INTERCONTINENTAL TIME AND FREQUENCY TRANSFER USING A GLOBAL POSITIONING SYSTEM TIMING RECEIVER *

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ABSTRACT

The Deep Space Network (DSN) has a requirement to maintain knowledge of the frequency offset between DSN stations within 3×10^{-13} and time offset within 10 microseconds. It is further anticipated that in the 1987-1990 era the requirement for knowledge of time offset between DSN stations will be less than 10 nanoseconds.

The Jet Propulsion Laboratory (JPL) is using the Global Positioning System (GPS) Space Vehicles, as a development project, to transfer time and frequency over intercontinental distances between stations of the DSN and between the DSN and other agencies. JPL has installed GPS timing receivers at its tracking station near Barstow, California and at its tracking station near Madrid, Spain.

The details of the experiment and the data are reported. There is a discussion of the ultimate capabilities of these techniques for meeting the functional requirements of the DSN.

INTRODUCTION

The Jet Propulsion Laboratory (JPL) operates the Deep Space Network (DSN) for the National Aeronautics and Space Administration (NASA). The DSN contains three complexes located in California, Spain and Australia which allow a continuous view of non-earth orbiting spacecraft. The DSN has a requirement to maintain knowledge of frequency offset between complexes of 3×10^{-13} $\Delta f/f$, and a knowledge of time offset to within 10 microseconds. It is further anticipated that in the 1987-1990 era the requirement for knowledge of time offset between DSN complexes will be less than 10 nanoseconds. Clearly, new measurement techniques will be needed to meet these requirements.

Among the new measurement techniques being investigated by JPL, to meet these requirements, is the use of Global Positioning System (GPS) timing receivers. The GPS timing receivers presently being used by JPL were developed and built by the National Bureau of Standards (NBS). Part of this development was funded by JPL.

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Description of the Receivers

The NBS receiver is described in last years proceedings (ref. 1), it uses only the one frequency containing the CA code which is transmitted by each space vehicle. The receiver locks on the space vehicle's signal, therefore it needs only a small omnidirectional antenna rather than a steerable dish. The receiver is controlled by an internal microprocessor that automatically handles schedules, length of reception time and other tasks. Once the receiver is set up, normal operation only requires occasional human intervention. For instance, the reception time is decremented 4 minutes every day which of course is a little different than a sidereal day. This is done to make it a bit more convenient by having to deal only with whole minutes. It is necessary to adjust the schedule every few weeks to keep the viewing angles correct.

Configuration of the System

At present JPL has two GPS timing receivers, one is located at the Goldstone Tracking Station Complex (GTS) near Barstow, California. This receiver gets its 1 second timing pulse from a cesium clock, Goldstone clock 5, GTS(C15) which is located about 20 Km from a hydrogen maser clock Goldstone Station Reference GTS(SR) which is at another station in the same complex. The hydrogen maser clock is the same one used in Very Long Baseline Interferometry (VLBI) which measures, among other things, the time offsets between the DSN complexes. A clock trip using a portable cesium clock is made once a week between GTS(C15) and GTS(SR). These clock trips are done in conjunction with the regularly scheduled weekly VLBI measurements.

The second GPS timing receiver is located at the DSN tracking station near Madrid, Spain. The Madrid receiver gets its timing pulse from a hydrogen maser clock which is that station reference clock MAD(SR). MAD(SR) is another hydrogen maser clock used in the VLBI measurements and is at the other end of the weekly VLBI measurement between California and Spain.

Two other receivers involved in this test were located at NBS in Boulder, Colorado and at the United States Naval Observatory (USNO) in Washington, DC. The NBS receiver is identical to those used at JPL, it gets its timing pulse from the NBS clock 9 which is a clock in the NBS ensemble. A daily offset of clock 9 to UTC(NBS) is available at months end and of course the receiver is accessible by telephone with a modem. The USNO GPS timing receiver is a Stanford Telecommunications receiver of similar functional design to the NBS receiver. Its schedule is decremented approximately 28 minutes per week (1). The receiver gets its timing pulse from UTC(USNO, MC). There are corrections available to UTC(USNO).

[1] The USNO receiver schedule is decremented 27 minutes one week and 28 minutes the alternate week. This allows an approximation to a sidereal day. This will be changed to 4 min/day decrement starting around the first of 1983.

Procedures for gathering and processing the data

The receivers will store internally one to two weeks of data depending on how much data is acquired each day. The data from the receivers are acquired by telephone usually once a week. In the use of the NBS type receiver, the receivers themselves are accessed. In the case of the USNO receiver, the data is acquired from a public database service provided by USNO. In both cases the data are transmitted at a 300 baud rate and are received and printed out on a terminal. The data are then input by hand into a Hewlett Packard 9845 calculator.

All of the data were taken as a mutual view of the space vehicle by pairs of timing receivers. This method promises the best results and is the simplest with respect to processing the data. As more space vehicles are added to the GPS constellation, there will be additional opporunities for mutual view around the world.

The receivers are programmed to take data for 10 minutes (600 seconds). These data are then reduced in the receiver to a single data point which represents the time offset between the local clock and the GTS clock. The difference between the two values of local clock and GTS time is then calculated. This is done for each space vehicle that is available for mutual view each day. These values are then averaged to produce a single value for the day. If data points are missing, then a linear interpolation is made on the original measurement.

Results

The first and easiest measurement that was made was between clock 5 at GTS and NBS clock 9. Easiest because the NBS receiver was already set up and operating. The distance between stations is approximately 1200 Km and regular clock trips are made between GTS and NBS so the measurements can be verified.

Figure 1 shows the results of the UTC (NBS) - GTS (clock 5) with the Cesium portable clock trips results also shown. Because of different antennas being used at NBS a receiver calibration was not available, therefore the 1st clock trip was used as a calibration. The second trip disagreed by 36 ns and the third by 5 ns.

This receiver is now probably a de facto permanent installation at GTS and will probably eliminate the need for most future clock trips between NBS and GTS.

A second GPS timing receiver was installed at the DSN station in Spain. A schedule of mutual observation of two space vehicles (SV5 and SV8) was started. These are the only two space vehicles that are mutually observable from both complexes. The space vehicle observation schedule was made to have the same angle of observation from both stations. Some slight adjustments were made to equalize the angles from 41° to 45° above the horizon. The space vehicles are over Greenland at observation time and seen within a few degrees of each other in the sky at each station.

A clock offset measurement is made every day from each space vehicle and the mean is used as the value of the clock offset. The same procedure for getting a value of clock offset is used between GTS(C15) and MAD(SR) and between UTC(NBS) and GTS(C15) with the exception that only two space vehicles are available. A plot of the clock offset values is seen in Figure 2. Figure 3 is the same graph with a frequency offset removed.

The frequency offset between the GTS(C15) and MAD(SR) was calculated using 10 days of data. The calculations assumed statistical independence between the measurements using the two space vehicles. A typical offset measurement was 9.5×10^{-13} $\Delta f/f$ with a (confidence) standard deviation of the mean of 2.8×10^{-14} $\Delta f/f$. This is within the requirements to have knowledge of frequency offset to within the 3×10^{-13} $\Delta f/f$ DSN specification.

Confirmation by independent GPS measurements

Unlike the clock offset measurements between GTS and NBS, the measurements from California to Spain cannot be confirmed by frequent clock trips. One attempt at confirmation was a daily indirect time difference measurement made through the U.S. Naval Observatory (USNO). This was accomplished in two steps: First, there was a daily mutual view schedule maintained by NBS, USNO and Goldstone. Second, USNO and Madrid maintain a mutual view schedule, which results in daily time offset measurement between their clocks. These direct and indirect time offset measurements between Goldstone and Madrid are nearly statistically independent.

Figure 4 shows the differences in the measurement of the time offset between Goldstone and Madrid by two different paths. There was a mean offset of 140 ns. An explanation of this could be an error in the coordinates of the receiver. There is some reason to believe this is true at Goldstone and there have been no checks made at Spain. The new firmware to be installed in the NBS designed receivers in 1983 will contain a navigation program. Then it will be possible to verify the antenna location within a few meters.

A good candidate for the cause of the daily variation is the different scheduling methods used by JPL and NBS and that used by USNO. This problem should clear up in 1983 when USNO starts decrementing 4 minutes/day. At that time the test will be rerun. Some of the daily variations are probably caused by ionospheric changes. There is no attempt to account for this in the NBS and JPL receiver at this time but one would expect this error to be less than is presently seen.

Confirmation using VLBI measurements

Approximately once every week a VLBI measurement is made between GTS and MAD and between GTS and the DSN Australian complex. One of the results of the VLBI measurement is the time offset between the involved stations. By using the regular clock trips between GTS(C15) and GTS(SR), the GPS timing receiver results can produce an approximately weekly time offset between GTS(SR) and the MAD(SR) - Figure 5. These time offset measurements can be compared to the time offset results of the VLBI measurements as seen in Figure 6.

A linear fit on each of the two sets of data shows an excellent agreement. These measurements will be continued throughout 1983. It is planned to make measurements internal to the stations to find the difference between the VLBI and the GPS measurements.

CONCLUSIONS

1. The present GPS timing receivers can meet the 1985 requirements specified for the DSN. With better data collection and the addition of software filters in the data processing, there is reason to believe the intercontinental time measurements, with the existing equipment, can approach an accuracy of 10-20 nanoseconds. Certainly, one can expect to further refine the measurement of frequency offset.

2. The GPS and VLBI measurements of time offset will compliment each other for some time to come.

3. It has been shown that the GPS timing receiver is an operational item of equipment capable of replacing regular clock trips over short distances and shows promise of replacing clock trips over intercontinental distances.

ACKNOWLEDGEMENTS

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1. Unprecedented Syntonization and Synchronization Accuracy via Simultaneous Viewing with GPS Receivers; Construction Characteristics of an NBS/GPS Receiver, D.D. Davis, et al., Proceedings of the 13th Annual Time and Time Interval Applications and Planning Meeting.

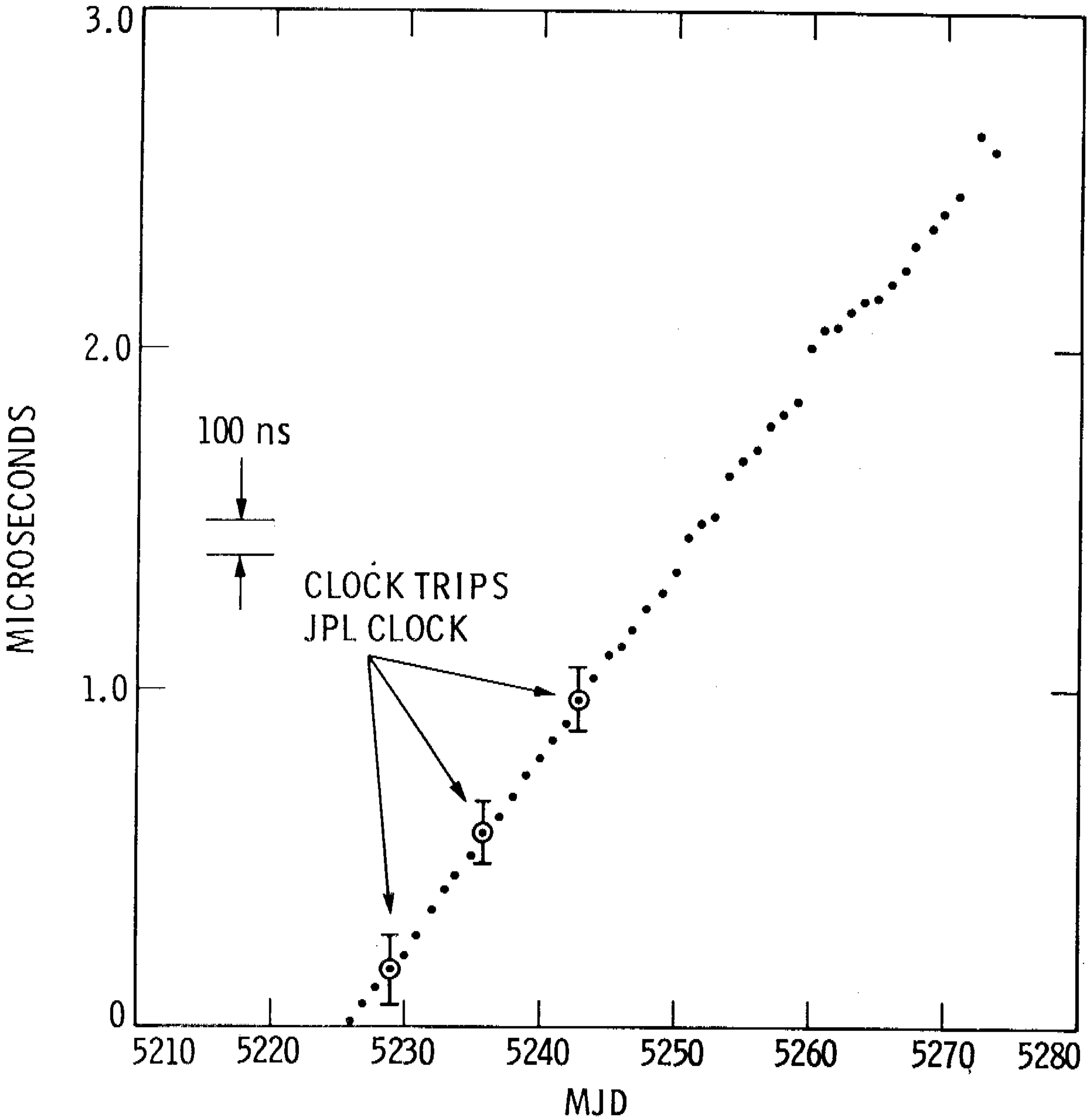

Figure 1. UTC (NBS) - Goldstone (Clock 5)

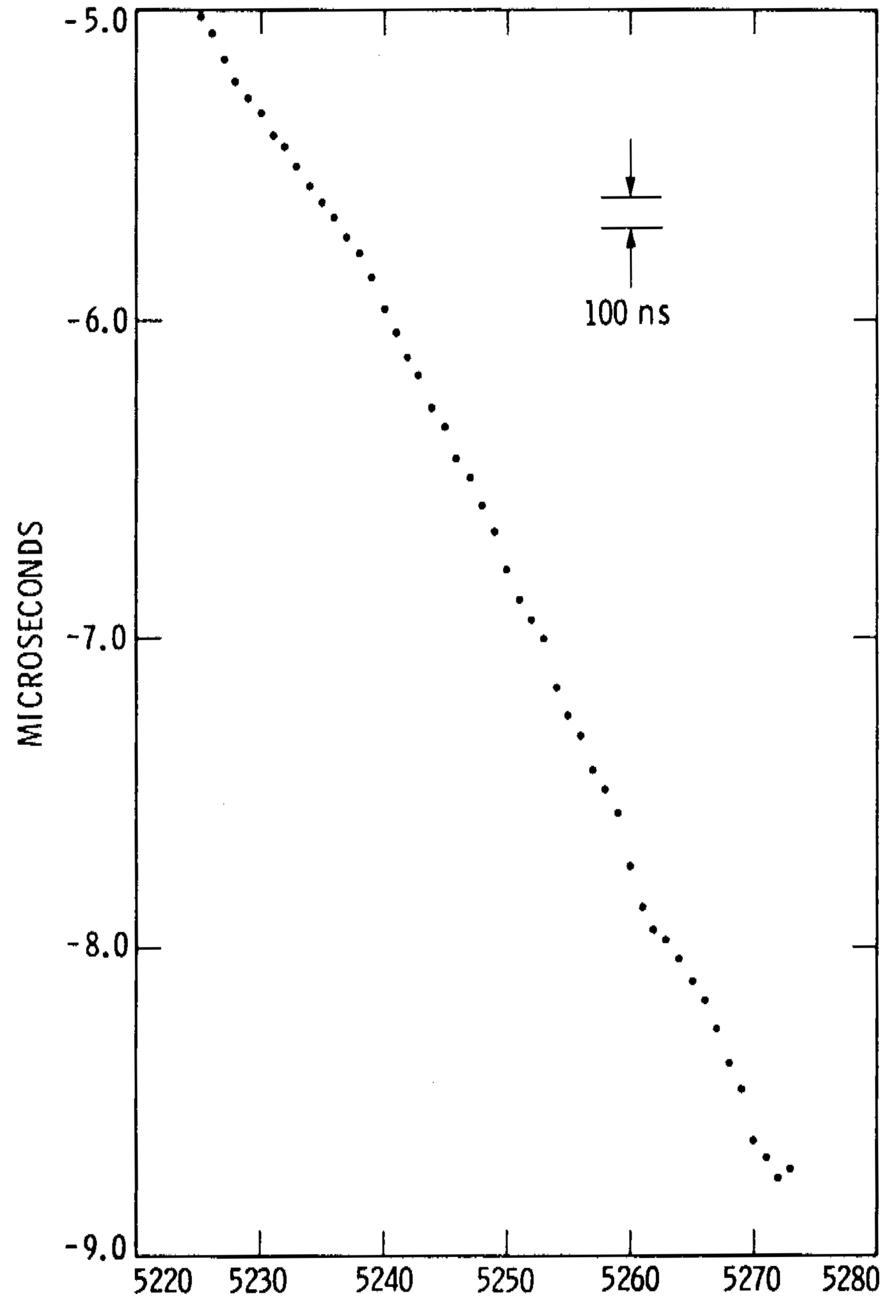

Figure 2. Goldstone - Madrid as Directly Measured by CPS Timing Receivers [Goldstone (Clock 5)] - [Madrid (Station Reference)]

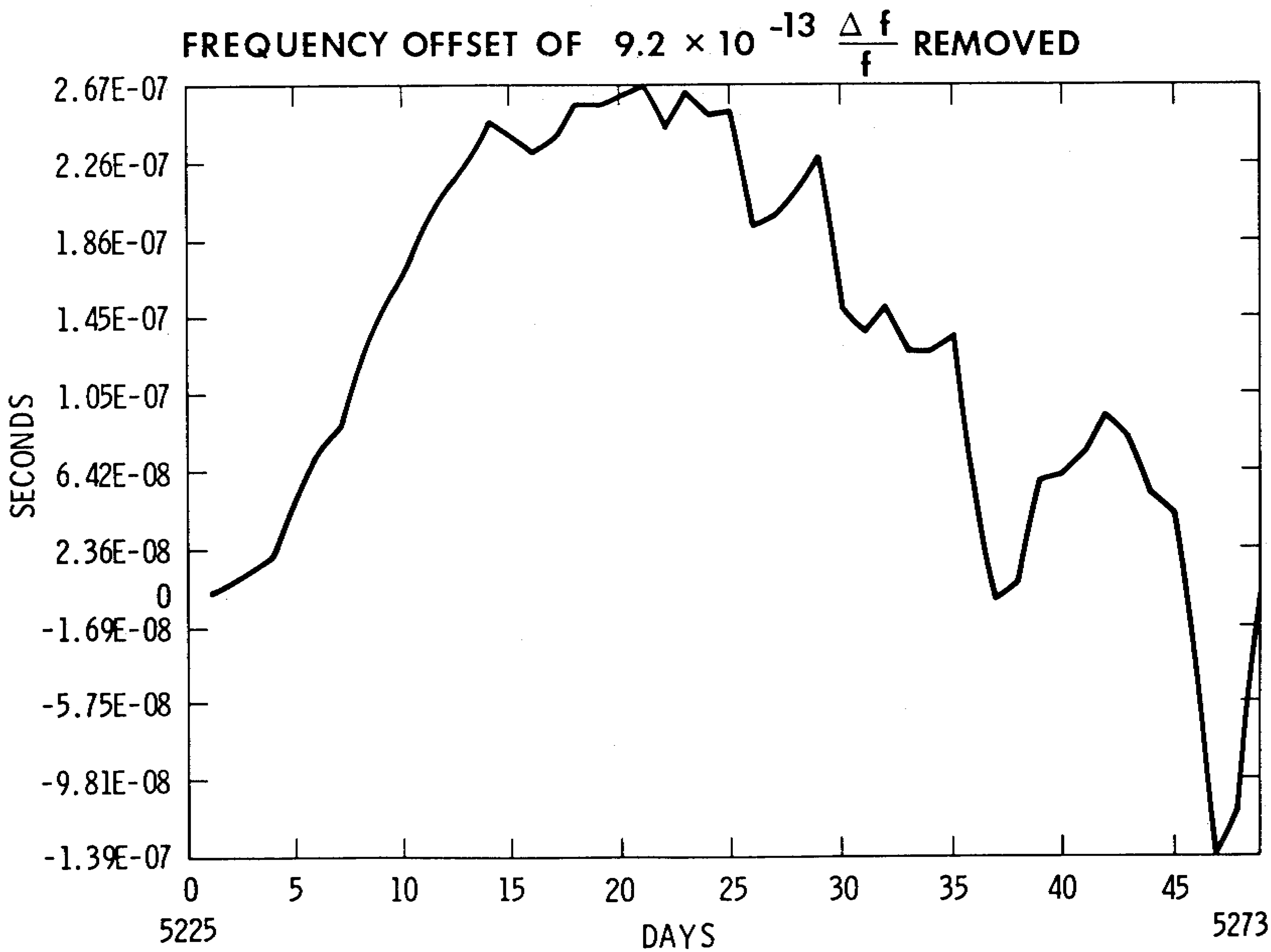

Figure 3. Goldstone (Clock 5) - Madrid (Station Reference)

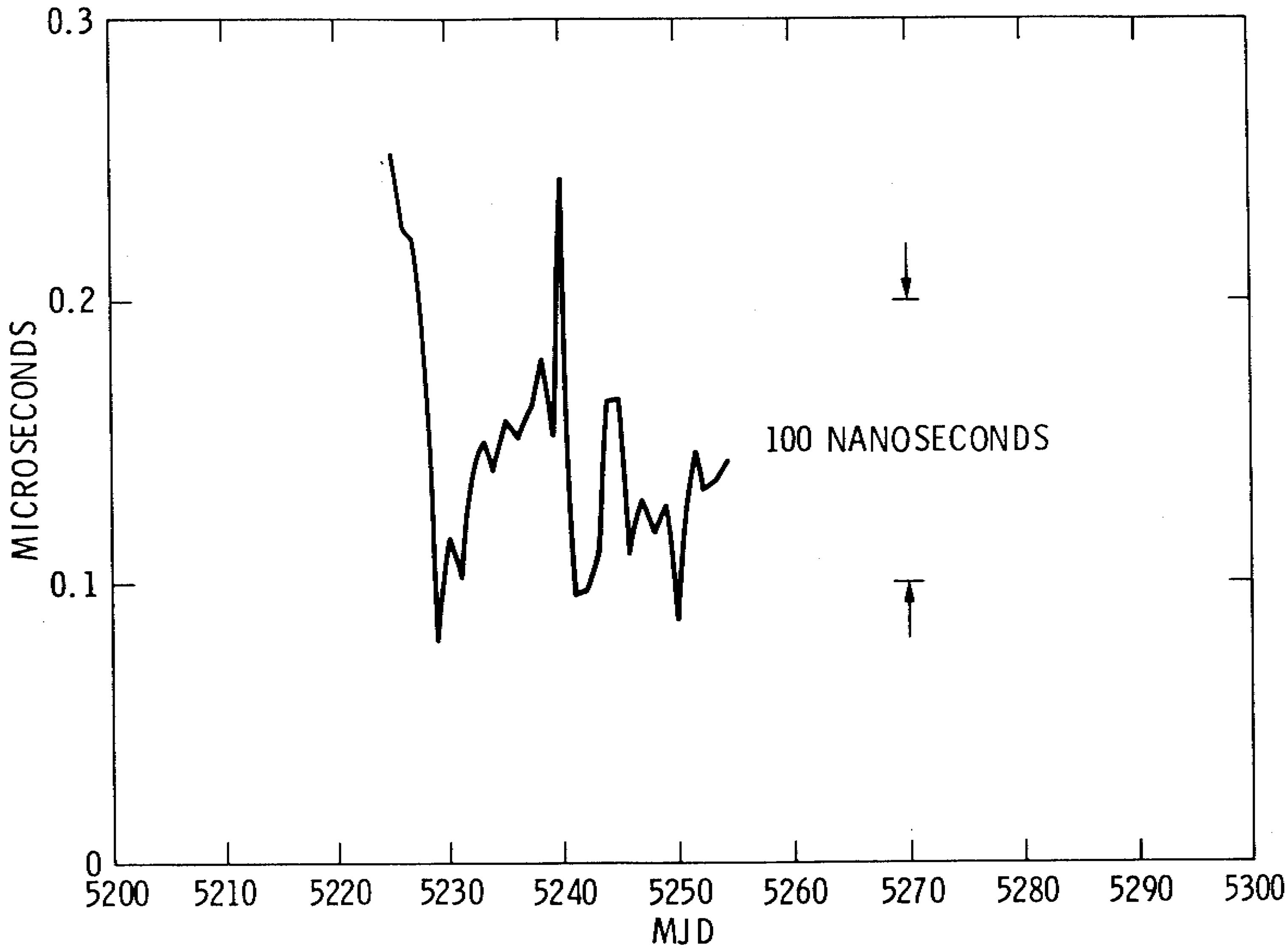

Figure 4. Difference Between Goldstone to Madrid Time Directly and Through USNO

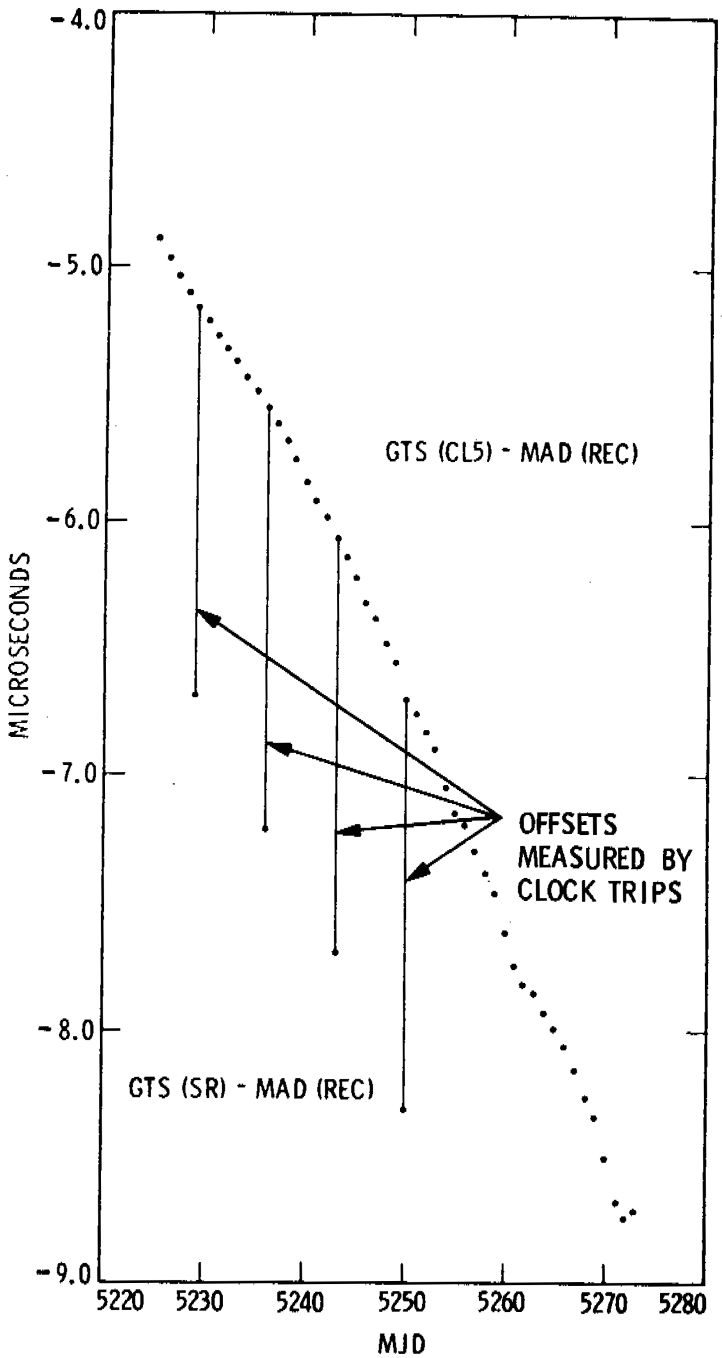

Figure 5. Goldstone - Madrid Directly Showing Offset to Goldstone (Station Reference)

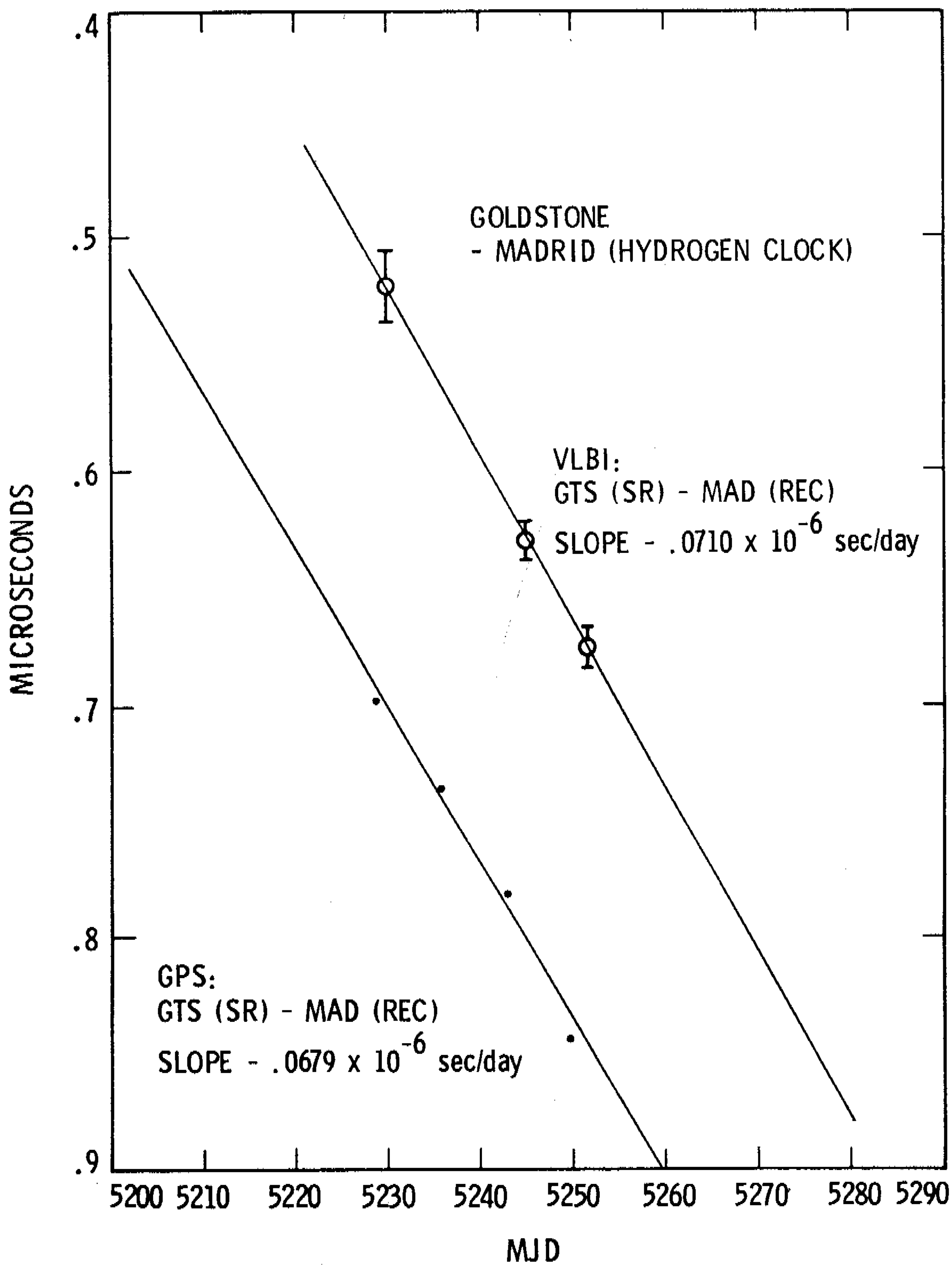
.4
.5
.6
.7
.8
.9
MICROSECONDS
GOLDSTONE
- MADRID (HYDROGEN CLOCK)
VLBI:
GTS (SR) - MAD (REC)
SLOPE - .0710 x 10^-6 sec/day
GPS:
GTS (SR) - MAD (REC)
SLOPE - .0679 x 10^-6 sec/day
5200 5210 5220 5230 5240 5250 5260 5270 5280 5290
MJD

Figure 6

QUESTIONS AND ANSWERS

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If you make comparisons where you use one intermediate station, it is extremely important to select observations which are simultaneous pair-wise, in other words, to establish the difference between station A and B at the same time and between B and C, possibly at another time, but again pair-wise at the same time. These times don't have to be identical but they must be identical until we can verify the origin of these biases which were discussed in the first paper. When one makes a bias observation, then you can see that the time transfer undergoes a change, and unless you establish exactly theorized simultaneity, you will of course have errors due to that change.

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They are almost simultaneous. The USNO decrements 27 minutes one week and 28 minutes the other week, whereas we are decrementing 4 minutes a day, so there is some of that going on, and the two receivers that look directly, they are right in step with each other. We decrement 4 minutes a day with those, so that could be a source of error, sure.