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DEMONSTRATION OF INTERCONTINENTAL DSN CLOCK SYNCHRONIZATION BY VLBI

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ABSTRACT

The prototype system for Deep Space Network (DSN) clock synchronization by VLBI has been demonstrated to operate successfully over intercontinental baselines in a series of experiments between Deep Space Stations at Madrid, Spain, and Goldstone, California. As predicted by analysis and short baseline demonstration, the system achieves reliable synchronization between 26 m and 64 m antenna stations with 17 and 37 K nominal system temperatures using under one million bits of data from each station. Semi-real-time operation is feasible since this small amount of data can be transmitted to JPL and processed within minutes. The system resolution is 50 to 400 ns, depending on the amount of data processed and the source intensity. The accuracy is believed to be comparable to the resolution, although it could be independently confirmed to only about 5 μs using LORAN C.

INTRODUCTION

The prototype for a semi-real-time system for DSN clock synchronization by radio interferometry was first demonstrated on a short baseline in August 1972.[1,2] A series of three experiments has now been conducted between Madrid, Spain and Goldstone, California, to demonstrate that the system performs as expected on intercontinental baselines. The series of experiments had three primary classes of objectives, all of which were achieved:

1. To confirm that the system achieves the predicted resolution with the predicted amount of data; this implies that there are radio sources available which act as strong enough point sources over the long baseline.

2. To check the system accuracy by demonstrating consistent results at different times of day and with different radio sources and, by direct comparison with other clock synchronization systems, to within the accuracy of these systems.

3. To gain experience in operating VLBI systems so as to uncover potential problem areas and facilitate the design of a higher-accuracy, operational clock synchronization system.

Using one 64 m and one 26 m antenna, several sources were available which were strong enough to achieve resolutions of from 200 to 400 ns with about 1 million bits of data and 50 to 100 ns with several million bits. We believe that the system accuracy is consistent with these resolutions. However, the absolute accuracy could be confirmed only to the approximate 5–10 μs accuracy of LORAN C.

DESCRIPTION OF EXPERIMENTS

The three experiments were conducted on April 12, April 30, and June 11, 1973. On the first of these days, two 26 m antenna stations were used, DSS 12 at Goldstone and DSS 62 at Madrid. The last two experiments used the 64 m antenna at DSS 14, Goldstone together with DSS 62. To maximize the use of station time and to obtain a rough check on the accuracy, the last two experiments were run simultaneously with another VLBI experiment (conducted by J. Faneslow of JPL). The purpose of this other experiment was to measure the platform parameters, the source positions, and UT1. The two independent experiments agreed in their estimates of clock offset to within about 10 μs, the approximate accuracy of the platform parameter experiment.

The data were acquired and processed in the same manner as for the first clock synchronization demonstration.[1,2,3] Coherent bursts of about 0.31 Mbits of usable data, as limited by the computer memory size, were taken at 10 second intervals and recorded onto magnetic tape. Since the sampling rate was 0.5 Mbps, the burst length was only about 0.62 second, but the burst frequency was limited by the 200 bpi magnetic tape density. Each full tape of data consisted of 72 bursts. However, some tapes contained less data due to tape failures. In the joint experiments, the source schedule of the platform parameter experiment was followed, which sometimes allowed only 2 or 3 minutes between sources. When only one tape unit was operational, the number of bursts of data on each tape was reduced due to the time required to change tapes. Other short tapes were caused by tape errors.

The tapes were mailed to JPL for processing. The maximum likelihood estimator function[3] was calculated for each burst of data, and then the function values were accumulated in a nonoptimal manner over enough successive bursts of data to achieve an adequate estimator signal-to-noise ratio. The accumulation was nonoptimal only because fringe phase coherence was not maintained between bursts. This resulted in little degradation for strong input signal-to-noise cases, when only 2 or 4 bursts were required, but in significant degradation for weak sources and when both stations had 26 m antennas. The system was not designed to operate in these situations because too much data is required for satisfactory operation.

RESULTS

Estimates of clock offset were obtained for two tapes of data on April 12, using two 26 m antennas, and for ten and five tapes of data on April 30 and June 11, respectively, using one 26 m and one 64 m antenna. The nominal system temperatures were 17 K at the 64 m station and 37 K at the 26 m stations. Successful estimates were not obtained for all pairs of tapes on any day. On the first day, this was because the signal-to-noise ratios were too low on all but the strongest source. On the two days using the 64 m antenna, the failures are believed to be due mainly to tape failures. This is discussed further in the next section.

The clock offset estimates are presented in Table 1, together with estimates of the resolution obtained and of the amount of data required for reliable measurement. The first three columns identify the case by date, time (GMT), and radio source name. The fourth column indicates the number of subcases into which the data were divided, and the fifth column indicates the number of coherent bursts of 0.31 Mbits of data that were combined noncoherently in each subcase. The sixth column is the average estimate of clock offset for the case, in microseconds, with positive values indicating that the clock at DSS 62 is early. The seventh and eighth columns are the estimated resolutions for one subcase and for the entire case in nanoseconds. For cases with more than one subcase, the resolution for one subcase is taken as the sample standard deviation, and the overall resolution is this standard deviation divided by the square root of the number of subcases. For the four cases having such a low signal-to-noise ratio that there was only one subcase, the estimated resolutions were obtained from the value of the estimator function. These estimates are quite unreliable. The final column in Table 1 is the estimated amount of data required to obtain reliable estimates for that source, on that day, and with the system parameters used. It is the amount of data required for an estimator signal-to-noise ratio of 10 and a resulting resolution of 366 ns.

Data Requirements for Reliable Results

Of primary importance is that reliable results were obtained with four radio sources with one million or fewer bits of data when using the 64 m antenna. These sources are 4C39.25, OJ287, DA193, and NRAQ190. The flux densities were not estimated directly from the data, because this requires considerable additional computer time. However, from the estimator signal-to-noise ratios and

Table 1

Clock Offset Estimates, Estimated Resolution, and Data Required for Reliable Performance

Date, 1973	Time, GMT	Source	Number of subcases	Number of bursts per subcase	Estimated clock offset, μs	Resolutions for one subcase, ns	Resolution for entire case, ns	Minimum data required, Mbits
4/12	2152	4C39.25	4	36	134.63	345	172 (2 tapes)	10
4/30	1756	NRAQ190	15	4	125.77	340	90	1.1
	1812	3C84	8	8	125.17	510	180	5
	1845	DW0224+67	8	8	124.41	470	170	4
	1906	NRAQ190	6	8	125.59	220	90	0.9
	2118	3C371	1	38	122.7	400*	400*	14
	2203	4C39.25	8	4	125.49	190	70	0.4
	2242	QL553	1	72	126.6	370*	370*	22
	2300	QJ287	23	2	125.56	240	50	0.3
5/1	0007	3C371	1	54	123.3	220*	220*	6
	0022	4C39.25	9	4	125.24	150	50	0.2
6/11	1726	DA193	16	4	203.16	220	60	0.5
	1848	OI363	8	8	203.39	470	170	4
	1905	DA193	16	4	202.71	190	50	0.4
	1923	4C39.25	16	4	203.25	210	50	0.4
	1941	3C371	1	71	200.8	1000*	1000*	50

*For these cases the signal-to-noise ratio is so low that the estimates of resolution and data required may have large errors.

the nominal system temperatures, we estimate the correlated flux densities for these sources to range from 1 to 2 f.u. There are enough radio sources of this strength that clock synchronization is attainable at any time of day between DSS 14 and Spain or Australia. Similar performance will be achievable between Spain and South Africa when DSS 63, a 64 m station, is operational in Spain.

Resolution and Consistency

The results for the ten cases of April 30 are shown as a function of time in Figure 1. The straight line has a slope equal to the rate of change in the clocks, −0.6 μs/day, as predicted by the fringe rate data taken in the platform parameter VLBI experiment on that day. The error bars shown are the estimated resolutions. At best, the accuracy would be the resolution plus a degradation of up to about 100 ns due to propagation and geometrical effects. This should be added in a mean square sense. (There is also a constant error due to time delays in the stations, which would not show up in the results.)

Overall, all of the clock offset estimates fall as close to the straight line as expected except for the case for DW0224+67 and the two cases for 3C371. Although these sources are quite weak, especially 3C371, there appears to be some significant error for these cases. The cause for this error has not yet been satisfactorily explained. However, one likely cause is that the time delay predictions were in error due to the high declinations of the sources, +67 deg. for

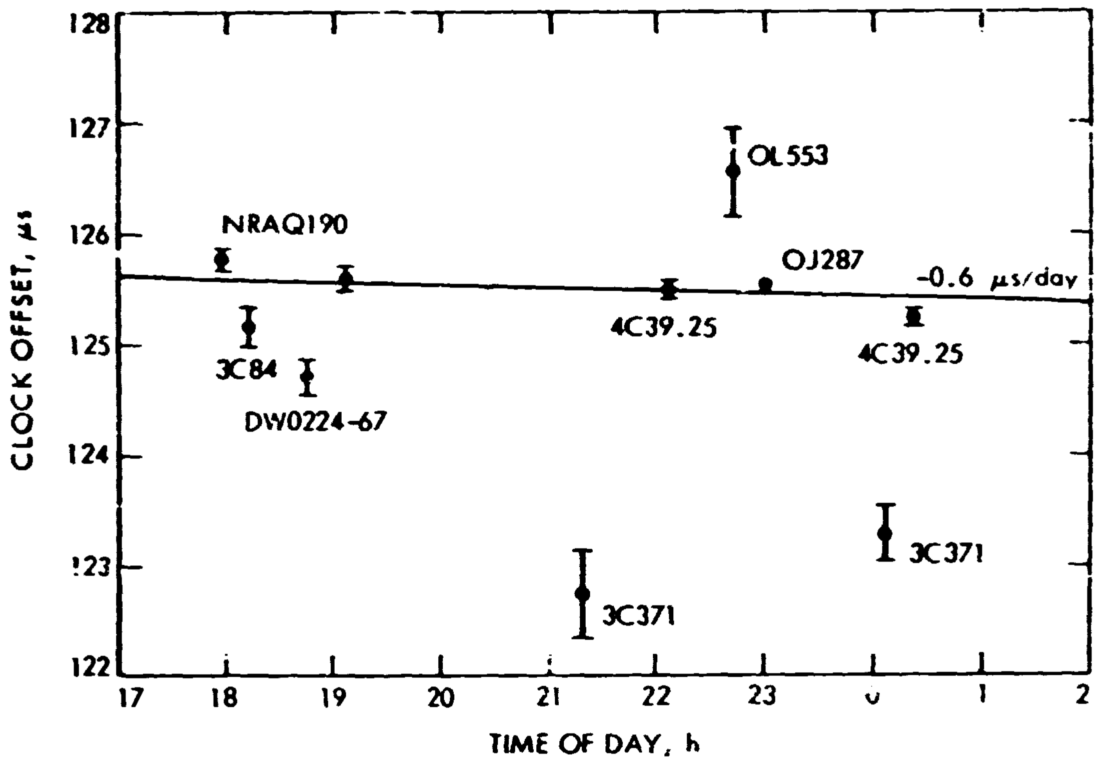

Figure 1. Clock Offset Estimates for April 30, 1973, with 1σ Resolutions

DW0224+67 and +69 deg. for 3C371. The highest declinations for the other sources are +56 deg. for OL553 and +41 deg. for 3C84. Furthermore, the geometry was so unusual for 3C371 that the received frequency was higher for DSS 62 than for DSS 14, just the opposite from the usual case, because the antennas were pointed on the opposite from usual sides of due north. This can happen only with high declination sources.

Comparison to LORAN C and Platform Experiment

The clock offset estimates obtained in these experiments agree with estimates made on each day using LORAN C, to within the approximate 5-10μs accuracy that could be expected. For the last two days, the results also agree with the VLBI platform parameter experiment, to the accuracy of that experiment. There was, however, a constant 200μs offset with respect to LORAN C. This was determined to arise because some of the 1 second period reference signals at DSS 62 occurred 200μs early because of reference to the wrong edge of a 200μs duration pulse.

The comparisons to LORAN C and the platform experiment are shown in Table 2. The first column identifies the experiment date. The second column is the

Table 2

Comparison of Clock Offset Estimates

Date, 1973	LORAN C uncorrected (DSS 62 to LORAN C), μs	LORAN C corrections (DSS 12/14 to LORAN C), μs	LORAN C offset estimate (DSS 62 to DSS 12/14), μs	VLBI platform parameter estimate, μs	Offset estimate of this experiment, μs
4/12	−62	+1	−61	–	−65
4/30	−74	+7	−67	84	−74
6/11	+3	−4	−1	−9	+3

difference between the DSS 62 and the LORAN C Mediterranean chain clock. The nominal accuracy is about 2 μs, but ambiguities often cause errors in 10 μs increments. The third column is the sum of all known corrections from the LORAN C Mediterranean clock to the DSS 12 or 14 clock, that is LORAN C to the U.S. Naval Observatory (USNO), USNO to the National Bureau of Standards (NBS), NBS to the Goldstone master clock and the Goldstone clock to DSS 12 or 14. Each of these legs introduces some error, typically on the order of 1 μs. The fourth column is the estimate of clock offset between the stations obtained from LORAN C. The last two columns are the offsets obtained by the VLBI platform parameter experiment and by this experiment, corrected for the known 200 μs error at DSS 62.

The clock offsets measured in this experiment agree with LORAN C to within an average of 5 μs and to the VLBI platform experiment to an average of 11 μs. These results are consistent with the accuracies of LORAN C and the platform experiment.

PROBLEMS, CAUSES, AND SOLUTIONS

The two major problems in the series of experiments were that results were not obtained for any day until the data from the last experiment were processed and that good results were not obtained at all for a number of cases for which the signal-to-noise ratio should have been adequate. A number of possible causes for lack of results were studied while an unsuccessful attempt was being made to process the data. These investigations will influence the design of the final operational system.

The delay in achieving results was caused primarily by the 200 μs error in the predicted clock offset. This area of clock offset was not searched until after the large offset error was discovered by the VLBI platform parameter experimenters. Even then, there was a delay in obtaining good results due to a discrepancy between the software and the hardware which was caused by a system modification made after the short baseline experiments. One of the ramifications of this [illegible] was overlooked. Aside from leading to a more complete analysis of the system, this processing problem will have no effect on the future system.

Search Range and Variable Bandwidths

The 200μs offset error will have an effect on the future system. It pointedly illustrates that large errors can occur, even when the system is supposedly calibrated with LORAN C. It also illustrates the problems which could occur if synchronization is lost and the best available timing information available is by radio broadcast, with errors on the order of milliseconds. An operational system should be capable of efficiently searching as wide a region of clock offsets as possible. This is best accomplished by enabling data acquisition with a number of selectable bandwidths and sampling rates. Lower bandwidths and sampling rates enable wider searches because the wide region encompasses fewer samples. Programmable digital filtering would be the most flexible and economical method for achieving this.

Local Oscillator Frequency Adjustment

One possible cause for bad data was that the third (10 MHz) local oscillator (LO) was offset at the Goldstone station in order to compensate for the fringe rate or doppler frequency difference. This LO was manually adjusted for each case, and it is possible that the frequency synthesizer was improperly set for some cases. This problem can be avoided by accounting for the fringe rate entirely in the data processing. There would be some cost in computer time.

Synchronization of Samples to Station Clock

Another possible trouble area is in synchronization of the samples to the station clocks. In these experiments, the hardware was resynchronized to the frequency and timing system (FTS) 1 pps and 1 MHz signals at the beginning of each burst of data, i.e., every 10 seconds. It would probably be more reliable to synchronize the system to the station clock only once for any experiment. Since the resolution of the present FTS is only on the order of 0.1 to 1.0μs, a higher-resolution clock will be required in any case for the more accurate clock synchronization system. This high-resolution clock could either be a part of the clock synchronization hardware or be in the form of a new timing system.

CONCLUSION

The prototype VLBI clock synchronization system has been demonstrated to operate as predicted over transcontinental baselines. Resolutions of 50-400 ns were achieved, and the accuracy is believed to be approximately the same. A wideband system is being designed which will achieve a resolution of 1-10 ns, depending on the available receiver bandwidth. The accuracy of this system will be limited by atmospheric and geometric effects and by errors in calibrating time delays in the stations rather than by the system bandwidth and resolution.

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QUESTION AND ANSWER PERIOD

MR. CHI:

Are there any questions?

DR. WINKLER:

What clocks have you used between the two stations for which you showed us before the last slide, the second to the last slide?

DR. HURD:

Well, all the experiments used rubidium. I think there might have been a maser at one station, but there was at least one rubidium in the system. That is the advantage to this type of system; since we are taking the data over such a short period of time, the oscillators ability isn't a problem.

DR. WINKLER:

May we see the second to the last slide again, because I have several questions on that.

(Slide.)

DR. WINKLER:

There is something on that slide which, I think, even if you have two very poor rubidium standards is simply incomprehensible.

DR. HURD:

Well, to fill this buffer in the existing system takes six tenths of a second — it is a 320 kilobit buffer being filled at a 500 kilobit rate.

DR. WINKLER:

Yes.

DR. HURD:

So, to —

DR. WINKLER:

But my question aims at clarification of the meaning of the error bars which you have here which evidently must be connected with your estimate of internal precision of each individual synchronization experiment. Evidently there must be very much larger external errors.

There simply is no clock which would jump around four, five or six microseconds between one and two hour intervals. Even the worst crystal would do much better than that.

So, you must have considerable external errors, which are completely ignored here.

DR. HURD:

Well, as I tried to point out, I haven't explained why the few larger error results occurred. These were weaker sources; they were in peculiar positions in the sky; and we didn't calibrate the atmosphere. The atmosphere couldn't cause that much error, though.

DR. WINKLER:

What sense do the error bars make then? If you put error bars on which appear to have absolutely no significance whatsoever --

DR. HURD:

Oh, the error bars represent the errors due to statistical errors and due to receiver noise.

The error bars are the observed standard deviations of the errors for that source. In other words, they are how consistent the measurements were for that particular source. For example, for the first point on the curve, I believe that one tape of data was divided into 18 cases. Each case was an accumulation of four of these batches of data. So that we had for each batch of data roughly one million bits of data for each of 18 cases. The error bars represent the standard deviation of the estimate for those 18 cases. In other words, it is how well we would have done, you know, if the system had been perfectly calibrated.

MR. CHI:

The error bars enumerate the number of data points?

DR. HURD:

Well, no. If you gather statistical data and you want to make an estimate of it as to how accurate you are estimating some parameters, you divide it up into several batches, and compute the sigma, the standard deviation of these batches, and then you divide that sigma by the square root of the total number of batches to get the standard deviation on the entire amount of data, and that represents the error just due to receiver noise, not due to atmospherics, not due to anomalies in the clock changing during the time. Well, you can see, even with the worst cases, there are not very many signals from the line, four or five sigma.

DR. WINKLER:

Yes, but what you seem to claim is that your clock essentially has shifted by several microseconds every few hours.

DR. HURD:

No, I am claiming that that measurement was a bad measurement. I am claiming that it was a poor measurement, it is a bad result. I am not just showing the good results.

MR. CHI:

There is a question, Dr. Reder.

DR. REDER:

Isn't there really a misunderstanding between the two of you? Are these measurements taken on the same day?

DR. HURD:

Yes.

DR. REDER:

They are taken on the same day?

DR. WINKLER:

Yes.

DR. REDER:

Then I will be included in the misunderstanding.

DR. HURD:

These are results on the same day, and they don't all agree. The results for the stronger sources do agree, as well as we expected. The results from some weaker sources have unexplained large errors.

DR. CLARK:

Tom Clark, NASA-Goddard. I have two questions or comments.

I would first of all be curious in making these clock calculations which you had here. You obviously have made some assumptions as to the positions of the sources, and the length of the baseline. That is, those factors included in the geometry.

It would be interesting to know what assumptions were made in that case.

Second of all, for the much wider band width system which you described, there is one effect which you didn't indicate how it would be taken out, about which I am curious. This is differential phase response over the pass band, which is going to cause an instrumental delay dispersion.

Do you plan some sort of instrumental phase calibration to be taken with this data?

DR. HURD:

I feel that since I am using the full continuous band width, phase stability requirements on the system will be less critical.

On the second point of view, to answer your question as to how good I expect this to be; the projections are for a total system stability, from and including the front end maser and the receiver system, which is supposed to be stable to 10 centimeters, over a 12 hour period or so, with certain assumptions on how much the temperature can change and things like that.

So, at the 10 nanosecond level, I think that the system stability will not play an important role here. I think that atmospherics will be dominating. I think that how good you do with the system depends on what you do with the atmosphere.

To get 10 nanoseconds, I think you would agree that we can probably a priori model the atmosphere that well, especially at S band.

DR. CLARK:

The question I was asking, however, had to do with the differential phase response over the pass band. You are going to just have to rely on the networks themselves calibrating that out for you.

DR. HURD:

The entire differential group delay is 10 centimeters, it can vary 10 centimeters over a day.

DR. CLARK:

No, I am talking about at one instant of time, over the pass band, the group delay which you are measuring, the time delay number you are measuring is essentially rate of phase change over the pass band. Now, from that, that number has to be subtracted from the instrumental phase response, and I was asking --

DR. HURD:

I don't even measure the phase.

DR. CLARK:

Well, that still has to be defined. This is a group delay, and group delay is $\Delta\phi/\Delta\omega$, so the instrumental phase response, the dispersion of the filters in the pass band are an important factor to you.

DR. HURD:

The tentative spec on the system is 10 centimeters for eight hours total change. That is, change in the total delay through the system.

Clearly, the differential delay at the two edges of the pass band is going to be much better than the total delay in the whole system.

DR. FLIEGEL:

Henry Fliegel, JPL.

I believe the question was that if you want to measure the absolute difference between two clocks at two different stations, that you have to calibrate the different phase delays and different channels that you are using.

DR. HURD:

I am not using different channels.

DR. FLIEGEL:

Or across the one channel that you are using then, if it is broad banded.

DR. HURD:

By utilizing the entire continuous band width, what you are buying, in a loose sense, is the average change in the group delay as a function of frequency, rather than being particularly concerned with the differential phase delay at two edge bands, and I think it is clearly easier to average this thing out.

DR. FLIEGEL:

Let's get together over coffee. I think that there is an issue here that we are not getting across.

DR. HURD:

That is not my area of expertise, in any case.

MR. KAUFMANN:

I have a question in regard to this system relative to moon bounce. Is it more economical, what kind of savings do you envision, and is the performance greater, and if so, how much better?

DR. HURD:

Well, performance is cetainly much greater. The moon bounce system accuracy is 10 to 20 microseconds.

The major cost of the moon bounce system is in maintaining the system. There is over a million dollars worth of equipment involved in the system, and if you make reasonable estimates as to what your average long term maintenance figures are going to be for this amount of equipment, it turns out to be quite a lot of money. The cost is considerably more than the amount of money which is now budgeted for maintaining that system, which is 40 thousand a year.

I mentioned to Bill that a VLBI system would cost in the neighborhood of a couple hundred thousand to build. This includes three data acquisition systems for a reliable digital system.

MR. CHI:

Thank you, Bill.