TIME AND FREQUENCY STABILITY FOR THE CRUSTAL DYNAMICS PROJECT

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ABSTRACT

The Crustal Dynamics Project utilizes very long baseline interferometry (VLBI) and laser ranging to artificial satellites and the moon to determine vector baselines between stations with precisions of about one part in 10^8. Both laser ranging and VLBI require initial relative epoch timing of about one microsecond for stations distributed over the globe. Very stable frequency standards are the key to VLBI because they are used to maintain frequency coherence between stations. In order to have less than one radian rms X-band phase perturbation accumulated in a 1000 second integration period, the frequency standard must have a stability of 1×10^{-14}. In the VLBI data analysis to determine accurate baselines, the clock offsets and variations must be solved for in order to fit the data with less than 0.1 nsec (3 cm) rms deviation over 24 hours. This is a fit to 1×10^{-15}. Over the next six years the Crustal Dynamics Project plans to improve the accuracy of the VLBI technique by about an order of magnitude. This will require a frequency stability of about 1×10^{-15} for periods of hours to days and solutions for frequency variations to about 1×10^{-16}.

The NASA Crustal Dynamics Project was formed last year to apply the NASA-developed techniques of satellite laser ranging (SLR) and very long baseline interferometry (VLBI) for the measurement of crustal motions of the earth. Both of these techniques have the virtues that measurements with an accuracy of 1 part in 10^8 can be made over baselines of several thousand kilometers, and these baseline measurements can be made across any terrain, sea or land, The Crustal Dynamics Project is determining regional deformations and strain accumulations in active earthquake regions by making frequent measurements of baselines between many stations in the active areas near plate boundaries. By making regular measurements of baselines between a global set of stations on the different tectonic plates, the Project is determining the tectonic plate motions and the internal stability of the plates. Quite frequent measurements with a global set of fixed stations are being used to determine very accurately the motion of the pole of the earth and variations in earth rotation.

Both SLR and VLBI require initial relative epoch timing of about one microsecond for stations distributed over the globe. In addition, the VLBI system has a very stringent requirement for frequency standard stability because frequency coherence must be maintained between the VLBI stations. Figure 1 is a diagram of a pair of stations used for a VLBI measurement. The figure shows two antennas at remote distances on the surface of the earth receiving signals from the same radio source, a quasar. The signal received at both stations is translated to base band using a very stable hydrogen maser frequency standard. The base band signal is digitized and recorded. The recorded data from the two stations are then processed in a correlator which determines the time delay between the arrival of the quasar signal at the two stations. Since the two antennas are located on a rotating earth, the delay has a diurnal sinusoidal signature which is a function of the quasar position and the baseline length and orientation. By measuring the delay and delay rate signatures of a number of quasar sources, one can calculate very accurately the vector baseline between the two stations.

The hydrogen maser clocks at the two stations are independent; thus they will have neither the same epoch time nor the same frequency behavior. In the VLBI solutions for the baselines, it is necessary to solve for the clock offset and the rate difference between the clocks, and in some cases even clock frequency drift.

The use of very stable hydrogen masers as frequency standards is the key to the success of VLBI. In order to have less than one radian rms X-band phase perturbation accumulated in a 1000 second integration period, the frequency standard must have a stability of better than 10^{-14} for periods of up to a few minutes. In the VLBI data analysis to determine accurate baselines, the clock offsets and variations must be solved for in order to fit the data with less than 0.1 nanoseconds (3 centimeters) rms deviations over 24 hours. This implies modelling behavior to about 1 part in 10^{-15}. Figure 2 shows a rather typical example of a plot of delay residuals after the clock offsets and the linear rate difference between the clock have been solved for and removed. This data is from stations at Haystack Observatory, Massachusetts, and Owens Valley Radio Observatory, California. The rms fit of this data is approximately 0.1 nanoseconds. Typically, from data like this we are able to determine the baseline from Haystack Observatory to Owens Valley Observatory to a precision of a few centimeters. Repeated measurements of that baseline over the past four years have shown an rms deviation of 4 centimeters for this 4,000 kilometer baseline. This is a precision of 1 part in 10^{-8} in the determination of the baseline.

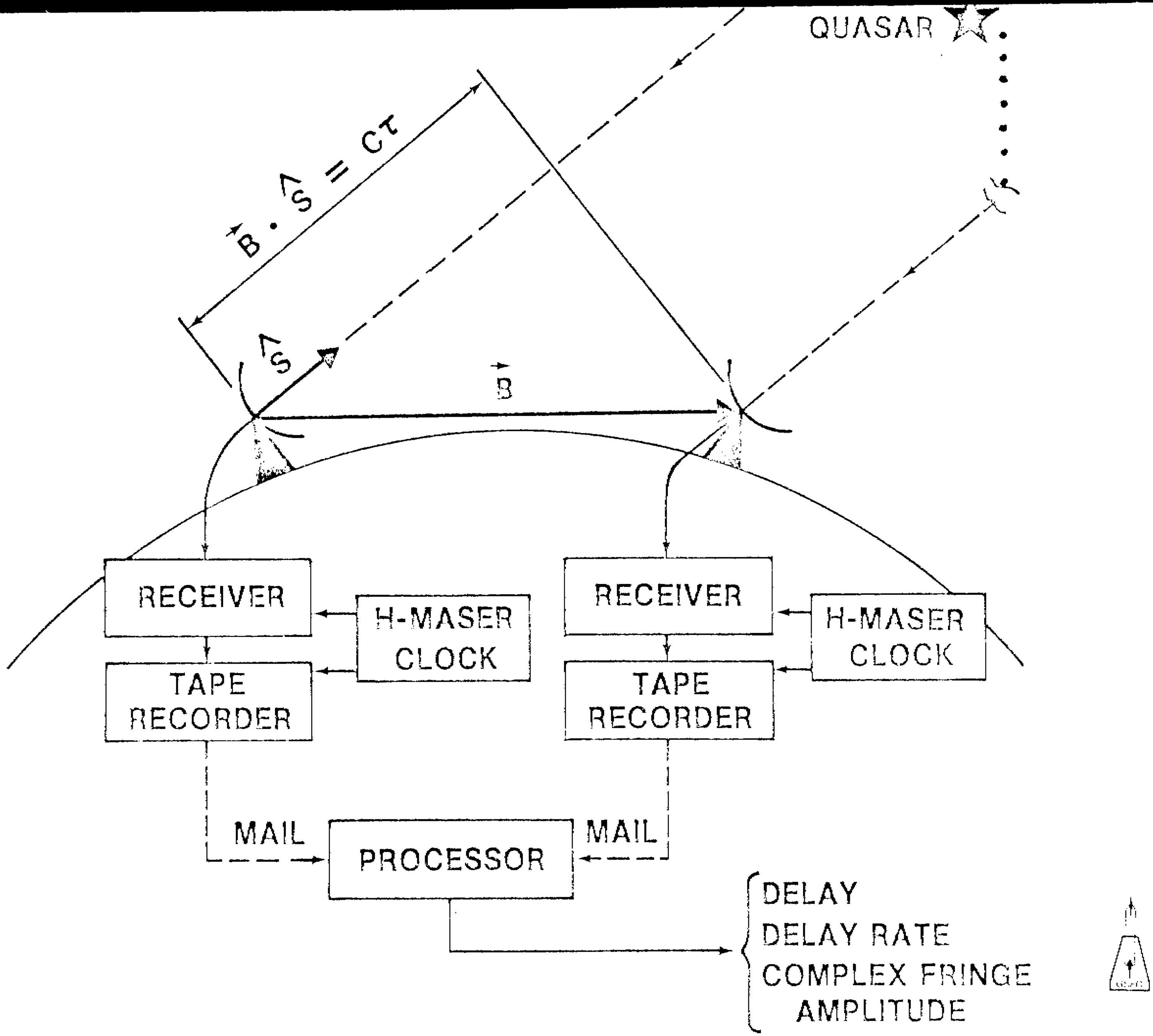
The Project has acquired data that has higher quality than that shown in Figure 2, and also worse. Sometimes there have been malfunctions which degraded the measurement precision. The purpose of this paper is to show how well we can recover accurate baselines when there are problems with the frequency standard and distribution system at the VLBI station. One such malfunction is a sudden change in rate of the frequency standard. An example of this is shown in Figure 3 which is a plot of delay residuals in which only the clock offset has been removed so that the rate difference between the two clocks are shown. There are two rate changes evident in Figure 3. The first change in rate between the two clocks occurred at approximately 4.4 days and was a rate change of 4×10^{-14}. The second rate change at about 6.4 days was a rate change of 7×10^{-13}. In this experiment, there were three stations involved--Haystack Observatory, Owens Valley Radio Observatory and the Harvard Radio Astronomy Station in Texas. With the data from the three stations we were able to determine that the changes in the rate of the clocks occurred at Haystack Observatory. With a clock change like this, the VLBI solution's clock model can be broken up into segments corresponding to the time periods during which the clock was behaving in a normal manner. In the example in Figure 3 there were three segments used in the solution, the first segment from 0 to 4.4 days, the second segment from 4.4 to 6.4 days, and the third segment from 6.4 to 8 days. In the solution, three clock rates were determined, one corresponding to each time segment. As long as there is enough observing time to permit an accurate determination of the clock epoch and rate for each segment, the precision of determination of the baselines is still a few centimeters.

The data set just shown in Figure 3 was selected because it was a particularly bad set which contained three different malfunctions of the frequency and distribution system. The other two malfunctions become more apparent when the data is plotted with the three clock rates removed, as shown in Figure 4. With the greatly amplified delay residual scale ($\pm$ 5 nanoseconds), diurnal signatures are quite apparent in the data. Since the viewing of the radio sources with the interferometer produces a delay which is a diurnal signature, a diurnal signature produced in the frequency standard and distribution system is of great concern because it can alias directly into the baseline results and create a significant error. In this particular case, the diurnal sinusoid showning in Figure 4 was caused by two different failures at the Harvard Radio Astronomy Station. The first failure, which caused most of the diurnal sinusoid, was a component failure in the frequency distribution and calibration system. This extended over the entire period of the observation. The second problem was caused by the failure of the temperature control system for the hydrogen maser room which occurred on October 19. This is illustrated in Figure 5 which is a plot of the hydrogen maser temperature as a function of time. Normally the temperature is controlled to a small fraction of a degree. After the failure, the hydrogen maser room varied in temperature about one degree with a diurnal signature. Hydrogen masers have a temperature coefficient of a few parts in 10^{-14} per degree C, so a diurnal temperature variation does produce a diurnal frequency change in the output of the hydrogen maser. Fortunately, the time constant of the frequency change with temperature change is longer than the diurnal period, and the amplitude of the diurnal frequency variation is attenuated considerably. Consequently, the diurnal sinusoid due to the temperature control failure was significantly smaller than the diurnal sinusoid due to the frequency and calibration system failure.

In order to determine the effects of such a diurnal signature on the accuracy of the baselines determined from this data, an analytical simulation of this problem was conducted. For this simulation, theoretical observables were used for data for the three stations, a one nanosecond diurnal sinusoid was added to one clock, and the baseline lengths were solved for using standard procedures to determine the errors caused by the diurnal clock variation. Next the simulation was repeated using real observed data from other sessions where there were no clock failures. The simulations were performed with a solution for one day. One day was chosen because that would produce the worst case result. Figure 6 shows the simulation results for three different variations in analysis strategy. In the first case, linear clock terms were used in the solution for determining the relative clock rate, and the resulting error in baseline length with this simple clock parameterization was almost 20 centimeters. Such a simple parameterization ignores the fact that there are terms other than linear variations present in the residuals. In the normal process of analyzing the data, we also have the capability of putting in higher order polynominal clock terms. The second case utilized a quadratic clock parameterization for the malfunctioning station and linear clock terms at the other stations. The worst error in baseline length for this second case was only 2.2 centimeters. The simulations with real VLBI data gave similar results.

In these first two solutions, the source positions were used as a priori positions and the solutions were done with those source positions fixed. In the third case these source positions were solved for in order to see what the effects would be if one solved for the source positions at the same time one was solving for clocks and baselines. The result was that large errors occurred when source positions were solved for even when the quadratic clock terms were used in the solutions. The reason for this is quite understandable. Since the delay of the signal from a source has a diurnal signature, the diurnal clock error will cause an error in the determination of the position of the source which in turn produces an error in the baseline solution. The result of this third case indicates that one should not solve for both baselines and source positions in a single experiment solution. Accurate positions of radio sources can be determined from solutions with large batches of data which cover several years of time. With such a large span of data, the clock effects will tend to cancel themselves out, and the resulting positions determined for the sources will be quite accurate. These accurately determined source positions can then be used in the individual measurement solutions using the quadratic clock terms as in case 2 to produce accurate baseline results. By following this type of strategy one can produce baseline determinations with a few centimeters precision even with malfunctions of the type described above. This result is consistent with the history of baseline measurements with a precision of 4 centimeters that have been obtained over the past four years.

Good geophysics can be done with 4 centimeters baseline precision, and the Crustal Dynamics Project has deployed both VLBI and laser systems around the globe for measurements of plate motions and stability, and has initiated campaigns in California for measuring regional deformation. However, higher measurement accuracy will result in better geodetic results. Thus, the Project goal is to achieve a 1 centimeter measurement precision. Actions are underway now in the frequency standard area that are aimed at improving the performance of the VLBI system. It was mentioned earlier that there is a temperature controlled room for the hydrogen maser at the Harvard Radio Astronomy Station. That is the first installation of temperature controlled rooms for hydrogen masers. The Project is in the process of installing such temperature enclosures for all of the hydrogen masers that are being used in the Project. The goal is an order of magnitude improvement in the stability of the frequency of the hydrogen masers operating in the field. In addition, the new hydrogen masers are equipped with extensive monitoring capability for recording the environmental parameters that affect maser operation. It is our plan to determine the relationship between the environmental parameters (temperature for example) and the maser frequency in order to determine the actual frequency performance from the measurements of the environmental parameters. By determining the fine frequency variations due to environmental changes, we expect to be able to know the frequency of the masers to an order of magnitude better accuracy than we do today. This should reduce clock errors in our solutions by an order of magnitude. There are other error sources, such as atmospheric propagation, which contribute errors to the overall baseline solution at the centimeter level. The Project has efforts underway to reduce all of the known error sources to the millimeter level in order to reach the goal of one centimeter baseline accuracies.


QUASAR
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$\hat{S}$
$\vec{B}$
RECEIVER
H-MASER CLOCK
TAPE RECORDER
RECEIVER
H-MASER CLOCK
TAPE RECORDER
MAIL
MAIL
PROCESSOR
DELAY
DELAY RATE
COMPLEX FRINGE AMPLITUDE

FIGURE 1

HAYSTACK-OVRO 130   8/ 4/79. RUN CODE 10330-2052

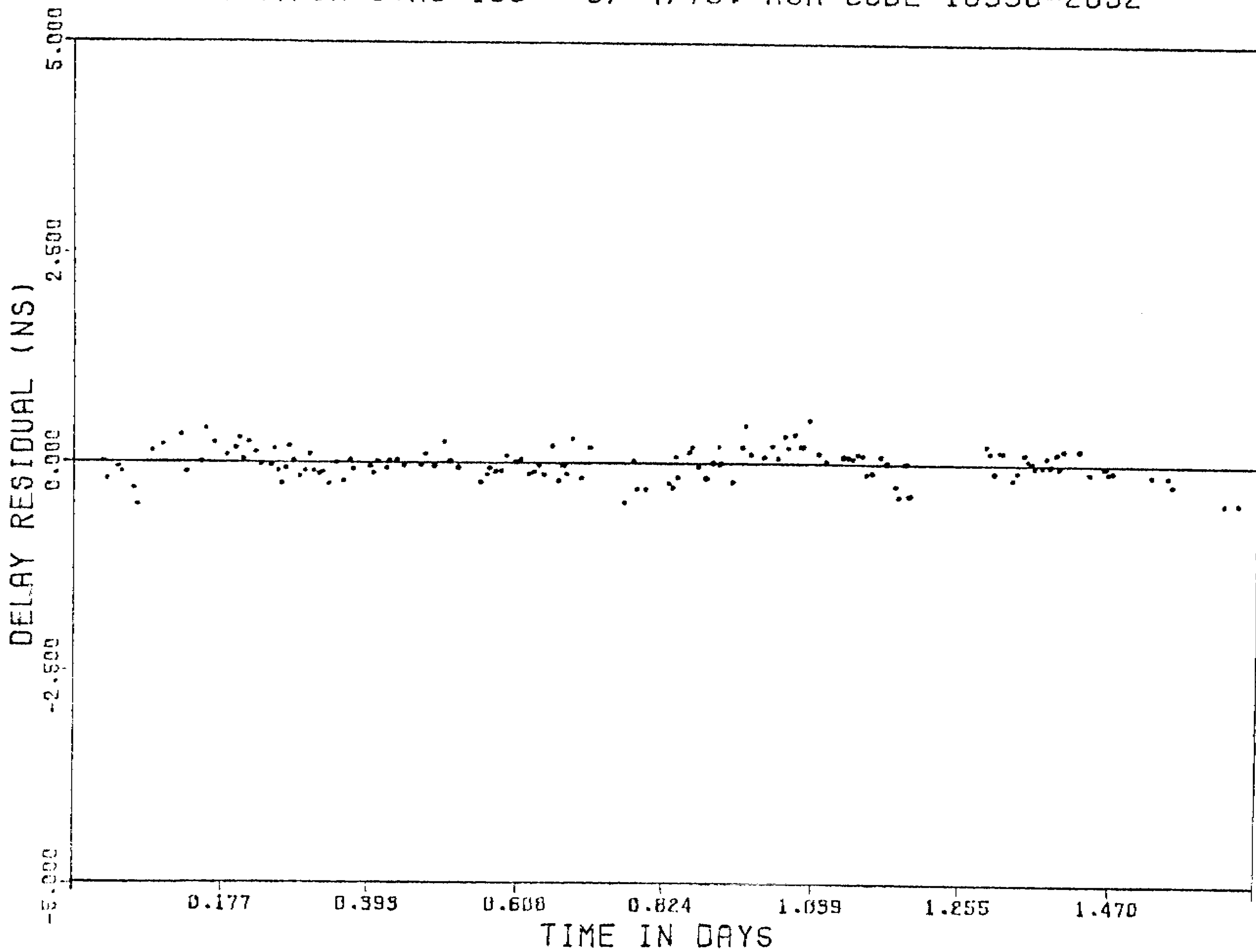
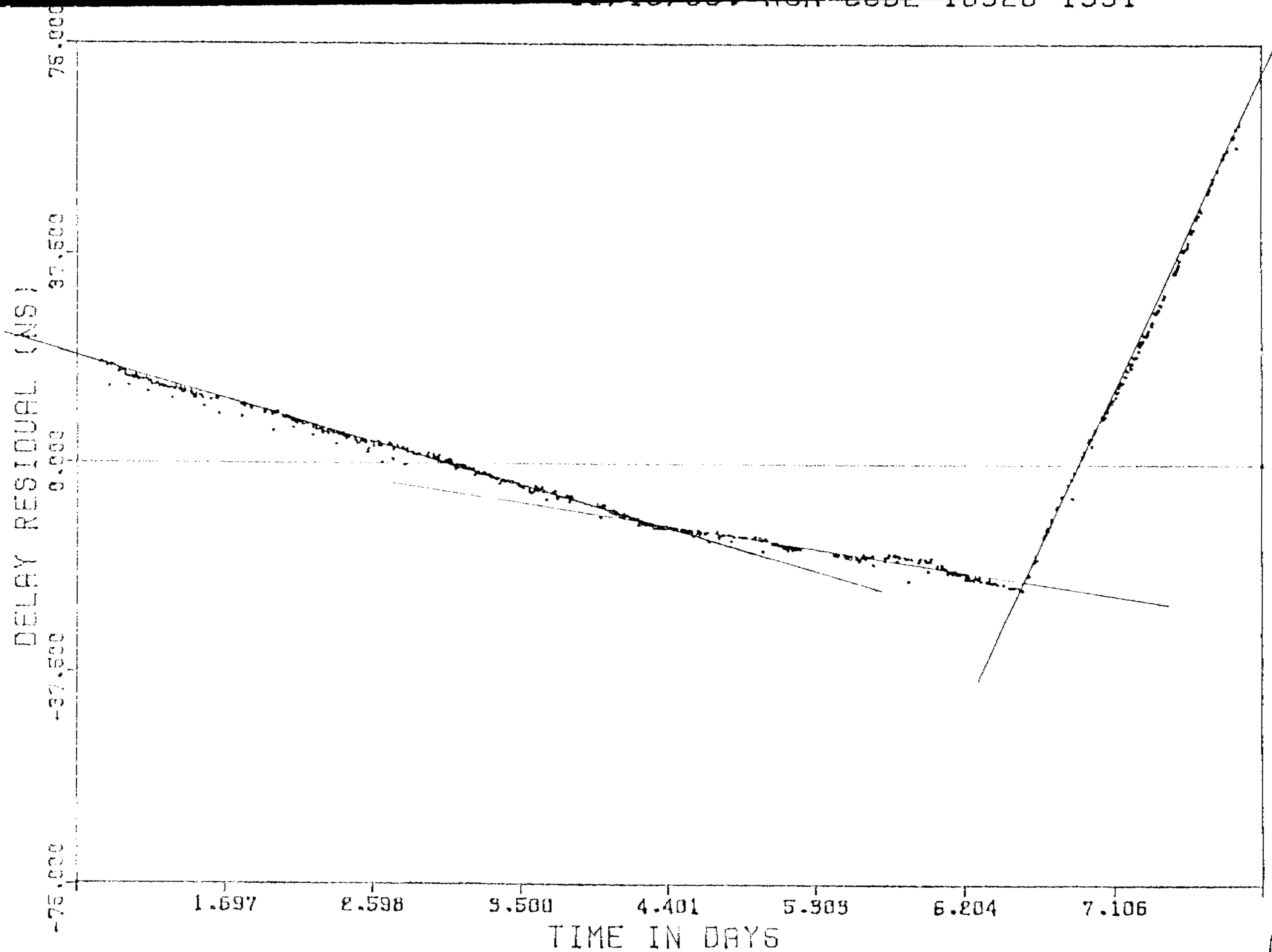


FIGURE 2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37.500
0.000
-37.500
-75.000
DELAY RESIDUAL (NS)
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2.598
3.500
4.401
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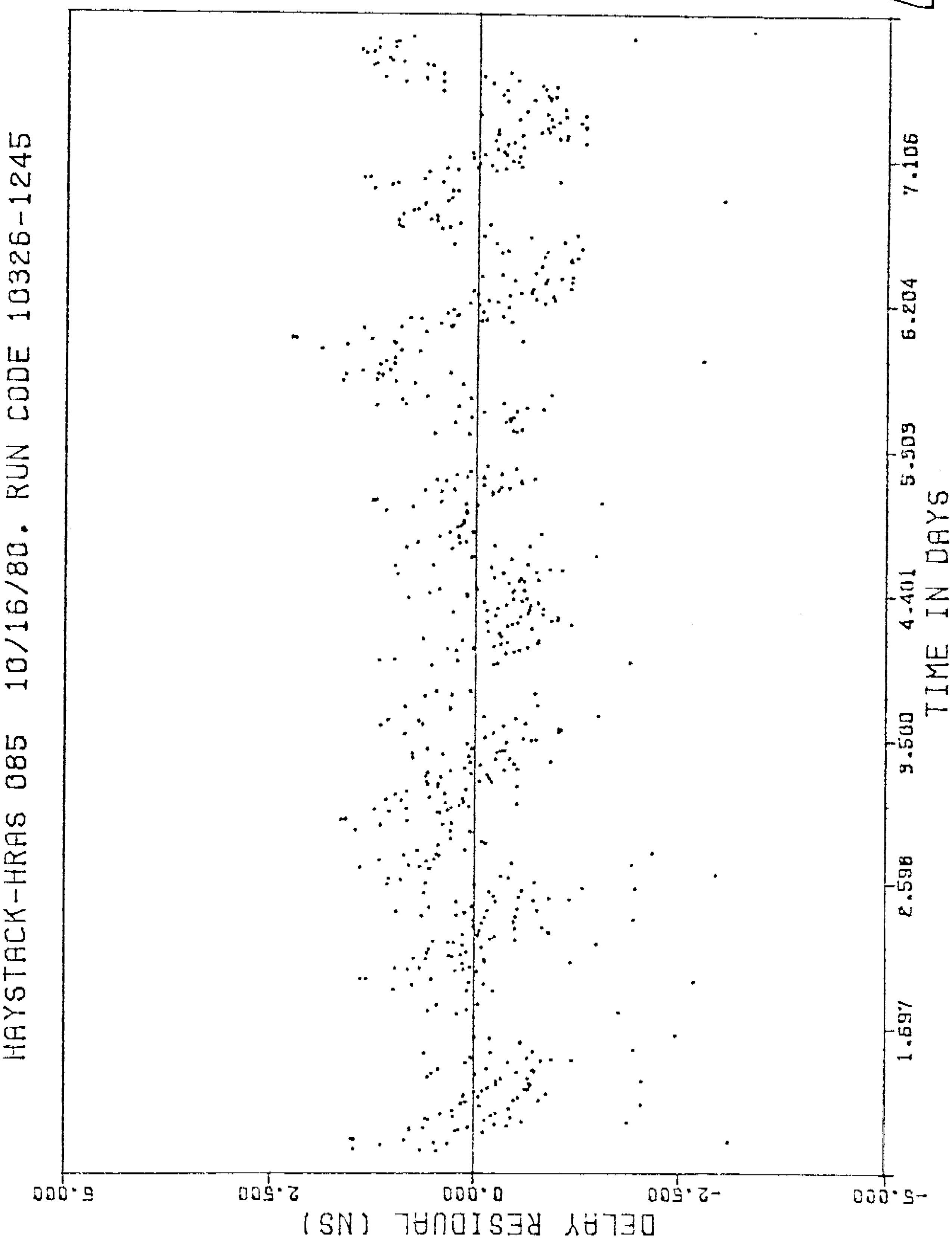
6.204
7.106
TIME IN DAYS

FIGURE 3


HAYSTACK-HRAS 085 10/16/80. RUN CODE 10326-1245
TIME IN DAYS
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2.598
3.500
4.401
5.303
6.204
7.106
DELAY RESIDUAL (NS)
5.000
2.500
0.000
-2.500
-5.000

MR-2 TOP CABINET TEMPERATURE (FT. DAVIS)

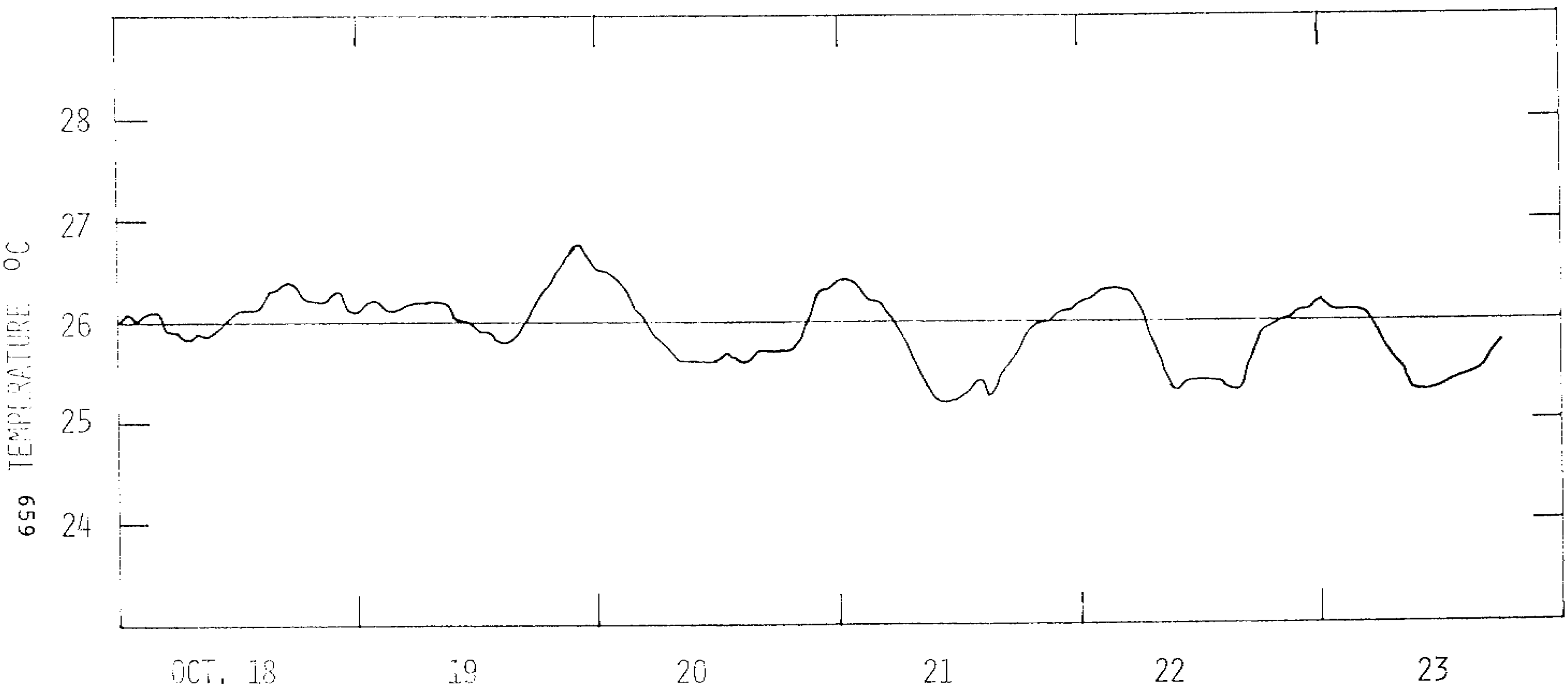

FIGURE 5

SIMULATION RESULTS FOR THE HAYSTACK-FT. DAVIS-OWENS VALLEY BASELINE LENGTH ERRORS CAUSED BY 1 NS DIURNAL SINUSOID TIME ERROR AT HAYSTACK

SOLUTION PARAMETERIZATION	WORST ERRORS (CM) HA-OV	HA-FD	FD-OV
o LINEAR CLOCKS AT HAYSTACK & OVRO	-12.1	-19.9	-4.7
o QUADRATIC CLOCK AT HAYSTACK, LINEAR CLOCK AT OVRO	- 2.4	- 0.3	-1.8
o QUADRATIC CLOCK AT HAYSTACK, LINEAR CLOCK AT OVRO, SOURCE POSITIONS	-18.7	-18.6	-9.5

FIGURE 6

QUESTIONS AND ANSWERS

CHAIRMAN HOWE:

You have gone to some length to attempt to look or take out the one nanosecond diurnal sinusoid term. I might suggest that you also look at perhaps other effects since you can monitor temperature, but you might look at humidity, temperature gradients, and even power line fluctuations.

You can make certain assumptions about unit correlation with these long-term effects, but you will see them definitely on the relatively inexpensive data logger.

DR. COATES:

We do monitor the environment; we monitor the temperature, the pressure, and the humidity, I didn't mention pressure. Some masers are pressure-sensitive; the ones that we have been using in these experiments are not contributing a pressure effect that is significant, but we do monitor all of these parameters.

The new masers that we have are almost independent of power lines variations. We have gone to great extents to eliminate that as a factor. When we are after extreme stabilities that we are talking about here, we need to really go all out. You are quite right.

DR. VICTOR REINHARDT, NASA/Goddard

I think this shows pretty conclusively that the effects due to temperature and pressure, humidity, are well-modelable, and I think for the JPL tests as well as the JPL, DSN, VLBI uses and other uses, there is no reason that these things can be just modeled out very easily in the least squares fit, especially since with Paul Kuhnle's new test facility, each of the masers is very well characterized for each of these things when we go out into the field.

So, I really, for the long-term, don't see this is a problem; just as something that is getting into the system. So, the VLBI people, now that they are aware of the problem, can just easily put that into their programs because a few more parameters of fit really doesn't make a significant difference in terms of computing time in this case.

DR. THOMAS, The Jet Propulsion Laboratory

I wonder how you isolated the diurnal sinusoid to the clock and not to other possible effects like other instruments, the ionosphere, and so forth.

DR. COATES:

There are other effects that you can see that are systematic. We do SX determination of the ionosphere. However, in the particular example I gave, you could see that the difference between two sets of data is quite large. The effect was determined very precisely by looking at three stations' data that shows there was something at one station. It was something like an extensive active ionosphere which would show up at all the stations.

There was a diurnal sinusoid at the beginning of the observing period. In the middle of the observing period, there was an increase in that diurnal sinusoid. That increase in the diurnal sinusoid matches with the change in the temperature control on the maser enclosure.