ONE NANOSECOND TIME SYNCHRONIZATION USING SERIES AND GPS

L. A. Buennagel
D. J. Spitzmesser
L. E. Young
Jet Propulsion Laboratory
Pasadena, California

Abstract

Subnanosecond time synchronization between two remote rubidium frequency standards is verified by a traveling clock comparison. Using a novel, code ignorant Global Positioning System (GPS) receiver developed at JPL, the SERIES geodetic baseline measurement system is applied to establish the offset between the 1 Hz. outputs of the remote standards. Results of the two intercomparison experiments to date are presented as well as experimental details.

INTRODUCTION

Traveling clock intercomparisons with better than a nanosecond agreement demonstrate that time synchronization is now possible using a new technique. The technique is known as Satellite Emission Range Inferred Earth Surveying (SERIES) and was developed at the Jet Propulsion Laboratory by a group with a background in Very Long Baseline Interferometry (VLBI.) The traditional sources for VLBI are quasars, distant and dim astronomical objects. The quasar signal strengths are five or six orders of magnitude less than the GPS satellite signals. Using brighter sources permits relaxing the severe discipline imposed on VLBI researchers, such as long observation times as well as high instrumental and frequency standard stabilities. The major departure from the VLBI approach is the absence of any bit stream alignment or correlation in the data reduction stage. The major inheritance for SERIES from the VLBI tradition is an irreverence for "codes"; indeed, it has been said that no one knows the code being broadcast by the quasars, but that has not kept them from being successfully used.

The SERIES technique, then, is built around a novel GPS receiver, one that does not have a preset bit stream generator inside; there is nothing correlating with the received signal. Instead, the SERIES receiver collapses the received spread spectrum signal, extracting the transitions of the spaceborne pseudorandom code generator. These transitions provide the event common to both stations for the baseline parameter estimation, the primary SERIES application.

EXPERIMENTAL OBSERVATION

The situation for a SERIES experiment is indicated in FIGURE 1. A GPS satellite is shown illuminating two SERIES stations, each with a rubidium standard. In this case, the standards are assumed to be synchronized, thus their ticks are shown aligned vertically. Moreover, at the moment depicted, exactly an integral number of half wave lengths of the transition fit between the satellite and the lower station antenna. For the assumed case of no phase delays in the receiver, the square wave output of the SERIES receiver is in phase with the received transition and with its station clock.

Note the second station's receiver output. A non-integral number of wavelengths fit in the path between the satellite and the antenna. With the assumed zero delay in the receiver, the square wave output has a phase shift relative to its own station clock. Each station's measured receiver phase is recorded. During data reduction, the receiver phases measured at the same time at the two stations are differenced. This phase difference is modeled as propagation delay due to the projection of the baseline onto the line of sight to the satellite. In addition, since the two standards are never synchronized in phase or frequency, effects of these two offsets are present in the difference data and must be solved for in the parameter estimation. It is the estimation of these effects that permits the SERIES technique to provide time synchronization.

Each square wave coming from the receiver looks like any other, so there is an ambiguity as to just which event in the train of square waves either station saw. This ambiguity can be removed either by adequate prior knowledge of the baseline or by a fuller treatment of the data as a Doppler differential positioning problem. For the demonstration goals of the current SERIES task, the a priori baseline data was provided at about the 100 meter level. The Doppler approach is being implemented and is expected to remove this requirement for the SERIES system.

PORTABLE STATION

Figure 2 shows the station used in the SERIES system. One such single man station is placed at each end of the line to be measured. The camper shell is required for shelter but is not very full. The whole system occupies three half-electronic equipment racks, a total of about eighty inches of front panel space. The receiver takes eight inches, the rest is taken up by off-the-shelf items for the data system such as a nine track tape deck, a computer, the HP5370A Time Interval Counter which is the main measurement device and the station's rubidium standard.

Behind the camper is the system antenna, which is rolled over the marker defining the end of the baseline. A stylus drops from the base of the mount in order to measure any geometric offset from the intended position. Above the wagon and pedestal are the television pan and tilt mount for steering the antenna, the dish or main reflector and finally the feed and ground plane. The dish is a homemade affair of bent aluminum and half inch wire mesh. The feed is a helix wound on a 16oz. plastic drinking cup and the ground plane is a 10 inch pie pan.

BASELINE ESTIMATION

Whatever doubts that may have been raised about the seriousness of this effort should be allayed by Figure 3, which depicts how well the parameter estimation process treated the observations. This figure shows the plot of the residuals to the data taken on the 24th of August, 1982; the other experiment to date, on the 23rd of August, had similar results. The baseline being measured at the time of these experiments was approximately 21 kilometers long, at JPL's Goldstone tracking complex in Southern California. The computed phase difference was derived from the five parameter solution: the three dimensional vector between the stations, the epoch offset between the station clocks and the frequency offset between those clocks. Plotted on a full scale of 4 nanoseconds are 101 residuals, which have an RMS scatter of .6 nanoseconds, typical for experiments run for this baseline. While they are not identified in the figure, observations on all five GPS satellites are present, normally one after the other for good sampling of the baseline components. This estimation was limited to the two and a quarter hours that all five satellites were in common view.

The time at which the epoch offset estimate is correct is the start of the observation run; this was chosen as the time to express the intercomparison results and is indicated on the residual plot by the vertical arrow. Also on the residual plot are two gaps, the first for a traveling clock visit to station A, and again, half an hour later, for a visit to station B.

CALIBRATIONS

The transitions extracted by the SERIES receiver are found in three guises as broadcast by each GPS satellite, one at 1.023 MHz. on the upper broadcast frequency, designated L1, and two at 10.23 MHz., one on L1, and a second on the lower frequency, designated L2. A measurement of the delay from the L1 10.23 MHz. transition to that on L2 permits a direct calibration of the ionospheric delay along the line of sight to the satellite, much as in the standard GPS (two channel) receiver. The SERIES system obtains this calibration for each observation, removing ionospheric delay as an error source.

Because the SERIES system was not designed for time synchronization, two ancillary measurements were required for absolute clock difference measurements. During each day's experiment, the phases of certain local oscillators at each station were measured relative to the station clock using the same Time Interval Counter as was used for the other phase measurements.

In addition, it was necessary to measure the differential total delay through the two stations. This calibration was made on the 25th of August. Both stations were located at Station A and operated as on other occasions, except that the geometry was known and the clock bias was eliminated by operating both stations from the same frequency standard. The parameter estimation results were used to derive the differential total system delay. Again, "differential" is used because the absolute system delay is not obtained but only the difference between the two stations. The system differential as well as the second day's single cycle ambiguity were applied to obtain the final SERIES value for the station clock offsets.

TRAVELING CLOCK

The independent verification of the station clock offsets was a traveling clock measurement. The measurement setup is indicated in Figure 4, with the traveling clock visiting station A. The HP5370A Time Interval Counter (TIC) measures the offset between the host clock and the traveling clock. (By way of comparison, the figure notes the use of the TIC for the baseline estimation setup; in this case, the TIC is started on the host clock tick and stopped at a predetermined point on the receiver output waveform.)

Figure 5 presents the traveling clock data for the 24th of August. Each dot plots the average of 100 measurements of the time delay between the 1 Hz. outputs of the station clock and traveling clock. Typical RMS deviations of each of the 100 measurements were a half nanosecond. The lines, here hand drawn, depict the fit to the data taken at each station. A third order polynomial was used in order to interpolate the two station clock offsets to a common epoch. The RMS errors to the fits were about a half nanosecond. The common epoch for this day's intercomparison with the parameter estimation results is indicated by the vertical arrow. Note that the 1300 nanosecond offset exceeds the SERIES ambiguity interval of 997 nanoseconds. One ambiguity interval was added to the parameter estimate for this date.

The sequence of data points, alternating between the two stations, shows there were two and a half round trips for the traveling clock; the same was done on the 23rd. The effort spent on the repeated trips gave us confidence that there were no clock breaks in the traveling clock. Pains were taken in the measurement technique to insure repeatability, such as using digital voltmeter settings to define the reference points on the clock output wave forms, and using the same cables for connecting the traveling clock at each station. The traveling clock measurement can be seen to be accurate to about 0.5 nanosecond. This is reasonable performance for the HP 5065A Rubidium standard with (delta f)/f at one hundred seconds of $5x10^{-13}$, given a mean of about 10 minutes between measurements:

$$(5x10^{-13}) \text{ x 10min x 60sec/min x square root(2 clocks)} = 0.4x10^{-9}\text{sec.}$$

RESULTS

The results are tabled in Figure 6. The second column contains the SERIES determined offset between the two station clocks at the date and time listed in the first column. The third column contains the traveling clock estimate of the clock offsets, interpolated by means of the polynomial to the time shown in the first column. The difference between the methods was .6 nanoseconds for the first day and -.6 nanoseconds for the second.

In summary, the subnanosecond intercomparison of the clock offsets shows the SERIES technique to have more than just promise as an economical and flexible method for time synchronization with performance that will not degrade should the satellite codes involved pass from public access.

The authors would like to acknowledge the able assistance given to this experiment by Earl Lobdell, Sharon Schmitt, Ben Johnson, Bob Newsted, Mark Smith, and Jess Myers.

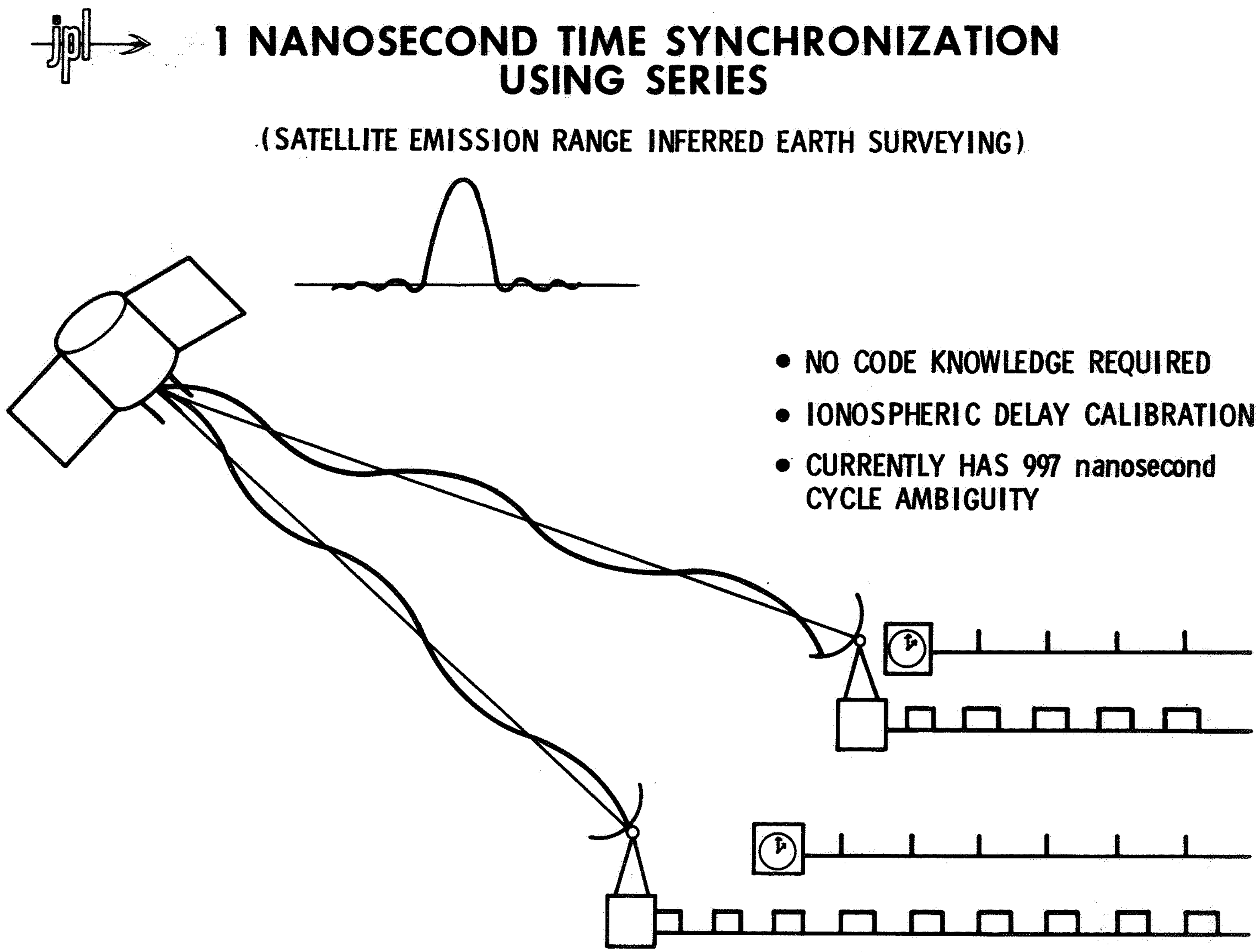

Figure 1. SERIES observable for parameter estimation.

Figure 2. SERIES portable station.

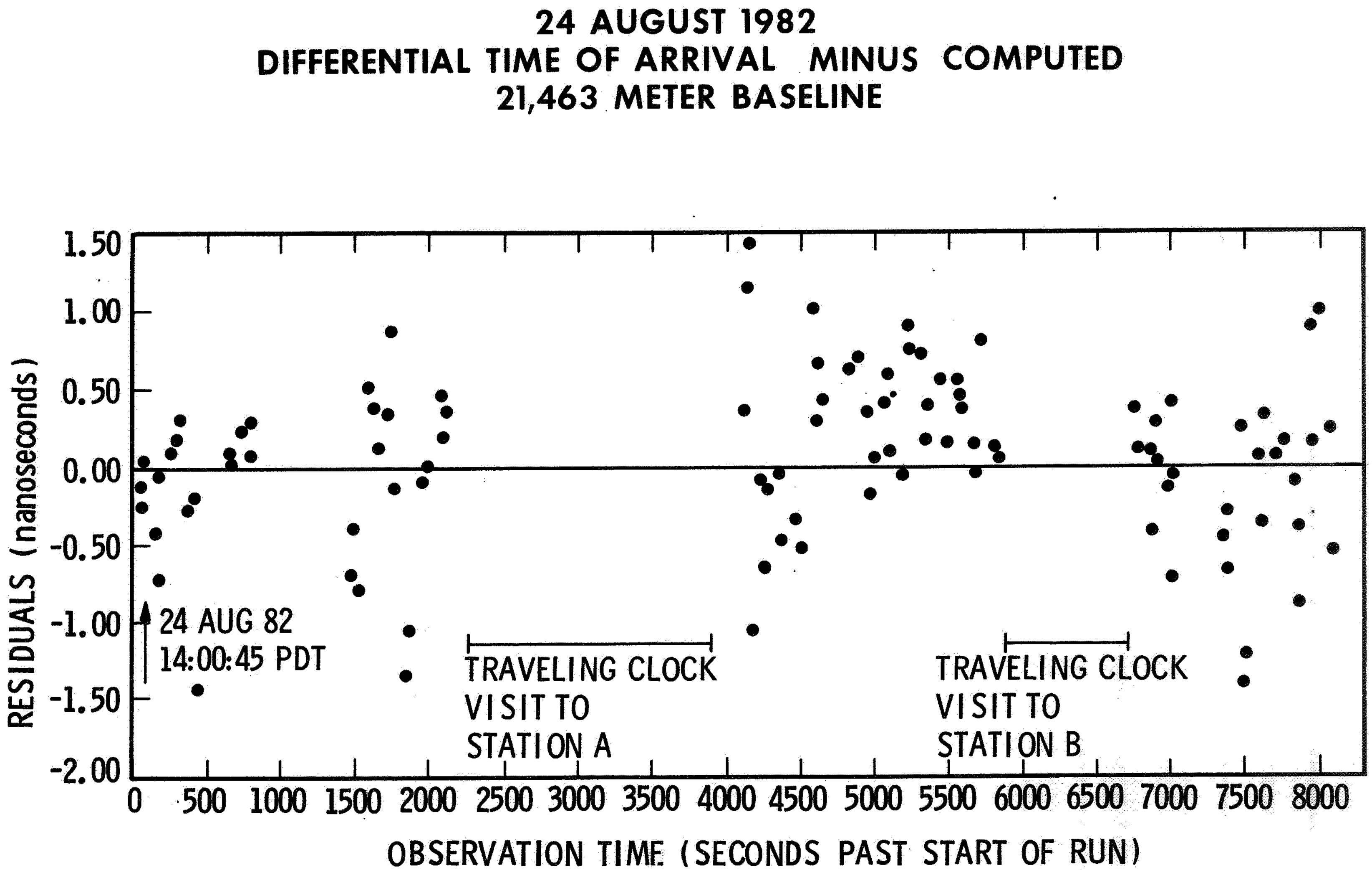

Figure 3. Residuals to differenced delay measurements.

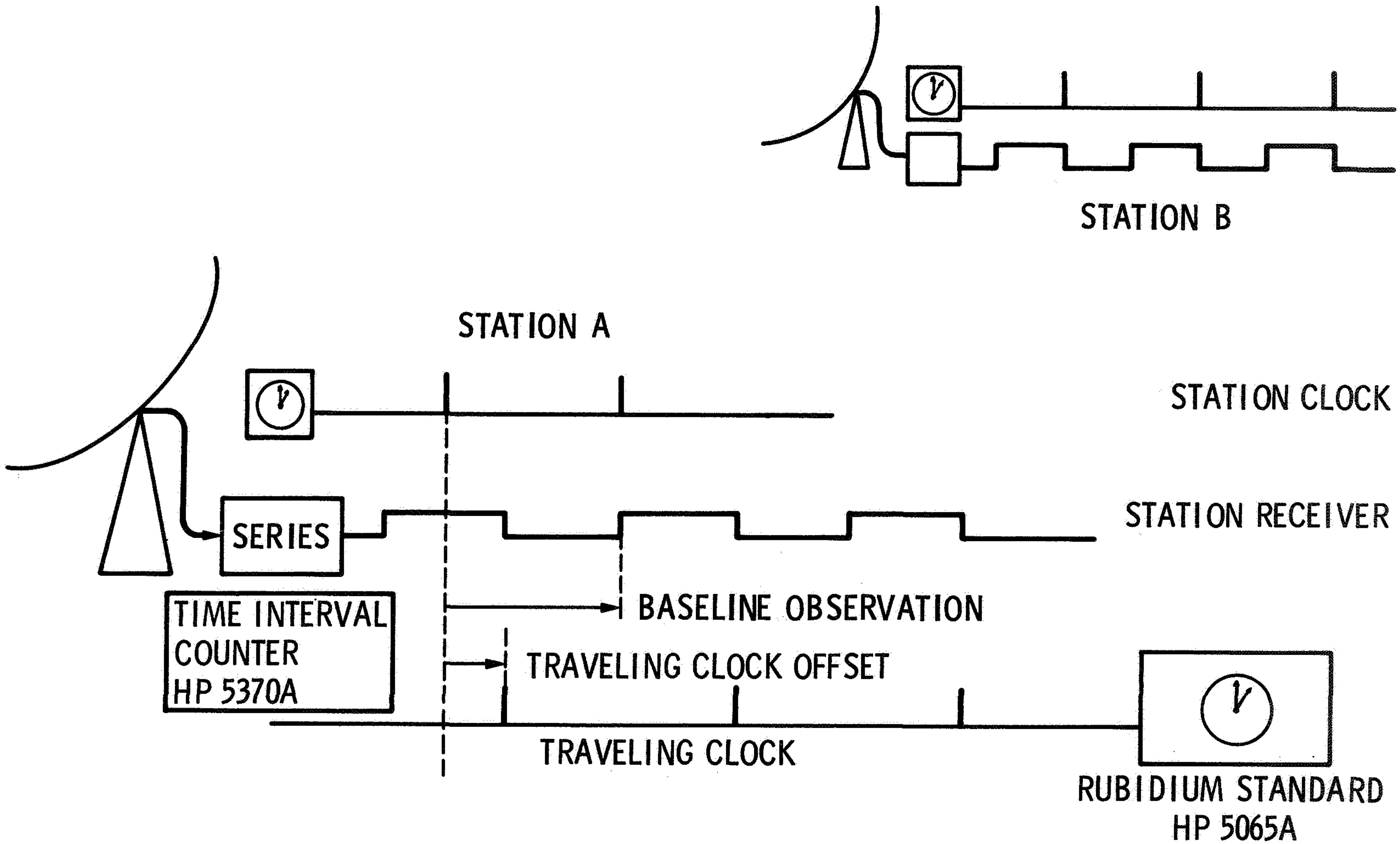

Figure 4. Measurement during traveling clock visit.

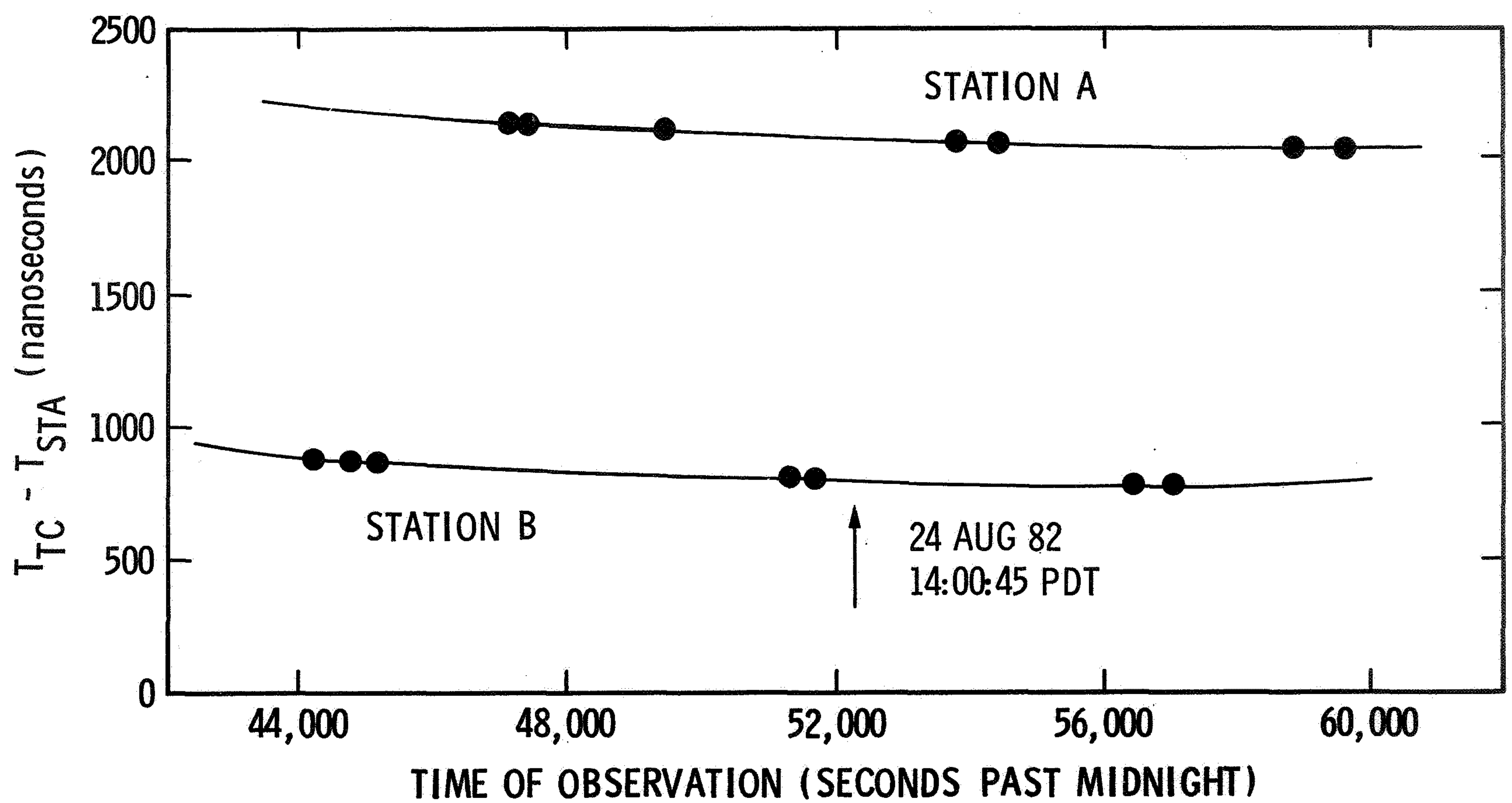

Figure 5. Offsets to traveling clock for each station.

	$t_{STA\ A} - t_{STA\ B}$ SERIES RECEIVER	$t_{STA\ A} - t_{STA\ B}$ TRAVELING CLOCK	DIFFERENCE BETWEEN 2 TECHNIQUES
23 AUG 82 14:36:45 PDT	-189.7 ns	-190.3 ns	+0.6 ns
24 AUG 82 14:00:45 PDT	-1302.0 ns	-1301.4 ns	-0.6 ns

- SERIES MEASUREMENT INCLUDES
  - MEASURE MIXER PHASE AT EACH RECEIVER
  - COLOCATE TO CALIBRATE TOTAL SYSTEM DELAY

Figure 6. Comparison of SERIES and traveling clock values.

QUESTIONS AND ANSWERS

MR. D. W. ALLAN, National Bureau of Standards

One comment and two questions: I believe that is the 5370 counter, is it not?

MR. L. A. BUENNAGEL, Jet Propulsion Laboratroy

53 or 5070, I don't know. The digit is at the wrong place.

MR. ALLAN:

Okay, fine. How do you determine the ephemeris for the satellite? What do you use for the ephemeris estimation?

MR. BUENNAGEL:

Okay. We have two problems. First of all it is a steered antenna, as you see, so we need to know where to point. For that, the Vandenberg Master Control Station provides, on a week or two basis depending on when we are calling up, et cetera, orbital parameters which are an almanac class message in the upload. Post facto, some two weeks or so after the observation, we get a tape from Anderle's group at the Naval Surface Weapons Center. I do not know what that tape is, and I have questions about it. I am afraid that it is the prediction tape sent to Vandenberg. The hope, in contrast, is that really is, as advertized, the 5-minute center positions of the satellites, so we use the post facto for the ephemeris positions of the satellites.

MR. ALLAN:

The second question is, how large a baseline do you think you can go up to?

MR. BUENNAGEL:

This experiment was terminated at the line shown here by bringing one end of the baseline back to JPL. That's 171 kilometers, a factor of eight. We expect to be able to do that. Our experience has been that we do better the further out we get. I do not want to advance an estimate that we are going to move baselines further out. We'll see what happens.

DR. KELLOGG, Lockheed

When you talk about some nanosecond precision, or whatever you choose to call it, the difference between the two, you described an antenna built in not only an imprecise manner but one which gave one pause. The distances you are measuring are from the phase center of an antenna to some other source, using VLBI techniques. Is the phase center of this tracking, non-rigid antenna reproducable within the sub-nanosecond level, converting to the speed of light, that's a pretty few centimeters?

MR. BUENNAGEL:

You are striking on an article of faith of the VLBI community that I personally have called into question. The argument goes, suppose there is a phase center not at the assumed geometric intersection of axes, which is the solution point. If it is off-axis, which would be argued against on the basis of symmetry, you would not be sampling that component because it is normal to the incident ray wavefront. If it is along axis of the antenna, it is indistinguishable from a clock term, which then in turn is lumped into the final step, namely the differential total station delay calibration required.

So you have ferreted out a nice matter. I have given the doctrine, the dogma, on how to deal with that, but I have my doubts, and given some time I want to investigate that.

DR. KELLOGG:

I'm glad you do. Thank you.

MR. BUENNAGEL:

A question in the back?

MR. J. M. PRZYJEMSKI, Draper Laboratories

Have you at any time measured any of these baselines using, perhaps, a surveying technique?

MR. BUENNAGEL:

Yes. We have measured baselines of zero meters out to two meters, 150 meters, and now this one, which are in fact known to three more places than I put on the graph.

MR. PRZYJEMSKI:

So that would be a third means of supporting these time transfer results that you have.

MR. BUENNAGEL:

The result of the comparison on this longest baseline is in agreement with the hybrid of the National Geodetic Survey answer and a VLBI measurement along the baseline of 2.2 centimeters length at the current time, but that really is a result that has to be described elsewhere, under other circumstances.

MR. PRZYJEMSKI:

I see. Another comment is, you mentioned that the further your baseline, the better you feel the results might be.

MR. BUENNAGEL:

No, just the better they appear to be.

MR. PRZYJEMSKI:

They appear to be. Would you feel that your ability to measure or compensate for differential ionospheric delays might cause you to have a greater error with increasing baseline length.

MR. BUENNAGEL:

In fact, none of the solutions to date have used the ionosphere calibration delay information. This six-tenths of a nanosecond agreement that we have here doesn't use that information. Moreover, it doesn't use any kind of atmosphere correction. At Goldstone that may not be so terrible, because it is very dry, its level, the winds are still. It is obvious that the more we push this, the more we are going to have to use other forms of data.

MR. PRZYJEMSKI:

Did you use L1NO2?

MR. BUENNAGEL:

We do routinely record that. It was touted as our first product but in fact we don't use it in any of that.

MR. PRZYJEMSKI:

Certainly that would give you a good result if the baseline was short, where the differential on the ionosphere may have a small or negligible effect on the result.

MR. BUENNAGEL:

We are a little bit pessimistic right now because the noise on the ionosphere delay is worse than the gain you get back putting in the corrections.

MR. PRZYJEMSKI:

I see. Thank you very much.

DR. VICTOR REINHARDT, Bendix Field Engineering Corporation

What technique do you use to extract the time ticks without knowing the code?

MR. BUENNAGEL:

It is described as a power divide, shift, and multiply technique. It is documented in a patent application on file under the name of Peter McDoren, the person who developed this technique. I am not a radio person. I cannot go into the details of that. I believe that you can find this application that has been documented.

I would enjoy a question from Dr. Alley, my former employer.

PROFESSOR ALLEY, University of Maryland

Thank you. I am a little surprised you have such good agreement on this traveling clock, Al. Did you take precautions to protect it during this transit?

MR. BUENNAGEL:

I have been alerted to expect challenge on that side. I am hiding behind the word "agreement" here. You will notice that there was some rigor used here, namely, more than one round trip and more than one day, as I have noted. I doubt that there was any protection at all. It was placed gently in a car and driven but beyond that, I did not make the trip myself so I do not know what the protection was.

PROFESSOR ALLEY:

I see. Thank you.

MR. BUENNAGEL:

Dr. Winkler?

DR. WINKLER:

Two things: The principle of collapsing a pseudo random noise code consists in compensating for the phase modulation. In case of simple $\pm$ 180 degree phase modulation, at whatever rate and in whatever pseudo random sequence, if you multiply your I.F. frequency by two, the result will always be zero phase angle, whether it is 180 or zero, and exactly the same thing can be done with whatever phase modulation you have, just that it has to be more complicated. This in fact is the technique which is used to track the pseudo random noise with VLF receivers.

But I have another question: You have emphasized that you don't need the code but you do need the ephermeris, and of course in the moment the code is withdrawn I doubt that you will have the ephermeris without being authorized.

MR. BUENNAGEL:

That, I think, will be a politcal question, and the answer thus far has been that because we are a nontactical user, that we may have the solution after the fact, two weeks, et cetera. Again, in a tactical or a real time point of view, that is terrible, but relative to the VLBI experiment that runs for days itself before the data is gathered, let alone the solution, 2 weeks is wonderful.

MR. L. J. RUEGER, JHU/APL

I was wondering if you could support the independent phase stability of these rubidium standards to that quality actually as independent time pieces, because half a nanosecond over that length of time is really quite remarkable.

MR. BUENNAGEL:

Again, I am hiding behind the word "agreement". I am familiar with documented properties, et cetera, but I think we have something.

DR. VIG:

Thank you for a most interesting paper, as evidenced by the number of questions.