PRECISE TIME TRANSFER USING MKIII VLBI TECHNOLOGY

K. J. Johnston, J. A. Buisson, M. J. Lister, O. J. Oaks,
J. H. Spencer, W. B. Waltman,
Naval Research Laboratory
G. Elgered, G. Lundqvist,
Onsala Space Observatory
A. E. E. Rogers,
Haystack Observatory
T. A. Clark, C. Ma,
NASA-GSFC
A. C. Johnson, K. Kingham, W. J. Klepczynski, G. Luther,
A. J. Kubic, and D. D. McCarthy,
United States Naval Observatory

ABSTRACT

It is well known that Very Long Baseline Interferometry (VLBI) is capable of precise time synchronization at subnanosecond levels. This paper deals with a demonstration of clock synchronization using the MKIII VLBI system. The results are compared with clock synchronization by traveling cesium clocks and GPS. The comparison agrees within the errors of the portable clocks (± 5 ns) and GPS (± 30 ns) systems. The MKIII technology appears to be capable of clock synchronization at subnanosecond levels and appears to be a very good benchmark system against which future time synchronization systems can be evaluated.

INTRODUCTION

The VLBI technique is quickly maturing. The positions of many antennas are now known to a few centimeters, celestial sources to ∿ 2 milliarcseconds, and corrections for the ionosphere and atmosphere are approaching the 1 cm level. This technique has essentially an all weather capability. Therefore if the instrumental delays are understood, as in the case of the MKIII system, there is no reason why one can not synchronize clocks at subnanosecond levels with only a few minutes of data.

The synchronization of clocks via VLBI has been the subject of many papers at PTTI meetings in the past. This measurement is simply the difference in time of arrival of a "noise" signature from a celestial radio source which is located at cosmological distances. These sources may be looked upon as fixed radio beacons in the sky. Counselman et al. (1977) pointed out that from a few minutes of data using a priori knowledge of the baselines, source positions, etc., the delay differences scattered by an rms of 2 ns for continental U. S. baselines. After estimating two earth rotation parameters, and an average clock rate difference, the "formal" scatter was reduced to subnanosecond levels (Counselman et al. 1977). In order to verify the accuracy of VLBI, two experiments were performed on March 28 and September 23, 1977 by Clark et al. (1979) in which observations were made in eight 360 kHz bands distributed between 8.4 and 8.5 GHz which resulted in "formal" synchronization below a ns. In this experiment careful corrections were made of the contribution to delay by the antenna feeds, receiver systems, and recorders, yielding absolute determinations of the clock epoch differences. Portable clocks from the U. S Naval

Observatory were taken to each site and the travelng clock data agreed to within 18 and 14 ns.

NEW TECHNOLOGY DEVELOPMENTS

The development of the Mark III VLBI system (Rogers et al. 1983) offers an improved design for clock synchronization in that the delays in the electronics and cables can be measured quite easily and changes in the delays are monitored.

The delay in the cables connecting the receiver at the focus of the antenna to the recording system are monitored. These cable lengths are sometimes of one hundred meters in length and are far from identical among antennas involved in VLBI experiments. The change in delay for cable length at Maryland Point Observatory for an experiment performed on October 18, 1982 amounted to approximately two nanoseconds. In an earlier experiment using MKII VLBI technology, there was a 59 ns difference between time synchronization when compared with portable clocks. This was well outside the errors attributed to either technique and was ascribed to an epoch difference between the MKII VLBI formatter and the station clocks (Spencer et al. 1981). This problem would not be encountered with the MKIII system.

THE VLBI EXPERIMENTS

A series of experiments were performed between NRL's Maryland Point Observatory, NEROC's Haystack/Westford Observatory and the Onsala Space Observatory in Onsala, Sweden. Experiments were performed on June 19, October 18, and November 23, 1982 and August 29, 1983. These experiments were always performed following a POLARIS measurement which are twenty-four hour measurements made to measure earth rotation parameters. The initial experiments in June and October 1982 established a reliable baseline between the 85' antenna of Maryland Point Observatory and the antennas of Westford/Haystack and Onsala. Figure 1 shows the locations of these antennas. The data were recorded in the standard POLARIS scheme (Robertson and Carter 1982) which has 14 frequency channels of 2 MHz width, 8 at X band between 8210.99 and 8570.99 MHz and 6 at S band between 2215.99 and 2300.99 MHz.

The delays associated with the antenna geometry and feeds were estimated. The delays due to cable lengths, receiver front end and back end, and tape recording system were measured during the experiments. The data was correlated at Haystack Observatory. The data was further analyzed at the Goddard Space Flight Center where the ionospheric delay was removed by differing the S and X band data. The X band data were used to estimate the delay. After adopting source positions, baselines, and correcting for the tropospheric delay using a model atmosphere, the delay epoch and an average clock rate were solved for along with an offset for Universal Time and polar motion. It was found that the formal error in the solutions accumulated around the time of the epoch of the solution. This 95% confidence level of the "formal" delay for the Westford-Maryland Point baseline was below the nanosecond level. The errors accumulate as a function of time around the solved for epoch. This is due to the frequency rate offsets between the oscillators used to generate the local oscillators at each site. An accurate assessment of the errors for an individual observation are given in Table 1. These do not include errors due to oscillator drift. Figure 2 shows the delay residuals for the 29 August 1983 experiment for the Maryland Point-Westford baseline. These residuals allow us to evaluate the "formal" error which is at the 0.4 nanosecond level. However for these measurements we have carefully accounted for the system delays at all the sites.

These are believed to be at the nanosecond level. Therefore these measurements are of the absolute delays between the sites at the nanosecond level. Improvements need to be made to reliably measure waveforms at the subnanosecond level.

Table 1

VLBI Error Sources

Position Location (2 cm)	0.07 ns
Atmosphere/Ionosphere Delays (2 cm)	0.07 ns
Receiver Delay	0.1 ns
Receiver Noise	0.01 ns
Source Position Error (QSO) (0″.001 over 7000 km)	0.1 ns

COMPARISON

In order to determine the absolute accuracy of the VLBI technique, portable clocks were dispatched successfully to the Maryland Point and Westford antennas for the last two experiments. For the August 1983 experiments, measurements were made using GPS receivers. Figure 3 shows a schematic representation of the experiment for August 1983.

GPS Receiver

The NRL GPS receiver provides precise time measurements of less than 50 ns between remote station clocks and the U. S. Naval Observatory time standard. The receiver measures directly the difference between a NAVSTAR satellite clock and the remote ground station clock. Data transmitted from the satellite allow computation of the difference between the satellite clocks and the U. S. Naval Observatory time standard.

The basic measurement of the receiver is a phase difference between the satellite clock and a user clock as measured on the ground through the satellite signal. This phase difference, referred to as pseudo-range, contains the phase difference of the two clocks and the phase difference due to propagation delay of the signal. The satellites transmit orbital data which allow software in the receiver to compute the precise position of the satellite. The ground position is precisely known and a theoretical distance to the satellite is computed. The propagation delay of the signal is computed directly from the theoretical distance, with ionospheric and tropospheric effects calculated from a model. These delays are subtracted from the pseudo-range phase measurements and the results are the phase difference between the satellite and the ground clocks.

Common measurements were made on August 29, 1983 when NRL GPS receivers were co-located at Maryland Point and Haystack/Westford observatories. Due to problems with initially implementing an experiment at remote field sites, reliable data were obtained on only one day. This difficulty made it impossible to fit the clock rate to the data. Only nearly simultaneous satellite passes were used. These are listed in Table 2. The average delay between Maryland Point and Haystack/Westford had an rms of 15 ns which is not very significant since there are only four data points. However this gives us some confidence that the data is reliable.

Table 2

Summary of GPS Time Transfer

Day no.	NAVSTAR no.	TIME (hrs:min:sec)	MPT -GPS (μsec)	TIME (hrs:min:sec)	HAY -GPS (μsec)	HAY -MPT (μsec)
241	4	20:08:57	-5.554	20:07:57	-1.653	3.901
241	3	21:17:09	-5.550	21:06:57	-1.676	3.874
241	6	23:02:15	-5.509	23:07:57	-1.648	3.861
242	5	00:57:39	-5.514	00:32:57	-1.645	3.869

In order to evaluate the accuracy of this data, Table 3 presents the sources of error in these measurements. By and far the largest source of error is due to the fact that we have made a very small number of measurements and cannot solve for the clock drift between the two stations.

Table 3

GPS Time Transfer Error Sources

Source	Expected Error
Ionosphere/Troposphere	5-15 ns
Ground Position	10-15 ns
Small Number of Measurements and Frequency Offsets between Station Clocks	15-30 ns
Satellite Ephemeris	5-10 ns

Portable Clock Measurements

Portable clocks were transported from USNO to the Haystack/Westford and Maryland Point observatories for the last three experiments and to Onsala Observatory for the final experiment. There was a clock jump of 190 ns for the portable clock transported to the Haystack/Westford Observatory in October 1982. There was also a clock jump during the Onsala measurement. Thus data were deleted. The last two clock trips to Maryland Point and Haystack/Westford were successful. Figure 4 displays the residual "time" versus the USNO master clock after a linear drift rate has been removed for the portable clock used for the August 1983 Maryland Point measurement. The VLBI experiment was performed on modified Julian Date of 45575.6 which is marked by an arrow in figure 4. Thus one can see that if a polynomial is fit to the data and the clock is not away from the master clock for periods longer than a day, one should probably approach an accuracy of better than 5 ns in clock synchronization. This accuracy was shown to be achievable by Spencer et al. (1981) who compared four clocks which continuously traveled between VLBI sites for a period of a week.

Comparison

Table 4 shows the comparison between the VLBI portable clock and GPS results. The VLBI measurement has been extrapolated to the time of the portable clock and GPS measurements. This clock synchronization is the difference in the clocks at the VLBI sites. This agrees to within 2 ns of the portable clock measurements and within 28 ns of the GPS measurement. The earlier measurement in November 1982 showed agreement between the VLBI and portable clocks of 2 ns. Thus these measurements are within the errors expected. These measurements are very promising but are only two data points in the case of portable clocks and only one measurement in the case of the GPS comparison.

Table 4
Time Transfer Between VLBI Stations
(Haystack-Maryland Point)

Day	UT	VLBI	GPS	Portable Clock	Δ
241	18^h00^m	3.891 μs	———	3.889 μs	2 ns
241	22^h21^m	3.814 μs	3.787 μs	———	28 ns

FUTURE IMPROVEMENTS

These measurements have shown that improved "station" clocks could help all three techniques of time synchronization. The difficulty in extrapolating time synchronization from one epoch where it was measured by VLBI, GPS, or portable clocks to another later or earlier epoch depends entirely on the reliability and modelability of the station clocks. The clocks are usually located at field sites as at VLBI stations where maintenance may not be ideal or as in the case of portable clocks, they are exposed to non-ideal conditions as they are moved from one site to another.

The GPS data can be vastly improved by taking a more extended data set, i.e., data obtained over several days in order to remove clock drifts, etc. Improvements can also be made in the electronics. In addition, simultaneous satellite passes should be used for the synchronization as was done here. Improved corrections can be made for the ionospheric and tropospheric delays. In this way the only major cause of error would be the satellite positions.

Finally improvements must be implemented to measure waveforms at subnanosecond levels. This applies to all techniques of time synchronization. With improvements in the GPS method, a series of experiments should be performed to obtain a larger data set to evaluate the accuracies of these techniques for time synchronization.

FUTURE USE OF VLBI

The VLBI system is capable of subnanosecond time synchronization with MKIII technology. It is difficult at this time to see an operational use for this accuracy. The need to use large antennas (in this case about 100-200 tons each) to obtain the signal-to-noise necessary when using natural celestial sources makes this system less than portable. In cases where time synchronization between sites with large antennas is wanted this may be practical. However at this time, the major use of VLBI should be as a benchmark system against which to evaluate other systems.

A CHALLENGE

The successful time synchronization experiments between the Maryland Point, Haystack/Westford and Onsala Space Observatory shows that these stations can perform these experiments with a minimum of instrumental development. These stations therefore provide an excellent testbed for future precise time synchronization systems. Therefore we challenge any precise system (< 10 ns) to an evaluation against the VLBI technique using these baselines.

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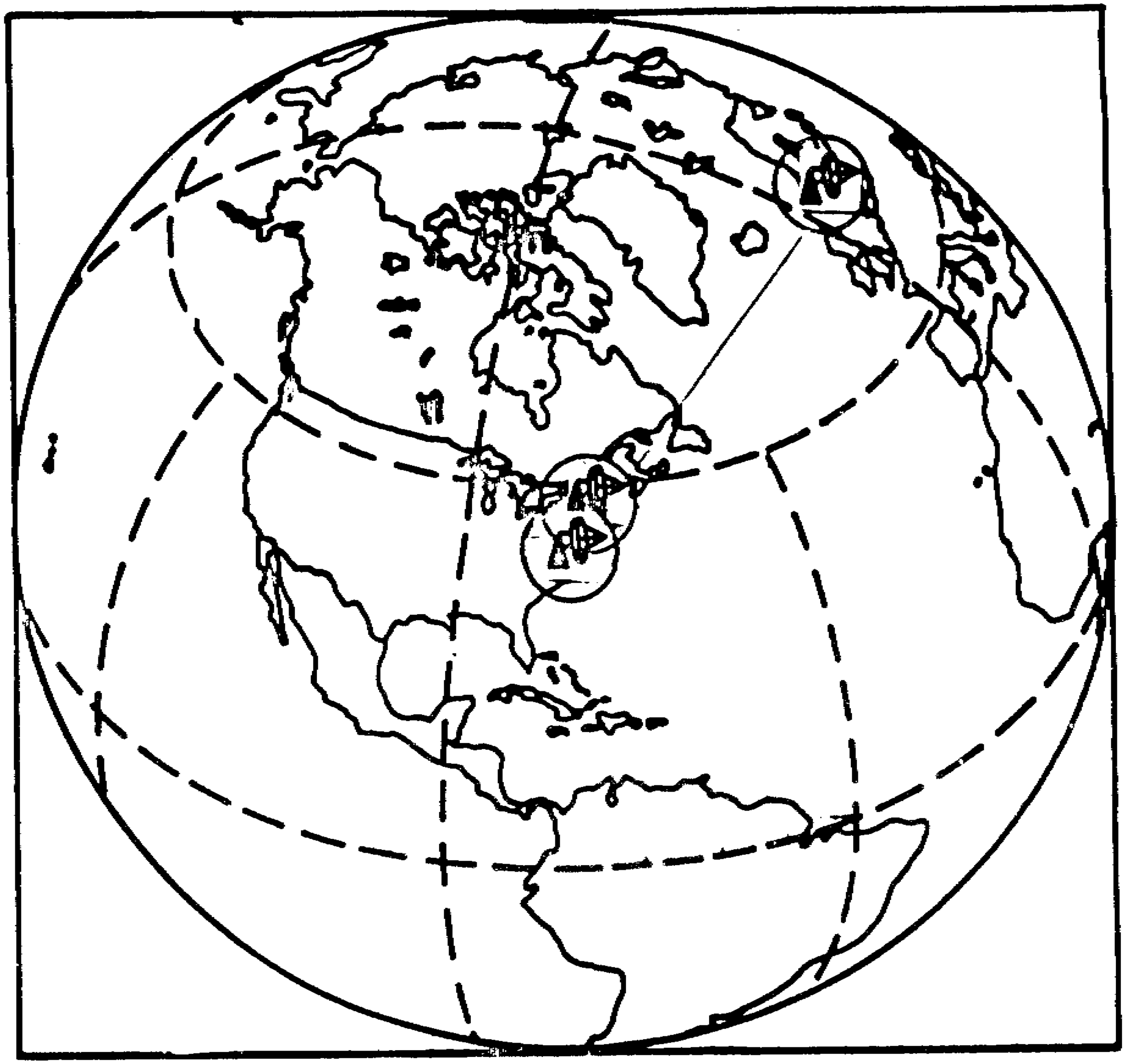

Figure 1 - The location of the Maryland Point, Haystack/Westford, and Onsala Space Observatories.

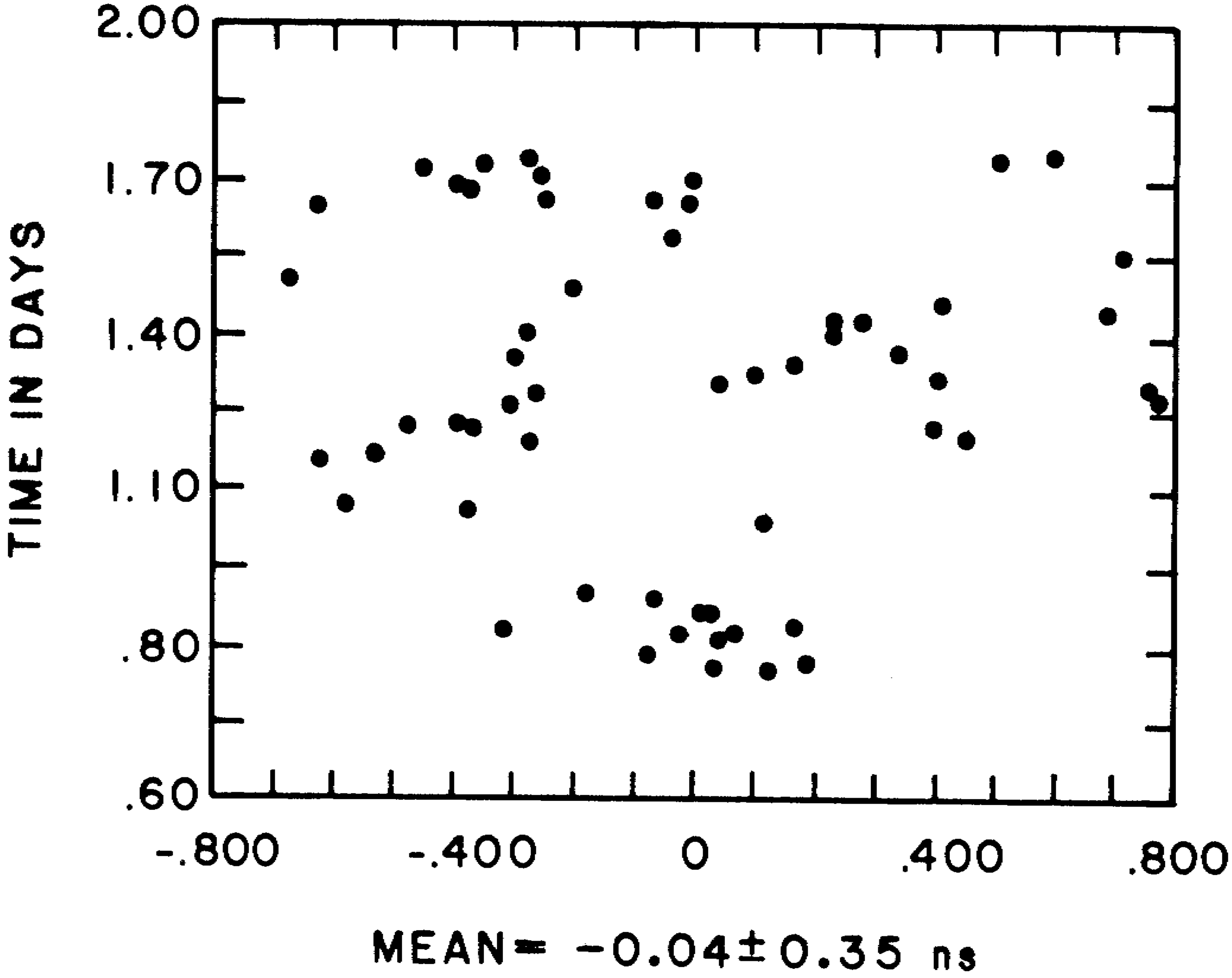

Figure 2 - The delay residuals for the Maryland Point-Westford baseline after the clock epoch and drifts have been removed from the data. The mean is 0.04 ns with an rms scatter of 0.35 ns.

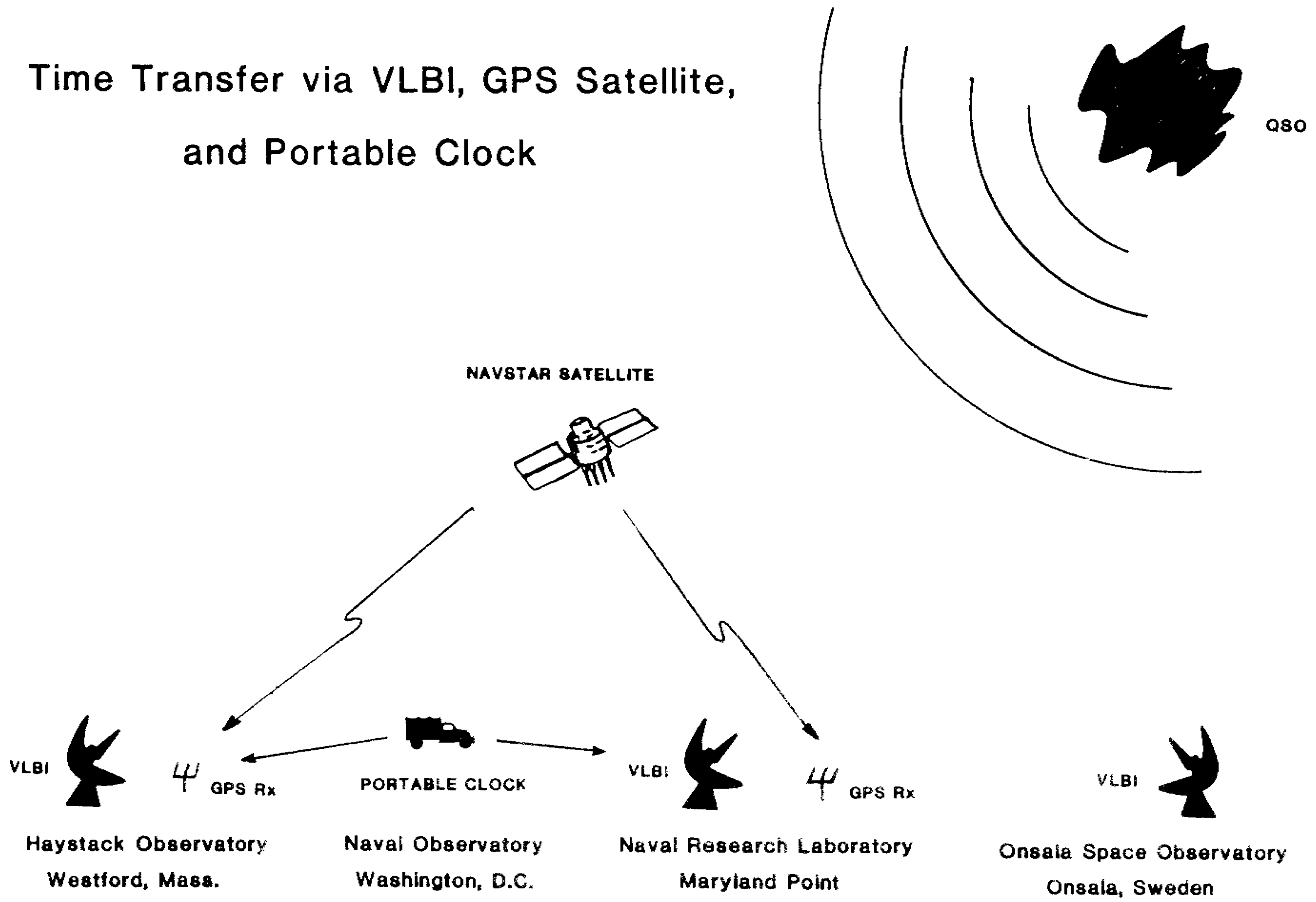

Figure 3 - Schematic representation of the August 29, 1983 experiment which compared VLBI, portable clock, and GPS techniques for precise clock synchronization.

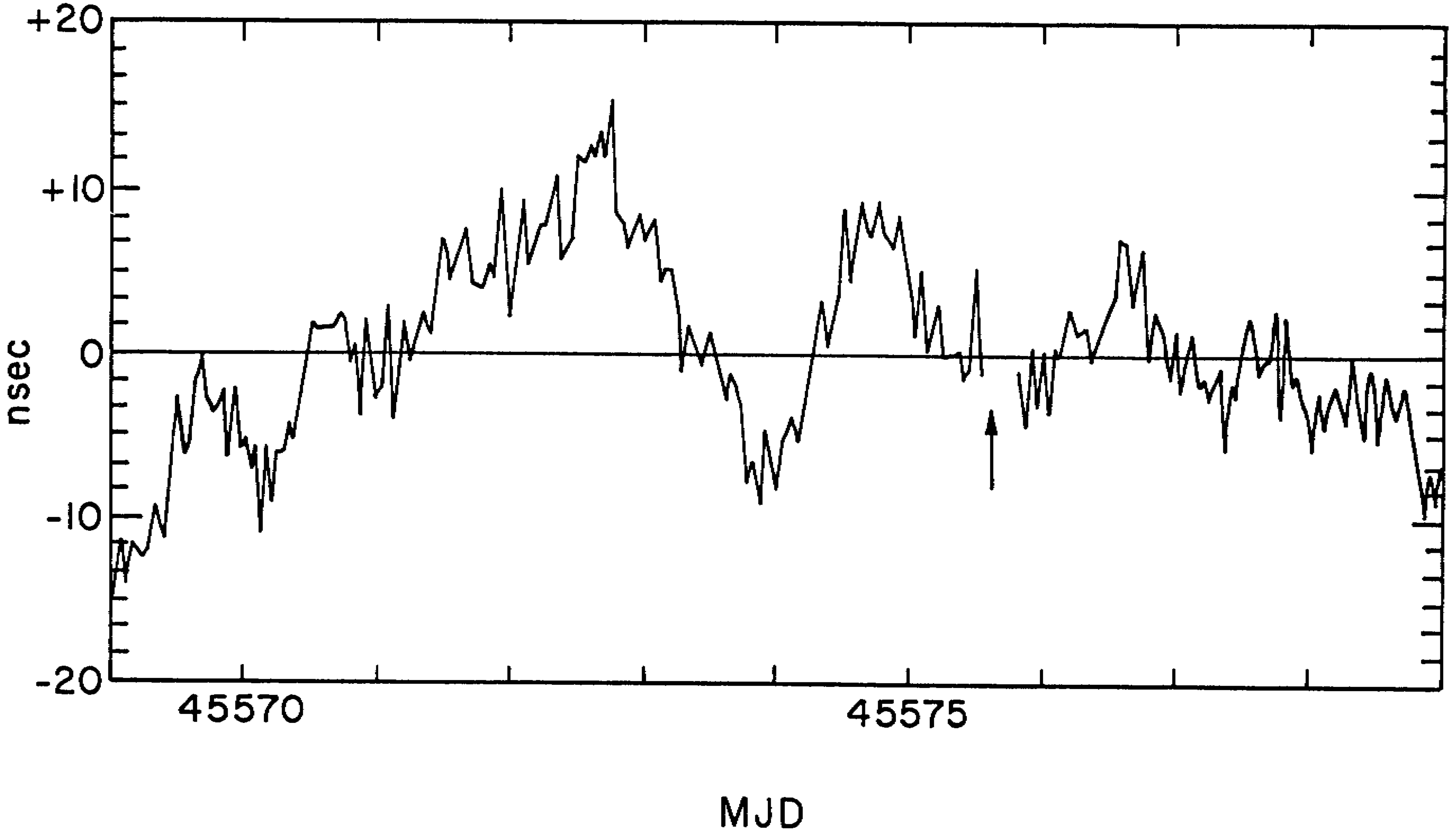

Figure 4 - The residuals in ns for the portable cesium clock used to transfer time between the USNO Master Clock and Maryland Point Observatory for the August 1983 experiment. A linear drift has been removed from the portable clock residuals. The time is in Modified Julian Days. MJD 45575 is 0^h UT on August 29, 1983. The arrow denotes the time synchronization at Maryland Point.

QUESTIONS AND ANSWERS

DR. WINKLER:

You are complaining about your oscillators, but I must say that none of the sites which I have seen takes proper care of them. It's the conditions of operation which ought first to be improved; and when I say that, I mean to include power supplies, public power. As you probably don't realize, if the input voltage changes by one volt, it will produce a frequency change in your maser later on, and if your temperature changes, it will produce phase shifts. You are talking about fractions of a nanosecond, and these things have to be considered as error. Second comment: A portable clock properly operated, and I think ours are, does not jump around. It develops rate changes, and it develops these changes particularly under the impact of temperature, exposure, and so on, but, of course, the portable clock will never be able to compete, certainly, with the ones now, with the precisions that you have mentioned of a few nanoseconds.

The benefit of the portable clock is that it is very convenient, can be sent almost anywhere and you do not have to calibrate delays, and this is something which has been completely ignored or is not mentioned. This brings me to the 3rd point; today where we had Mr. Veenstra's paper, he gave a very conservative estimate of the difficulty of making these delayed calibrations. When you talk about accuracy, you mean accuracy, that means what is the time difference between two stations and not what is the precision with which you determine these time differences.

I believe most of these numbers, which you have just seen, actually are estimates of precision.

MR. JOHNSTON:

For the VLBI number, I tried to estimate accuracy because we measured delay throughout the whole VLBI system very carefully; that is the one thing that the Mark III can do, because there are calibration signals sent throughout the system and you actually can measure these things now.

DR. WINKLER:

But when you compare the G.P.S. time and a two-way method such as the communication satellite spread spectrum intercomparison, one has to realize that they both deal with the difficulty of calibrating a spread spectrum signal and calibrating the delays starting with the antenna, the preamplifier, the correlator and so on, its exactly the same problem. The only difference is in the G.P.S. In addition, you have the problem of estimating the one-way delay change-through the troposhere and ionosphere, and estimating the errors of the satellite position, which you do not have in the two-way communication satellite experiments; and this did not come out properly this morning. So if you compare all of these methods, it appears to me that each one of them has unique advantages, but each one, of course, suffers from also unique problems which have not yet been completely solved. I would agree that the VLBI is an extremely useful thing to serve as a benchmark, because it's likely that in view of the Mark III capability to have internal calibrations and the fact that you deal with very large antennas, probably the delay through those large systems can be kept constant to a better degree than so many others; and you at least don't have the ephemeris problem, and so on. But I would not say that one system is better than another, without qualification. They each have individual unique features and problems.

MR. ALLAN:

I completely agree with Dr. Winkler's comments and would add a couple of others. First of all, G.P.S. uses common view. One must take care to make simultaneous measurements because of multipath and other concerns. We have found doing that, for example, for similar baseline, between Boulder and Goldstone that we are seeing three or four nanosecond precision. We have not verified the accuracy; but again the common view technique, all that is important to do, for accurate time transfer, is that you calibrate the differential delay between two receivers because it's a receiver only kind of signal, and you take one receiver from on point to another point and in fact transfer time, the same as you would with a portable clock, with the uncertainties, of course, of the propagation at that new site.

Another thing I would say, we compared GPS common view by Boulder between Paris and the U.S.N.O. and compared it with a portable clock trip that they made, and they agreed to one nanosecond. I don't believe that, either.

MR. JOHNSTON:

On the G.P.S. part of the experiment, I tried to use the common passes for G.P.S., but we didn't have a lot of data, and those were the best ones I could choose. I agree with what Gernot is saying, but I think if you want to find what the accuracy of these systems are--then, that's why I issued this challenge. It will make me clean up my numbers. We really need more data. We don't even have side-by-side comparisons. We need another system satellite. The problem is, I can't move my two-hundred foot antenna; it's too prohibitive in cost.

MR. WARD:

About this request for more data, I will make the commitment today that for the Sixteenth P.T.T.I., we will have five G.P.S. data points and at least a hundred VLBI points; just comparing the two systems with the Australian-U.S. baseline and the U.S.-Europe baseline and for the G.P.S. a direct measurement of Europe-Australia; and by that time we will have a system that will have the full calibrations in for the VLBI.

MR. JOHNSTON:

Presently, that is only partially implemented. Well, I have some data now, but it's only partial; but I guess I have about ten times more data than you have and I have some of it in the report with me. And a point for the useability of the VLBI, it's excellent and it produces UT-1 data. G.P.S. can't produce UT-1 data, but it's superior to the VLBI for deriving the kind of rate which I am interested in. I have some data that is showing accuracy to parts in 10^{16}.

We are doing an experiment over about a year-and-a-half--four experiments, three to get the calibration right. I really have to emphasize that calibration is not straightforward and easy. You have to really sit down and measure delays through the systems and constantly monitor them. If you don't do that part right, you come up with the unexpected, a hundred nanoseconds here and a hundred nanoseconds there. You can get the number right by always subtracting constants in the experiment. Calibration is really important.