is very good.

TABLE 1
Time Measurements (in microseconds)
Northwest, VA
7 June, 1986

Cesium	USNO MC -Cesium: via PC	USNO MC -Cesium: via GPS	PC - GPS	SV	Satellite Observation Time (minutes)	Satellite Track Limits (degrees)
CS1167	-14.245	-14.236	-9	13	20	43-48
	-0.230	-0.262	32	13	20	49-54
CS1178	1.178	1.158	20	13	21	60-65
	0.172	0.159	13	13	19	66-67
CS1036	-7.194	-7.185	-9	13	20	67-63
	-1.188	-1.180	-8	13	25	61-52
CS1251	-0.820	-0.787	-33	11	32	55-49

Note 1: Cs1167, Cs1178 and Cs1036 were adjusted after initial measurements were made.

Note 2: Using data obtained from the straight line fit through the values of USNO MC - PC1449 at the beginning and the end of the trip, the value of Cs1449-GPS obtained at Northwest, VA was reduced to USNO MC. This difference, USNO MC-GPS = -0.271 microseconds, was then compared to the filtered 3-day value of -0.262 microseconds. This smoothed value was obtained from TSA Series 4.

A similar set of data is given in Table 2 for measurements made at Ft. Detrick.

TABLE 2
Time Measurements (in microseconds)
FT. DETRICK, MD
28 June, 1986

Cesium	USNO MC -Cesium: via PC	USNO MC -Cesium: via GPS	PC - GPS	SV	Satellite Observation Time (minutes)	Satellite Track Limits (degrees)
CS1181	1.336	1.323	13	13	10	42-38
	-0.665	-0.690	-25	13	4	36-35
	-0.431	-0.591	-160	13	7	27-24
CS1146	-2.816	-2.662	-154	13	12	12-7
	-0.118	-0.124	6	6	18	13-18
CS1015	0.322	0.286	36	9	6	36-37
	0.466	0.466	0	9	4	38-39

Note 1: Cs1181, Cs1146 and Cs1015 were adjusted after initial measurements were made.

Note 2: Using data obtained from the straight line fit through the values of USNO MC - PC1449 at the beginning and the end of the trip, the value of Cs1449-GPS obtained at Ft. Detrick, MD was reduced to USNO MC. This difference, USNO MC-GPS = -0.120 microseconds, was then compared to the filtered 3-day value of -0.154 microseconds. This smoothed value was obtained from TSA Series 4.

However, two large diffences in the PC - GPS column occur for CS 1181 and CS 1146. The large differences for CS 1181 occurs after two relatively small values. The large differences for both cesiums could be due to the low altitude of the satellite being tracked at that time. It is also possible that satellite altitude is not a factor at all; the large differences could be due to some type of interference. The Ft. Detrick area is known to have severe interference at times; otherwise, the data scatter appears to resemble that of Table 1.

During the Fall of 1986 CS 1013 was sent to USNO for evaluation. For the evaluation process, the cesium clock was placed in an environmentally controlled area not subject to undue vibration. During this period direct measurements with USNO MC were made on a daily basis using counter readings and the GPS measurements were made using the USNO common-view schedule. Figure 5 shows the data scattering roughly ±25

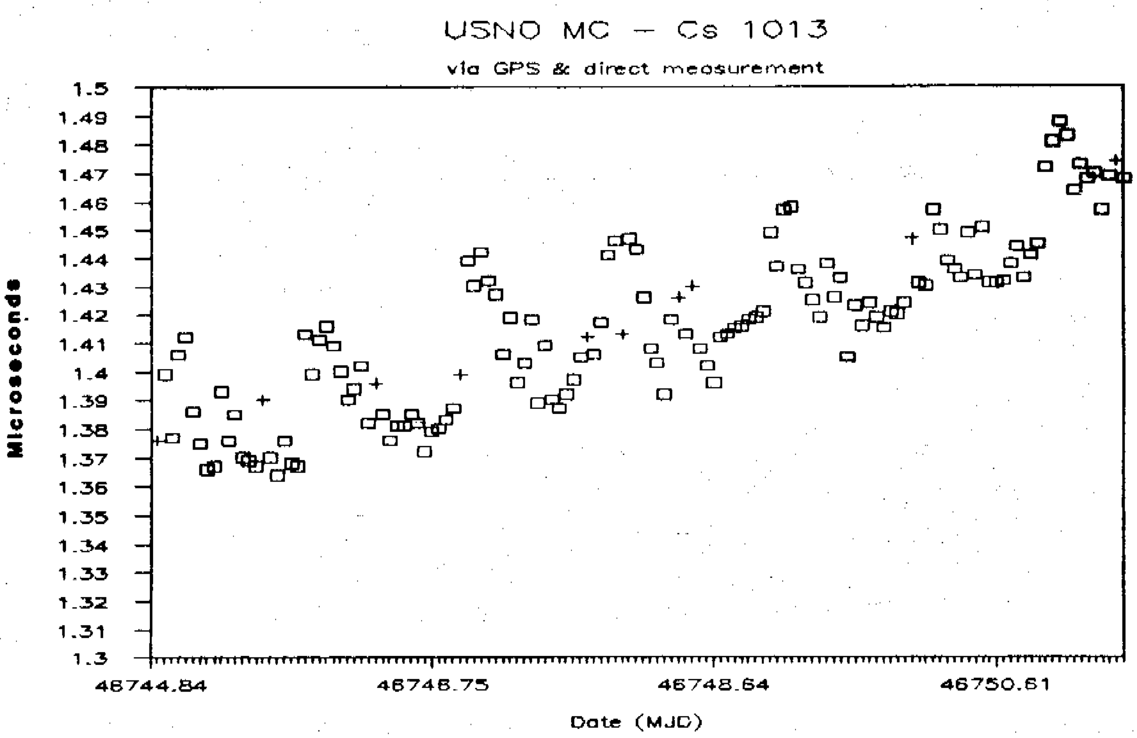

Figure 5 — The square symbols are the differences of USNO MC — CS 1013 obtained using GPS. The plus symbols are the direct measurements of USNO MC — CS 1013.

nanoseconds about a line drawn through the direct measures. This scatter is about the same order as shown in Figure 3 and Tables 1 and 2. The difference is that Figure 5 was generated using a common-view schedule exclusively. Figure 6 is the some plot but with the observations above and below 45^0 indicated. It appears that measurements obtained using satellites with an elevation of greater than 45^0 are generally more negative than those obtained using low altitude satellites.

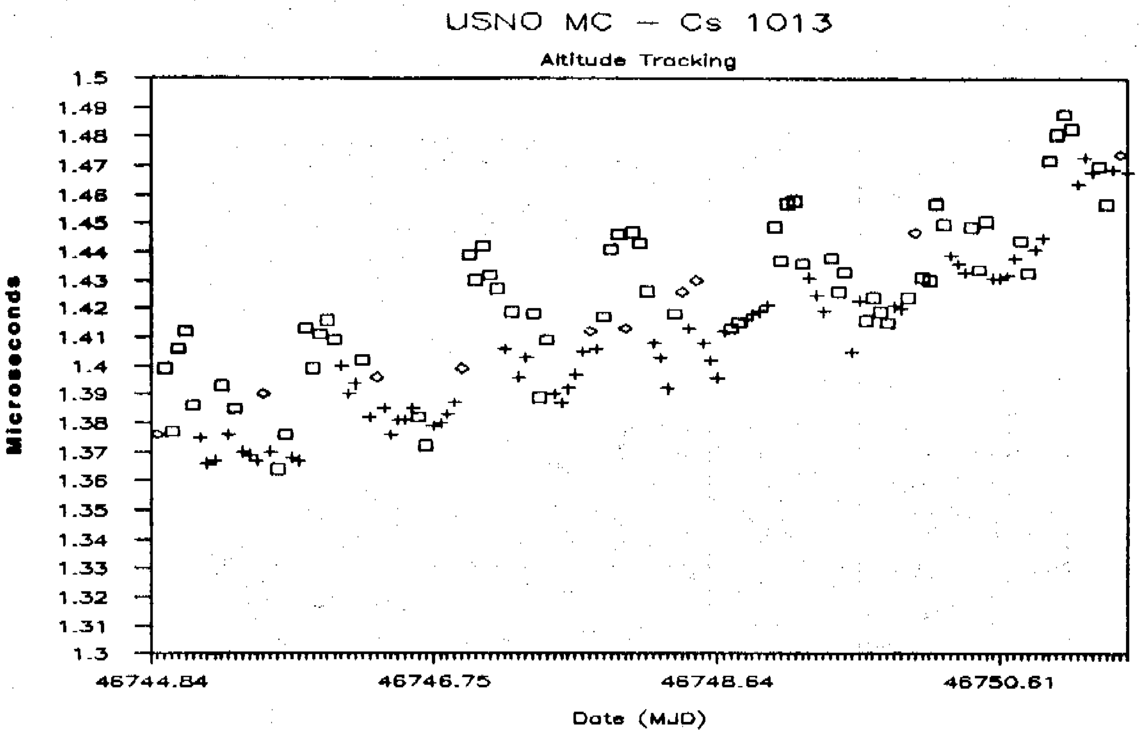

Figure 6 — The square symbols indicate the difference USNO MC — CS 1013 obtained from GPS measurements when satellite elevation was < 45 degrees, while the plus symbols are obtained from tracking GPS satellites when the elevation was > 45 degrees. Diamond symbols are the direct measurements of USNO MC — CS 1013.

DISCUSSION

The main thrust of this experiment was to evaluate a technique for replacing the traditional method of portable clock trips in disseminating precise time. This evaluation was to include not only the accuracies but the practical operational problems which could arise when using GPS receivers instead of portable cesium clocks.

It is clear that better than 50 nanosecond accuracy can be achieved for GPS field operations using the Datum 9390-5003 time/frequency monitor. With the exception of places such as timing laboratories, this type of accuracy will more than exceed most station requirements. This accuracy is achievable without any special procedures such as common-view. While common-view observations of the same satellite can result in high precision time transfer, it is not always practical to observe such a schedule on a clock trip. The satellite may be too low on the horizon or may be set "unhealthy". The travellers own schedule may not permit the time to wait for common-view availability. When the full complement of GPS satellites are orbiting the Earth, some of these considerations will not be as important.

On the practical side, using a GPS receiver does give rise to some considerations, namely:

A. Antenna Position - Any blockage of the antenna by trees, buildings, etc. will cut off satellite reception. Therefore, it is desirable to have the antenna mounted on a roof or in a large open area for unobstructed reception. A small tripod was found to be adequate for mounting the antenna.

B. Building Structure - In order to run the cable from the receiver to the antenna, access is needed to the outside such as through windows, etc. In some cases clock calibration trips are made to installations with security requirements which prohibit open windows or doors. Clock trips to naval vessels often result in cramped, sealed off areas.

C. Satellite Availability - With the current satellite configuration, there are extended periods when no satellites are available. This introduces delays.

D. Site Coordinates - Unless a well-known position has already been established at a field station, a position must be determined by the GPS receiver before any time transfers can be acccomplished. If a position determination is necessary, approximate coordinates (good to ±0.5 degree) must be available. Position determination requires four satellites.

E. Automatic vs Common-View Tracking - Common-view observations may not always be possible or even desirable. Field operations which involve quick set-ups and break-downs lend themselves better to the automatic mode whereby the GPS receiver selects the best satellite available for time transfer. Common-view observations should be made when possible.

F. Time Required - Setting up the GPS equipment and doing the time transfer can take longer than the usual cesium operation - antenna positioning and satellite availability being the chief problems. However, delay time will be considerably reduced if preplanning with regard to obtaining station coordinates and satellite passage times is done. Further efficiency will be gained in the future when sites are revisited (good positions will usually be available the second time around and the running of cabling to distant antenna locations will become more routine). An increase in the number of satellites will also reduce the time required.

Some of the features which make field use of a GPS receiver attractive include:

A. Portability - The GPS receiver, tripod, antenna, and cable weigh approximately 58 lbs. while a portable cesium clock with a time interval counter and tool bag weigh 180 lbs.

B. Power Requirements- The GPS time transfer unit has only one power need - while making measurements at the site itself. The receiver can travel as baggage (without continuous power) whereas a cesium portable clock must be kept "hot" for the entire trip.

C. Personnel - Generally only one person is required.

D. Cost and Accurcy - Use of GPS receivers will be more cost effective and inherently more accurate than the use of portable cesium clocks on long trips.

CONCLUSION

The traditional portable clock trip is currently in a state of flux. As the GPS system evolves, fewer calibration trips will be required and, of these, even fewer will require the use of a portable cesium clock. Instead, a light weight satellite time transfer unit will be used. However, given the scatter in GPS data as seen during this trip, measurements obtained using a good portable cesium clock are more accurate (a few nanoseconds) on trips of less than two days duration. On long trips, a portable cesium clock's accuracy can degrade several hundred nanoseconds. It is clear that GPS is more effective and will become more useful as a high precision method for synchronizing widely separated clocks.

ACKNOWLEDGEMENT

The authors are grateful to Ms. F. Neville Withington who gave generously of her time and expertise in matters concerning the preparation of the graphic material presented in this paper.

QUESTIONS AND ANSWERS

GERNOT WINKLER, UNITED STATES NAVAL OBSERVATORY: Two comments; number one, your experience at Ft. Detrick points out a practical difficulty for which one has to watch out in some locations. On the basis of many years of simultaneous TV reception experiments with Ft. Detrick, we know that the reason for some wild outliers is that the station, which has a high power transmitter, for several satellite antennas, at some times produces a very high field strength of interference. So, I have no question why at Ft. Detrick you have these outliers, two out of seven or eight observations. The receiver is, of course, spread spectrum, but it can be saturated if you right next to a very high power transmitter. My second comment; I am afraid that I am going to develop a similar reputation to the one I had many years ago when I argued about hydrogen masers; the common view is possibly today a good method for intercomparing stationary, well equipped laboratories. But, in your case, I would caution you not to do it because unless you know about these biases mentioned repeatedly by Mark Weiss and take them into account, just taking common view out in the field where you cannot guarantee that you start and stop at exactly the same moment, is a very dangerous thing. You would be much better off in not doing that. I believe that the right procedure, on the basis of some tests that I have made myself, is to use the averaged data over as many different satellites as you can get, particularly if your requirements are no more than 50 nanoseconds or so. Since these biases are usually less than 50 nanoseconds you should be safe. It is much less work and much less source for error and does not convey that false sense of security that you have a high precision measurements.

MR. LUKAC: We have already told George Luther, who is in Europe right now, not to track so much in common view but to try to get the high elevation satellites, use the automatic receiver mode, try to get several satellites, but don't go to common view, which may not be the best. We are finding this out more and more so I agree with you on that point.

HENRY FLIEGEL, THE AEROSPACE CORPORATION: The on advantage of common view, though, is that if the selective availability comes to pass as we all fear, then David Allan and others feel that common view will probably enable you to evade what is put on the clock. Although I agree with Dr. Winkler's comment for here and now, that is that averaged data may suit your purpose, we would like to see as many people go into the common view as possible.

MR. WINKLER: I still disagree!