Time and Position Accuracy using Codeless GPS

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December 7, 1993

Abstract

The Global Positioning Systêm has allowed scientists and engineers to make measurements having accuracy far beyond the original 15 meter goal of the system. Using global networks of P–Code capable receivers and extensive post–processing, geodesists have achieved baseline precision of a few parts per billion, and clock offsets have been measured at the nanosecond level over intercontinental distances. A cloud hangs over this picture, however. The Department of Defense plans to encrypt the P–Code (called Anti-Spoofing, or AS) in the fall of 1993. After this event, geodetic and time measurements will have to be made using codeless GPS receivers.

There appears to a silver lining to the cloud, however. In response to the anticipated encryption of the P–Code, the geodetic and GPS receiver community has developed some remarkably effective means of coping with AS without classified information. We will discuss various codeless techniques currently available, and the data noise resulting from each. We will review some geodetic results obtained using only codeless data, and discuss the implications for time measurements. Finally, we will present the status of GPS research at JPL in relation to codeless clock measurements.

1. Introduction

The Global Positioning System (GPS) consists of a constellation of satellites (currently 27) which broadcast ranging signals. When four or more of these signals are tracked by a ground receiver, it is possible to solve for the position and clock of the ground receiver if the orbits and clocks of the satellites are known. If several receivers are tracking the satellite constellation simultaneously, the position and clock of each ground receiver, the orbit and clock of each satellite and some earth orientation and media parameters can all be solved for.

Using the International GPS Geodynamics Service (IGS), a global network including approximately 50 Rogue and TurboRogue GPS receivers, analysts at the Jet Propulsion Laboratory and several other GPS processing centers have demonstrated that it is possible to determine absolue geocentric receiver positions to a few parts in 10^9 (corresponding to 1 cm level coordinate accuracy anywhere in the world) [Heflin, *et. al.*, 1992; Blewitt *et al.*, 1992]. GPS satellite orbits are simultaneously adjusted in these global solutions to about 35 cm (RSS 3–D) accuracy and receiver clocks to about 0.3 ns, based on consistency tests carried out at JPL. With the addition of data from low earth orbiting receivers such as the one on the TOPEX/Poseidon spacecraft, solution accuracy improves still further, with GPS orbits improving to $\approx$ 25 cm [Bertiger, *et. al.*, 1993]. All of these results were obtained using the full P–Code precision. In the near future, the GPS P–Code will be encrypted. What impact will this have on GPS results?

2. Global Network GPS Solutions

The method used at JPL to produce GPS results involves using a network of globally distributed ground receivers which obtain radiometric observables from all satellites in view (up to eight) at each ground station. This is shown schematically in Figure 1. The primary observable obtained by the receivers is the carrier phase as a function of time. The pseudorange, smoothed over a track, is used to establish the *a priori* bias of the carrier phase. The carrier phase, shown in Figure 4, provides a much more precise measure of satellite range variation than the pseudorange, as can be seen in Figure 3.

Because each ground station sees several satellites and each satellite is viewed by several ground stations, enough data are available to estimate not only the ground station positions and clocks, but also to estimate the satellite orbits, the effects of the troposphere, earth orientation, and geocenter. By accurately estimating and modeling these parameters and error sources, solution error is approaching the limit imposed by long period multipath and unmodeled tropospheric signal delays. Multipath reduction and enhanced modeling of tropospheric path delays are ongoing efforts at JPL.

It is important to note that the strength of the clock solutions results from a combination of the carrier phase and pseudorange observables produced by the receivers. The carrier phase is less noisy than pseudorange by a factor of about 500. Thus, the carrier phase can be used to precisely track the variations of the receiver (and transmitter) clock. When these variations are removed from the pseudorange data, the noisy pseudorange can be averaged over an entire satellite pass to produce a single "phase bias" number. When this bias is added to the carrier phase observable, a measure of range results which tracks variation in range with extreme precision (better than 1 mm over 1 second) and has a constant offset that provides absolute range with high precision ($\approx$ 10 cm).

Further improvements in the estimates of satellite orbits and media effects have resulted from the addition of the P–Code GPS receiver on the TOPEX/Poseidon spacecraft. Because this satellite orbits the earth every 112 minutes, it provides much stronger dynamical and geometrical information about the location of the GPS satellites than the ground stations do. Similarly, the location of TOPEX/Poseidon can be determined very accurately due to the strong geometry. Currently, TOPEX/Poseidon orbits are believed to be accurate to 3 cm in the radial direction [Bertiger *et al.* 1993], and GPS orbits determined simultaneously in a global network solution which includes Topex GPS tracking data are accurate to approximately 25 cm RMS (RSS over all three components) [Bertiger *et al.* 1993].

The combination of these advances has enabled the results quoted in section 1.

3. Effects of Anti–Spoofing

The unencrypted GPS signal consists of a dual frequency carrier at frequencies L1 = 1.57542 GHz and L2 = 1.2276 GHz biphase modulated with ranging codes. The L1 carrier is modulated with a 1 MHz Gold code, known as the C/A code, and, in quadrature, a 10 MHz pseudo–random noise code (PN–code) known as the P1 code. The L2 carrier is modulated only with a 10 MHz code, P2. In order to track the ranging codes, the receiver's code generator must been matched to better than one code chip of the incoming code, or 1 microsecond for the C/A code and 0.1 microsecond for the P codes. This makes the C/A code easier to acquire than the P code, but a more significant factor is that the C/A code repeats every ms, while the P code does not repeat until a week has past. The L2 signal exists to reduce errors resulting from the ionosphere. The ionosphere introduces a dispersive signal delay, which can be used to determine the ionospheric delay from the difference in delay between the P1 and P2 ranging codes. There is no C/A code on the L2 carrier.

In order to control the accuracy with which users of the GPS are able to determine their position using a single GPS receiver and to protect against intentionally generated interference of the P–codes (spoofing), the defense department has implemented two security measures. These are selective availability or "SA", and anti–spoofing, or "AS".

Selective availability degrades user accuracy by introducing errors into the broadcast satellite ephemerides and by varying the satellite clock rate. Single station errors due to SA can be as large as 300 m. GPS users utilizing "double difference" processing suffer no measurable degradation in performance due to SA. Because different receivers view common satellites, the variations in the satellite clock can be solved for. Similarly, because GPS satellite orbits are estimated in the network solution, the solution is not sensitive to broadcast ephemeris errors. Anti–Spoofing degrades user accuracy in a more significant way. When AS is turned on, the P-Codes are encrypted so without classified information the receiver is unable to correlate its model code with the broadcast signal. The C/A code remains unencrypted, but due to its longer period, only 1/2 to 1/10 the pseudorange precision is available. Because there is no C/A code on the L2 carrier, it can not be tracked directly, which limits or eliminates the ionospheric information available to the user.

Commercial GPS receiver manufacturers have devised several strategies to recover some of the information which is obscured by AS. All of these designs use some aspect of the broadcast signal, determined by observing the encrypted broadcasts, to remove some of the encryption.

Squaring & Delay and Multiply:

The fact that the ranging codes are modulated onto the carrier using a bi–polar ($\pm$ 1) modulation can be used in truly codeless receivers by squaring the incoming signal. Because $(-1)^2 = (+1)^2 = 1$, the squared signal is free of code modulation, encrypted or otherwise. After squaring, the remaining carrier can be tracked to provide high precision Doppler information. However, all pseudorange data is lost, so squaring receivers are not very useful for clock synchronization. A variation on the squaring technique which produces a range observable is delay and multiply. By delaying the received signal by 1/2 chip and multiplying by the undelayed signal, the 10 MHz P–Code clock can be extracted from the sign changes in the P–Code. This produces a range to the satellite which is ambiguous to the 30 m period of the clock. This ambiguity can be resolved through knowledge of the satellite orbit. This technique has been used to demonstrate sub–nanosecond time transfer over short baselines [Buennagel *et. al.*, 1982], but no commercial receiver implementing this strategy exists. Note that in squaring and delay and multiply, the noise is squared as well as the signal, so SNR is degraded compared to code mode by approximately 30 dB for high satellites.

Cross Correlation:

Other codeless designs use the fact that the encrypted P–Code broadcast on L1 and L2 are the same. The simplest exploitation of this is to cross correlate the L1 and L2 signals. This is the codeless scheme implemented in Rogue and TurboRogue GPS receivers, designed at JPL. In the Rogue codeless scheme, L1 data is derived from the C/A code. The L2 carrier phase and pseudorange are determined by cross–correlating the L1 and L2 signals, and adjusting the relative delay and phase until the correlation amplitude is maximized. This results in a differential phase and delay measurement between L1 and L2. The L2 observables are recovered by adding the C/A measurement to the difference measurements for phase and delay, respectively. A schematic of the cross-correlation process is shown in Figure 2.

Figure 5 shows estimates of the of the errors expected in TurboRogue codeless processing when the data is processed as part of a global network with 24 hours of continuous tracking. Multipath, cable and filter instabilities are shared with code mode tracking, and were included in the code mode results quoted above.

Cross correlated data is "less good" than normal p–code tracking in four respects. Most significantly, when L1 is correlated against L2, the noise of both channels is multiplied together. This results in a loss in SNR of approximately 20 dB for strong satellite signals (greater than 50 degrees elevation), and more for weaker signals. Even with this loss, carrier phase noise is insignificant to clock synchronization. Using the carrier smoothing technique discussed above, the pseudorange data can be smoothed over an entire satellite pass ($\approx$ 6 Hr.) to result in the 0.07 ns error given in Figure 5.

Another error results because, in TurboRogue, the relative delay between the L1 and L2 signals can only be controlled in 50 ns steps (the "Lx Lags" shown in Figure 2). In code mode, the feedback can be used to exactly match the delays of the receiver's code generator and the received signal. In cross correlation mode, though, due to the 50 ns lag spacing, it is usually not possible to directly match the delays of the L1 and L2 signals, but, rather, it must be calculated from measurements made at other delays. This requires a detailed knowledge of the shape of the L1 x L2 cross correlation amplitude. Errors in this model contribute 0.25 ns, labeled "Amp. vs. Lag Modeling" in Figure 5.

A third error results because the C/A code is used for the L1 observables. This error results from two level sampling and is proportional to the cube of the single sample voltage SNR. This error is labeled "Two–Level Sampling" in Figure 5 and contributes approximately 0.1 ns. This error is insignificant in code mode, because the P–code SNR is lower by 3 dB, and the chip length is shorter.

Of less significance, because cross correlated data is processed differently than p–code data, the total measured delay will be different. This has the effect of introducing a bias between code and codeless data. The constant part of these biases should not affect clock synchronization, because they can be measured and recorded. This can be operationally troublesome, however. The magnitude of this bias is $\approx$ 2 ns in TurboRogue, and tens of nanoseconds in Rogue.

Enhanced Cross Correlation:

The cross correlation technique can be improved by determining properties of the encrypted signal from observation and then applying this knowledge to algorithms which reduce the bandwidth of the encrypted signal. By reducing the bandwidth, more noise can be excluded from the measurement, and a higher SNR obtained. In theory, enhanced codeless can result in SNR's 13 dB higher than cross correlation, or only 7 dB lower than code mode for strong signals. No receiver manufacturer has yet published results that we know of living up to this promise, however.

Enhanced cross correlation implementations will invariably suffer from some of the errors shown in Figure 5. The precise values of each error depend on proprietary details of the implementation, and may be available from the manufacturer.

PPS/SM:

Finally, it should be mentioned that users authorized by the DOD can recover the full precision of the p–code by using a (classified) PPS/SM module to decrypt the encrypted signals.

4. Experimental Test of Codeless Clock Synchronization

In order to test the error predictions given in Figure 5, we observed the clock estimates for three TurboRogue receivers whose frequency references were connected to hydrogen masers. By looking at the change in the receiver clocks when AS was turned on, we get a crude estimate of the accuracy of codeless time transfer as compared to code mode operation. We refer the reader to Dunn, *et. al.* [1991] for a discussion of external tests of code mode time transfer accuracy.

The data used in this analysis were taken from September 22, 1993 through September 25, 1993. GPS week 715 was chosen specifically because anti–spoofing was on during part of this week. The data contains carrier phase and pseudorange measurements from 24 available GPS satellites tracked by approximately 42 globally distributed JPL Rogue receivers. The data were processed in the JPL precise orbit determination and parameter estimation software, GIPSY/OASIS II (GPS Inferred Positioning SYstem, [Lichten & Border, 1987 and Sovers & Border, 1990]). All non–fiducial station locations were estimated, as well as earth orientation parameters, GPS carrier phase biases, random walk zenith troposphere delays for each tracking site, and all transmitter and receiver clocks, except the clock at North Liberty, which was used as the reference clock. The coordinates of five "fiducial" site's were held fixed (unadjusted) in order to define the reference frame. The clocks were estimated as white noise parameters for each measurement epoch (no a priori constraint was applied to tie clock estimates at one time to clock estimates at another time). This is essentially a standard filtering strategy commonly used in precise geodetic analysis of GPS data. X and Y polar motion, polar motion rates, and UT1–UTC rates were estimated as constant parameters (reset every 24 hours). On days when AS was not in effect the GPS orbits were estimated with 5 solar radiation pressure parameters, 2 parameters estimated as constants and the 3 remaining parameters estimated as stochastic corrections to the constant solar pressure parameters. When AS was in effect, only the constant parameters when estimated for solar radiation pressure.

Figures 6 and 7 show the clock estimates for GPS TurboRogue tracking sites at Pie Town, New Mexico and Westford, Massachusetts relative to North Liberty when AS was turned on at the end of the day (UTC) September 23. The code mode data was taken from the Sept. 23 solution, while the codeless data was taken from the solution of Sept. 24. This increases the effect of clock errors due to errors in satellite orbits, troposphere estimation, and earth orientation parameters which would difference out if taken from the same solution. This test is not sensitive to errors due to delay variations in receiver hardware. Accounting for the clock rates, the shift in the estimate was 0.22 ns for Pie Town, NM and 0.72 ns at Westford, MA, both measured relative to North Liberty, IA. By subtracting these estimates, we find the clock jump between North Liberty and Pie Town was 0.41 ns. These are consistent with the estimates in Figure 5.

5. Conclusions

The GPS system has the potential to produce sub–nanosecond clock offset measurements over intercontinental distances. Anti–Spoofing increases the noise in the radiometric observables, but by using carrier smoothed pseudorange, the system noise error can be reduced to a level well below that expected from multipath. While biases between code and codeless operation result in operational difficulties, sub–nanosecond clock synchronization should still be possible with AS turned on.

Acknowledgments

The authors would like to thank Jim Zumberge and Willy Bertiger for their help in understanding the detailed processing of pseudorange by GIPSY. The research described in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

- Bertiger, W.; Wu, S.; Yunck, T.; Muellerschoen, R.; Willis, P.; Bar–Sever, Y.; Davis, A.; Haines, B.; Munson, T.; Lichten, S.; and Sunseri, R.; *"Early Results from the Topex/POSEIDON GPS Precise Orbit Determination Demonstration"*, AAS/AIAA

Spaceflight Mechanics Meeting, Pasadena, CA, Feb 22–24, 1993, paper AAS 93–154 [AAS, PO Box 28130, San Diego, CA 92198].

- Blewitt, G.; Heflin, M.; Webb, F.; Lindqwister, U.; and Malla, R.; *"Global Coordinates with Centimeter Accuracy in the International Terrestrial Reference Frame Using GPS"*, Geophysical Research Letters, Vol. 19, pp. 853–856, 1992.
- Buennagel, L. A.; Spitzmesser, D. J.; and Young, L. E.; *"One Nanosecond Time Synchronization Using Series and GPS"*, procedings of the 14th Annual Precise Time and Time Interval (PTTI), 1982. NASA Conf. Pub. 2265.
- Dunn, C.; Lichten, S.; Jefferson, D.; Border,J.; *"Sub-Nanosecond Clock Synchronization and Precision Deep Space Tracking"*, Procedings of the 23rd Annual Precise Time and Time Interval (PTTI), 1991. NASA Conf. Pub. 3159.
- Heflin, M.; Bertiger, W.; Blewitt, G.; Freedman, A.; Hurst, K.; Lichten, S.; Lindqwister, U.; Vigue, Y.; Webb, F.; Yunck, T.; and Zumberge, J.; *"Global Geodesy Without Fiducial Sites"*, Geophysical Research Letters, Vol. 19, pp. 131–134, 1992.
- Lichten, S.; and J. Border; *"Strategies for High Precision Global Positioning System Orbit Determination"*, Journal of Geophysical Research, vol. 92, 12751–12762, 1987.
- Meehan,T. K.; Srinivasan, J. M.; Spitzmesser, D. J.; Dunn, C. E.; Ten, J. Y.; Thomas, J. B.; Munson, T. N.; Duncan, C. B.; *"The TurboRogue GPS Receiver"*, Proceedings of the 6th IGS on Satellite Positioning, 1992, Columbus OH.
- Sovers, O.; and J. Border; *"Observation Model and Parameter Partials for the JPL Geodetic GPS Modeling Software 'GPSOMC' "*, JPL Publication 87–21, Rev. 2, Jet Propulsion Laboratory, Pasadena, CA 91109

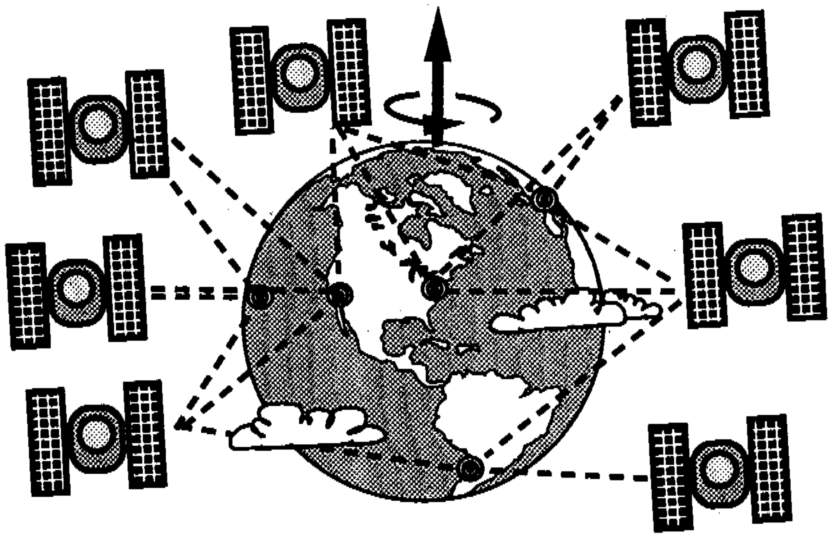

Figure 1: Global network solutions. Each satellite is observed by many receivers, and each receiver observes many satellites. Station positions, satellite orbits, troposphere and Earth rotation parameters are all estimated.

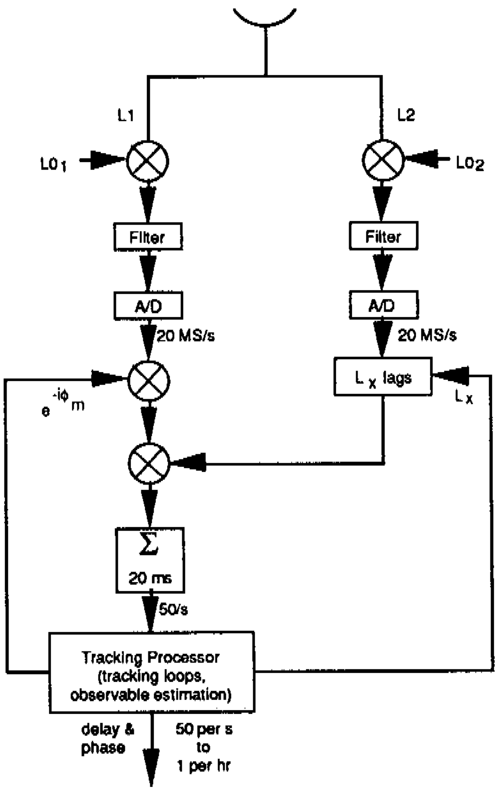

Figure 2: TurboRogue codeless Processing.

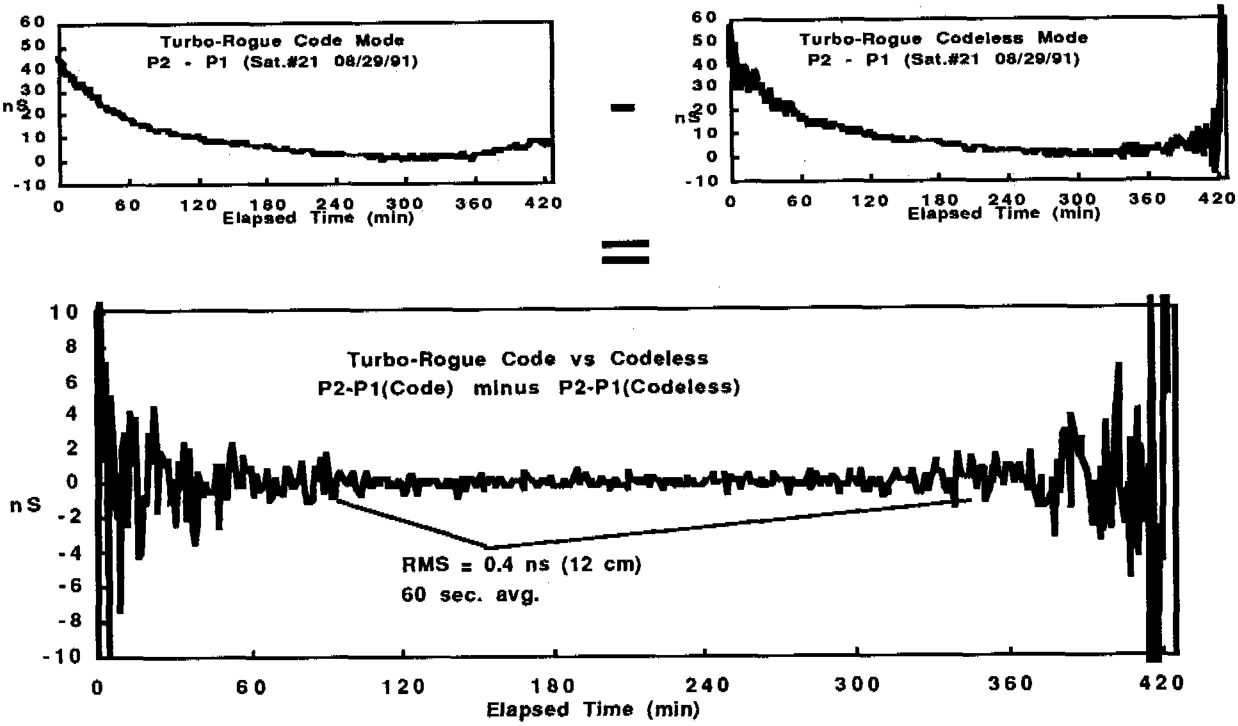

Figure 3: A comparison of TurboRogue code and codeless pseudorange. [Meehan, *et. al.*, 92].

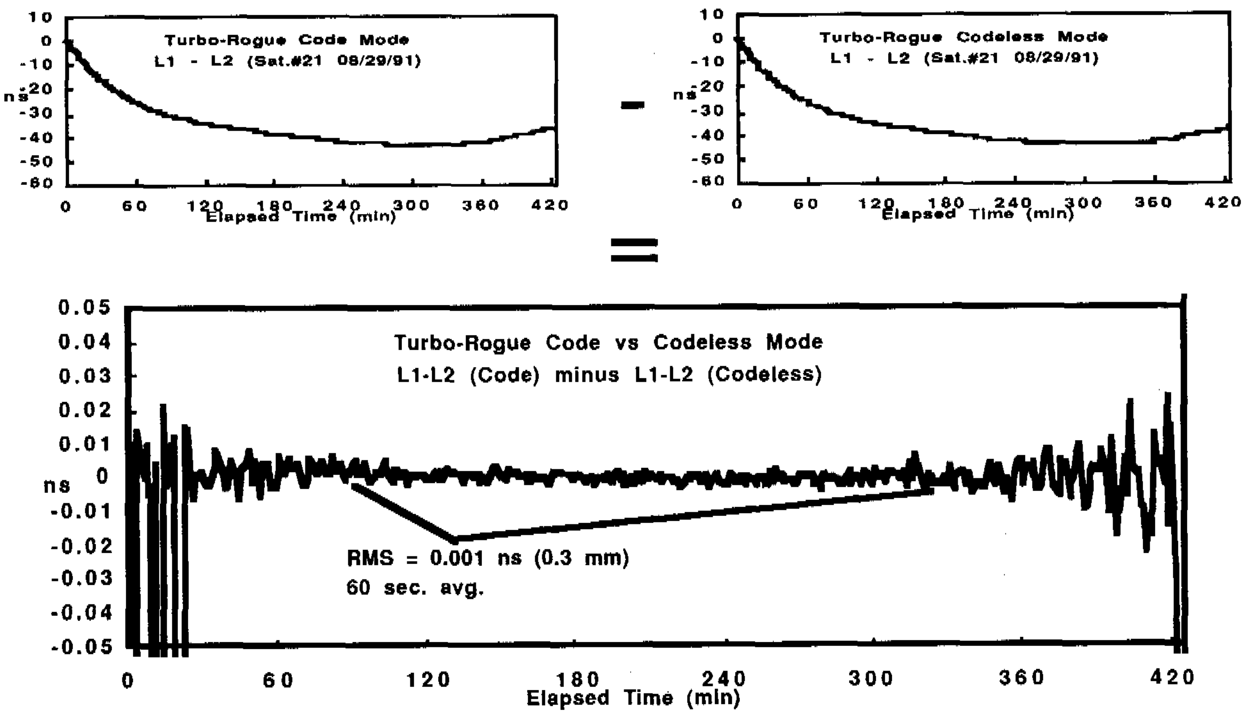

Figure 4: A comparison of TurboRogue code and codeless carrier phase. [Meehan, *et. al.*, 92].

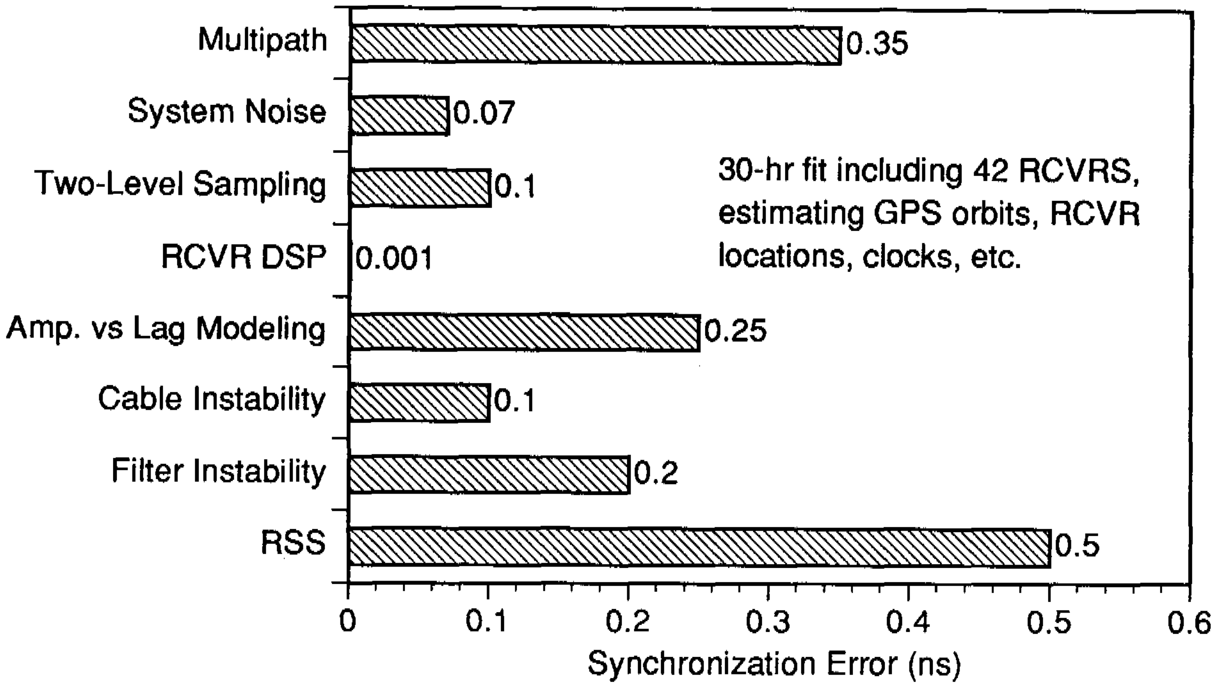

Figure5: Estimates of time-varying errors in clock synchronization between TurboRogue GPS receivers in the p-Codeless mode.

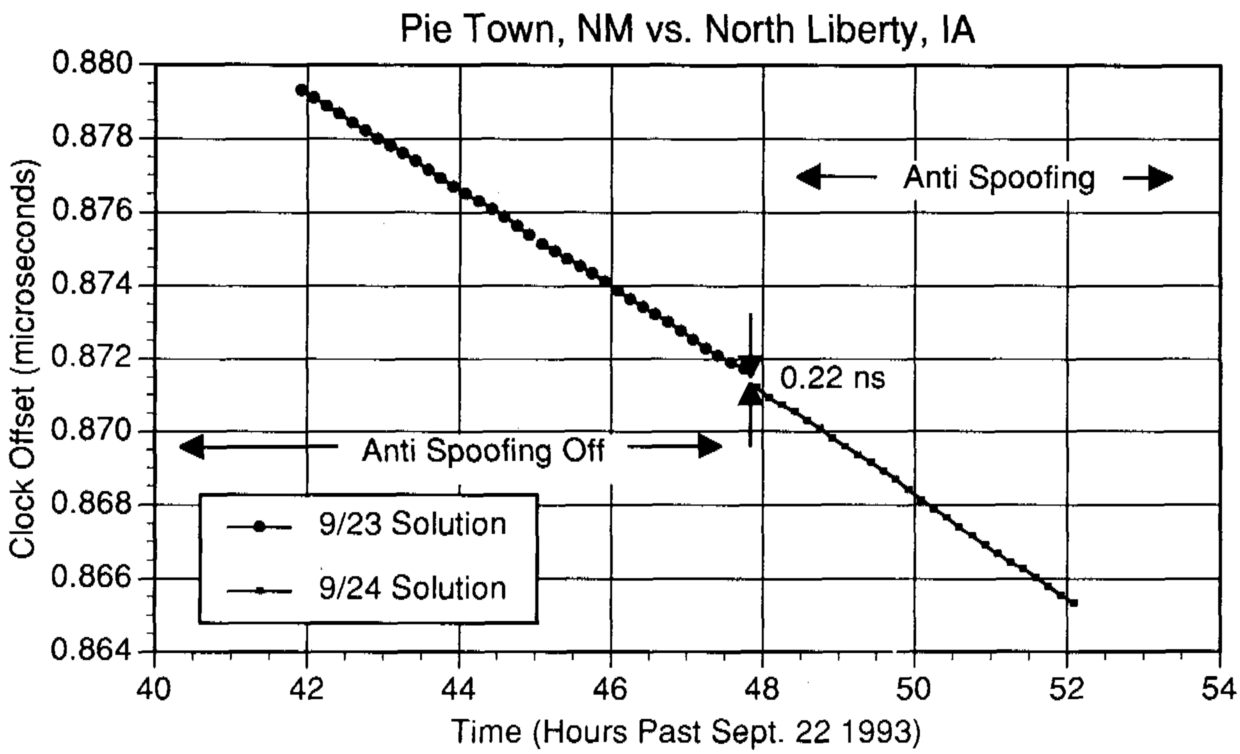

Figure 6: Receiver Clock Offset of Pie Town, NM.

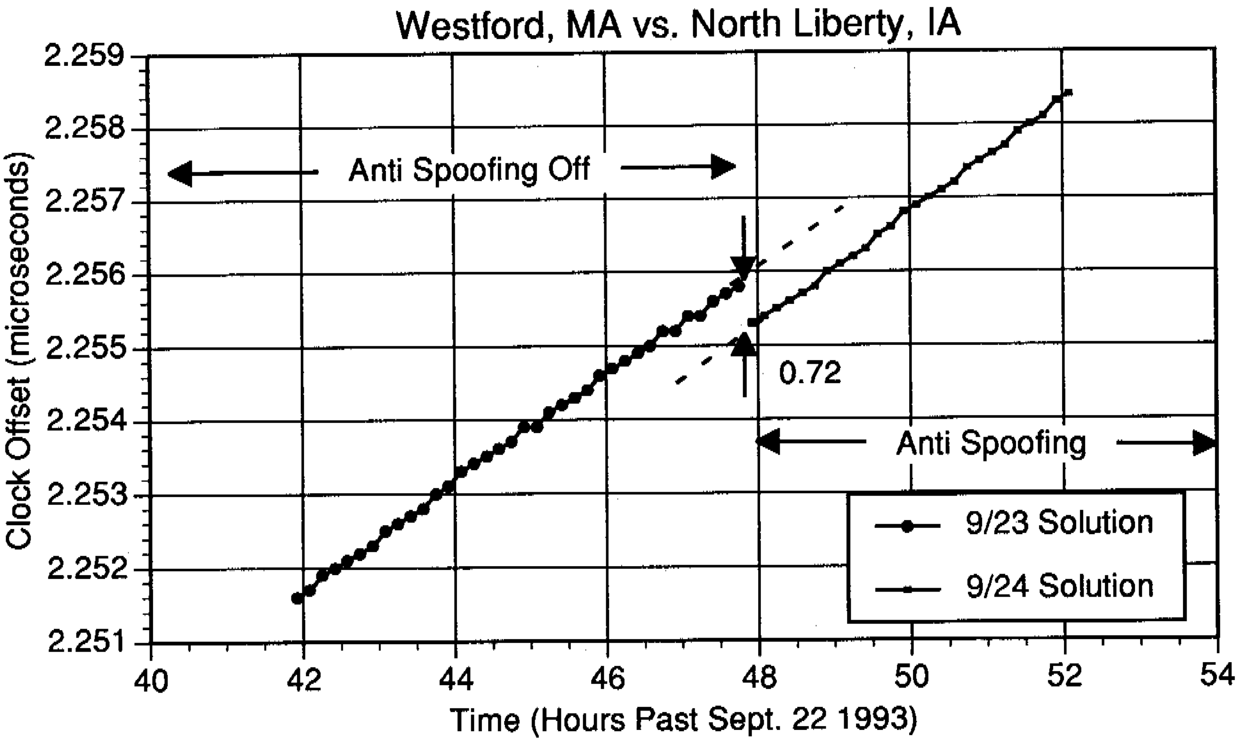

Figure 7: Receiver Clock Offset of Westford, MA.

QUESTIONS AND ANSWERS

Claudine Thomas, BIPM: I have one question. It might be a very naive question, but I'm not sure I have understood (or I missed something). You are speaking about clock synchronization using turbo–rogue receivers. But turbo–rogue receivers are geodetic receivers; we cannot do time with a turbo–rogue receiver.

Charles Dunn: Well the turbo–rogue receivers are geodetic receivers, but in fact they were designed with clocks synch in mind. We have a very wide-band front end and they can be run from an external frequency reference. So the frequency reference in the experiment was a hydrogen maser. The estimates that are produced by the software that are plotted here are of the receiver clocks. Now to connect the receiver clock to outside instruments – in other words, get an absolute offset between clocks – you have to look at the one pulse per second output of the receiver. We have looked at that and have shown that the delay of the one pps compared to the receiver clock is stable to two tenths of a ns over long periods of time, a month for instance.

Claudine Thomas: I mean your local hydrogen maser, for instance, is it put into the receiver with the 5 MHz?

Charles Dunn: That's right. The 5 MHz from the local clock is put into the receiver; the receiver phase locks an amount to generate a 20–MHz sample clock. And then that sample clock is used to take the GPS data. And so we are tied to the local frequency reference.

David Allan, Allan's Time: This is a question regarding maybe the accuracy of what you have done. It seems like from self–consistency you are really looking at stability of the system, time and stability and not accuracy. You have no independent check of the true time difference between the two hydrogen masers at these two locations for example, I believe. Is that correct?

Charles Dunn: Well it is true in this experiment that we do not have any independent tests. This was done fairly quickly for this conference. In the work that I presented two years ago, we used DSN sites and compared the clock offsets and rates generated by long baseline interferometric measures of quasars. So in other words, you correlate the signal from the quasars and you get the delay between the clocks very precisely. The offsets on those VLBI measurements are fairly imprecise, like 20 to 30 ns. And so that wasn't able to nail it down. The rates, however, are very precise; they are good to fractions of a ns per day. And our rates agree with their rates pretty well within our errors. And so all of that is still consistent with doing two or three tenths of a ns clock synch. To really nail it down, I agree you have to have some other way of doing it. And the spacecraft tracking demonstrations that we have been working on last summer and this December with TDRSS and Mars Observer should be the final nail in that. But they are not complete. And so I cannot talk about them yet.

Christine Hackman, NIST: You mentioned that you got your orbits from 40 stations around the world. I just wondered what happened when anti–spoofing came on. Were all these stations somehow able to – how did they keep tracking?

Charles Dunn: The receivers are able to tell when anti–spoofing comes on. They lose the P–code, they lose lock. And then they automatically go into cross–correlation mode and start looking for the encrypted signal. And then they are able to lock up usually in half a minute or so. And so there is more or less continuous data, although there is a phase break. The carrier phase will have a gap in here; and since it is not an absolute measurement of delay, that means that you have to reestablish what the carrier phase bias is. And then you have to use to the codeless pseudo range to level those carrier phase numbers and connect the phase across the gap.

Jack Klobuchar, AF Phillips Lab: This is kind of a complicated question. I gather that your biggest source of error is because you can't put that relative differential carrier phase to an absolute scale as precisely as you would like because of multi–path. Now if that is the case – and you mentioned you had some plans to improve the multi–path situation – can't you take advantage of the fact that multi–path is repeatable from day to day, because the satellites are repeatable with the 3 hour and 56 minute time difference, and basically subtract out the major parts of that multi–path from individual passes?

Charles Dunn: Well the number that I presented with multi–path being 50 centimeters comes from averaging the multi–path down over an entire track. It doesn't include trying to use daily repeatability to remove the multi–path. And that is one of the things that we are looking at, ways of determining the source of the multi–path so that you can model it and then remove it. And presumably the way that would work is that by using the daily repeatability of the multi–path, you could locate the primary sources and then subtract that from the data. Other things that we are doing are looking at the multi–path as a function of delay in order to estimate the multi–path in the receiver and then improve the observables. We are also looking into better antennas and a number of other things.

Bruce Penrod, TrueTime: Isn't the classic problem with using carrier phase for time transfer that you have to be able to have a pseudo–range code measurement accurate enough that you are within half of a cycle of the carrier phase? Isn't that the classic problem?

Charles Dunn: That's right. In fact, the pseudo range averages down to be less than a cycle. It is actually a false cycle, because in the codeless receiver mode we get full cycle measurements. If you average the pseudo range over an entire track of six hours, then you get down to where you can – well, the data I have shown doesn't have the integer cycles resolved. You can do better by doing that. The data I've shown just have the carrier phase leveled with the average pseudo range.

Bruce Penrod: I see your code data there and I can see that there is more than a few ns of noise from that data.

Charles Dunn: That's right, but if I average this down, it averages down to the number that is on the error plot. I think it was 10 or 15 centimeters, something like .07 ns. This is a nice zero mean kind of a thing.

Bruce Penrod: So you believe that you can resolve the carrier cycle ambiguity at these levels?

Charles Dunn: We definitely can resolve carrier cycle ambiguities. We do it in geodetic work when we need to do millimeter kind of stuff. The stuff I showed didn't have the cycle ambiguities removed; it was still limited by the uncertainty in the pseudo range.

Something I would like to point out is that even though the scatter on this is very small, the multi–path is more or less common to L–2 and L–1. So this plot does not show multi–path which is at 50 centimeters.