CALIBRATION CONSIDERATIONS FOR THE IGS/BIPM PILOT TIME TRANSFER PROJECT USING CARRIER PHASE

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Abstract

During the spring of 1998 a pilot project was begun between the Bureau International des Poids at Mesures (BIPM) and the International GPS Service (IGS) to investigate the accuracy of time and frequency comparisons using GPS phase and code measurements. The IGS has established a cooperative network of stations around the world which gather GPS data, analysis centers that provide analysis products from these GPS data and other contributed data. The precision of the data and products has made major contributions to geodynamics and earth sciences and presents the possibility of highly precise time and frequency comparisons.

To compare time information between two sites by whatever means requires the time of propagation of the signal through the equipment, cables, and space to be precisely and accurately known. IGS differential measurements with GPS carrier phase data are highly precise and must be accurately calibrated in order to provide time comparisons. This paper will address the problems and possible techniques for calibration for time comparison. Specialized equipment and GPS system simulators will be described that calibrate from signal reception in the antenna through receiver output.

PURPOSE

During 1998 a pilot project between the International Global Positioning System Service (IGS) and the Bureau International des Poids et Mesures (BIPM) was established to investigate the capability of using GPS carrier phase measurements for time transfer [1]. If this capability can be exploited, the high precision GPS measurements that are providing new dimensions in geophysical research could likewise provide time transfer users with an order of magnitude improvement. Such an increase is highly desirable as a means of comparing the new frequency standards being developed at the various worldwide timing centers. These new frequency standards are requiring a comparison capability far in excess of GPS Common-View capabilities. For the geophysical community, the improved timing capability could be used to relate their measurements to an accurate international time scale reference rather than using GPS Time as the common time.

GPS receivers deployed in the IGS are used to make high precision GPS satellite carrier phase signal measurements between receivers in the network. Careful site and equipment parameters are determined to account for equipment delays and other effects that would degrade the high precision desired. Considerable efforts have already been made in investigating the environmental stability of equipment and cabling delays that would change during or between the observation times and introduce errors [2]. However, the IGS measurements are based primarily on differential measurements between sites. Common and fixed delays in individual sites or between sites would appear as biases which could be removed without affecting the precise ranging measurements but would leave them ambiguous as to the actual time delay from the satellites through the equipment. Fiducial stations are established to provide a spatial reference within an international earth reference frame. To likewise establish a temporal reference, however, the actual delays and other effects corrupting time propagation through the equipment and between the local time reference or clock are required. This requirement is necessary to determine accurately the time interval from the time scale reference and maintain time epoch. The GPS receivers and associated equipment must be precisely calibrated to permit this kind of precise and accurate, timing measurements to be made at the IGS stations. With this calibration, time can be accurately determined throughout the network. This effort is to examine the ability to perform this calibration and translate this capability for use in IGS stations.

APPROACH

In precise geo-positioning the range to the satellite is described by the pseudorange equation for code phase measurements and by the carrier phase equation for carrier phase measurements [3,4]. The equation for pseudorange (ρ) is

$$\rho = R + c\cdot(b_u - B) + c\cdot(T + I + \upsilon)$$

where R = geometric range, c = speed of light, b_u = site local clock bias, B = satellite clock bias, T = tropospheric propagation error, I = ionospheric propagation error and υ = noise term. The local clock bias in this measurement is a combination of the internal delays in the antenna and antenna cables (Cal_C), internal delays in the receiver (Cal_{Int}), and the clock offset itself (Clk), as in

$$b_u = Cal_C + Cal_{Int} + Clk.$$

The equation for carrier phase ($\Phi_{u,s}$) is

$$\Phi_{u,s} = R + c\cdot(b_u - B) + c\cdot(T - I + \upsilon_{u,s}^{(\phi)}) + N_{u,s}\cdot\lambda$$

where $\upsilon^{(\phi)}{}_{u,s}$ is the noise term, which is not necessarily the same as the term in the pseudorange equation, $N_{u,s}$ is the ambiguous number of integer carrier wavelengths difference between the geometric range and measured range at the receiver, and λ is the wavelength of the carrier frequency. The inherent difference between the code and carrier wavelengths and ability of the receiver to measure a fraction of the wavelength that accounts for the carrier phase increased precision. The penalty for this increase is the ambiguous nature of the continuous carrier frequency signal. The precise and accurate determination of the value of Cal_C and Cal_{Int} so that it may be applied to the traceability of time through the observational receiver system is the object of this investigation.

SIMULATION AND RECEIVER INSTRUMENTATION

To precisely and accurately calibrate GPS geodetic receivers the approach of using a GPS satellite simulator was investigated. Previous efforts at NRL in testing the capability of military and civilian GPS Code receivers for timing output through the timing interface resulted in a simulator laboratory being developed. This technique of simulating the satellite constellation signal was used in tests of approximately 25 different types of military and civilian receivers for time dissemination using passive reception in a stand-alone configuration. These tests and others performed in this facility have resulted in GPS time dissemination measurements accurate to approximately two nanoseconds [5]. To be able to calibrate a GPS receiver to the 10 or 20 picosecond level needed for carrier phase measurements requires the integrity and accuracy of the simulator to similar levels.

The Northern Telecom model STR 2760 simulator is used for this effort [6]. This simulator is capable of providing Clear/Acquisition (C/A), Protected (P), or Secure P(Y) signals from up to 10 GPS satellites simultaneously on both L1 and L2 frequencies. It uses an external hydrogen maser reference signal to avoid frequency changes during the test runs. The simulator and the associated equipment configuration are illustrated in Figure 1. The particular times and coverage of the satellite constellation and control commands for the simulator are provided by the Alpha workstation. In this experiment the accuracy and precision of the simulator signals were also factors in the evaluation so the Secure mode (GPS AntiSpoofing signal) was set to zero in the simulations described below. The other factors in signal propagation, such as ionospheric and tropospheric errors, were also set to zero. An independent examination of the coherent interchannel bias between the carrier and code signals using a wideband digital sampling oscilloscope was undertaken. Each of the 20 RF output channels from the simulator were activated individually with code-only modulation. The phase at a time marker, placed a specified delay from the one-pulse-per-second output, was noted for each channel. The results indicated that all channels kept the same integer and fractional phase values from the 1PPS output. The uncertainty due the RF noise was approximately ±200 ps. Also, each code modulation pattern was inspected to insure that the interchannel bias was less than one nanosecond. This confirmed the simulator's capability to provide coherent phase information to the test receivers.

The local clock used was the in-house hydrogen maser reference for the Precision Clock Evaluation Facility. For these simulations accurate timing was not evaluated. Precision of the simulator and receivers in the different ranging mode required coherence throughout the configuration.

Two geodetic-quality TurboRogue receivers [7] capable of receiving eight satellites on two frequencies simultaneously were used to receive the simulated signals. Short cabling connected the receivers to the simulator to minimize delays or uncertainties. Actual installation cable lengths and antennas would cause greater uncertainty and will ultimately need calibration for operational use. These tests were designed to examine the internal delays and possibility of correlating the code and carrier measurements. If these two parameters may be sufficiently correlated without ambiguity in the calibration process, the calibration values would be more meaningful in operation.

As an independent measure of the delays through the equipment the one-pulse-per-second (1PPS) signals from the simulator and the receivers were collected and compared to the receiver measured values. These data can also be used to correlate the 1PPS generation in the receiver.

SIMULATION AND DATA REDUCTION

Two simulation runs were performed. In each run nine satellite signals were generated and data were collected in the two receivers for approximately 1800 seconds. The 1PPS signals were collected manually by alternately taking readings from the two receivers.

The simulator range data have a resolution of 10.0 mm. A least-squares method is used to fit a polynomial to the simulator range data and the coefficients of the polynomial are used to calculate the simulator filtered range data. The order of the fit is increased until the standard deviation of the fit is consistent with the 10.0 mm resolution. The carrier phase residuals are calculated by taking the difference between the receiver carrier phase measurements and the filtered simulator range data. In an ideal system this value should be equal to the integer number of wavelengths of the range when the receiver starts tracking the satellite. Starting with the carrier phase residual data expressed in wavelengths, the integer and fractional data are calculated. Changes in the integer part are due to cycle slips. The magnitude of the fractional part adjusted to be less than half. Continuous carrier phase fractional data are generated, adding an integer number of wavelengths to the carrier phase fractional data such that the absolute difference between samples is less than a half wavelength. The integer correction for the first sample is set at zero. This operation is necessary to correct for phase rollovers.

DATA RESULTS

Results from the first simulation run will be presented. The pseudorange residuals derived from the true range determined from the simulation command setup and the first channel in receiver #1 is shown in Figure 2. These residuals are uncorrected for the local clock offset; consequently, larger measured residual values than normal are shown on the ordinate axis. The precision and relationship of the code and phase values are being evaluated. The three pseudorange measured values, Clear/Acquisition (C/A), Precise Code on L1 (P1) and Precise Code on L2 (P2) are shown. The apparent jump in the P2 is relatively common in these receivers. All channels and satellites received are shown in Figure 3. The grouping of the data around the respective values shows good precision. The channel jumps are clearly shown, although not all channels show them.

If the biases and trends are removed and shown with the carrier phase values, the result is shown in Figure 4. A wavelength of L1 is shown for scale to demonstrate the precision capability of the receiver to measure the pseudorange under ideal conditions. The truth data from the simulator are quantized at the 10 mm level.

All pseudorange measurements from receiver two are shown in Figure 4. No jumps are evident and the biases between the C/A, P1, and P2 values are less. The carrier phase values for all simulated satellites from receivers #1 and #2 are shown in Figures 6 and 7 respectively. There is a bias between the pseudorange as shown in Figures 3 and 5. The primary source of the bias is the clock error value in each receiver's solution.

The significance of these data is the relative level of noise evident in the combination of simulator and receiver. Clearly, this setup shows that short-term noise will not be a limiting factor in calibration down to around 10 picoseconds. The other feature on the data is the walk in relative phase between all channels of both receivers and the simulator. Since the excursion is evident in both sets of receiver data, the most likely source of the phase change is in the simulator, the clock signals, or the distribution to the receivers. Such variations will likely be among the limiting factors of any approach to absolute calibration.

The primary concern in calibration, though, will be the absolute truth of the calibration. There must be a way to differentiate between the identical carrier cycles to be able to make a time comparison between simulator and receiver. The TurboRogue receivers provide a one pulse per second (1 PPS) that is derived from the receiver's internal clock. They also provide a correction in the output data stream between the generated time of the 1 PPS signal and the receiver's best estimate of time. All reported time and carrier phase data in the receiver are relative to this receiver clock. In principle, measurement of the 1 PPS against the simulator tick and application of the data correction should provide the necessary link.

It has been reported [8] that the internal factors in the receiver design cause ambiguities in the 1 PPS which are not corrected by the output data. Another critical factor in this approach is the 1 PPS signal itself (Figure 8). The rise time of the signal is much greater than the few picoseconds desired in the calibration process. Establishment of a specific point on the rising edge of the pulse is helpful, but even so, there is roughly a 100:1 ration between the nanosecond rise time and 10 picosecond measurement.

SUMMARY

These results have demonstrated that the STR 2760 simulator is an exceptionally quiet signal source. It also raises the possibility of wandering of the relative phase in the range of half a wavelength or more. The next step in this process will be to repeat the measurements with receivers of another design to sort out the receiver and simulator contributions to uncertainty in the absolute delay. We will also update the simulator firmware and software to reduce the possibilities of simulator-induced errors.

Once successful calibration of directly connected receivers can be achieved with the upgraded simulator, the next step will be to look at the complete receiving equipment. A special anechoic chamber, developed for this purpose, will be used. The configuration is shown in Figure 9. This chamber will be used to determine a calibration factor for the complete equipment suite from antenna to receiver output.

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[8] E. Powers 1998, "Hardware Delay Measurements and Sensitivities in Carrier Phase Time Transfer," Proceedings of the 30th Annual PTTI Systems and Planning Conference, 1-3 December 1998, Reston, Virginia, U.S.A.

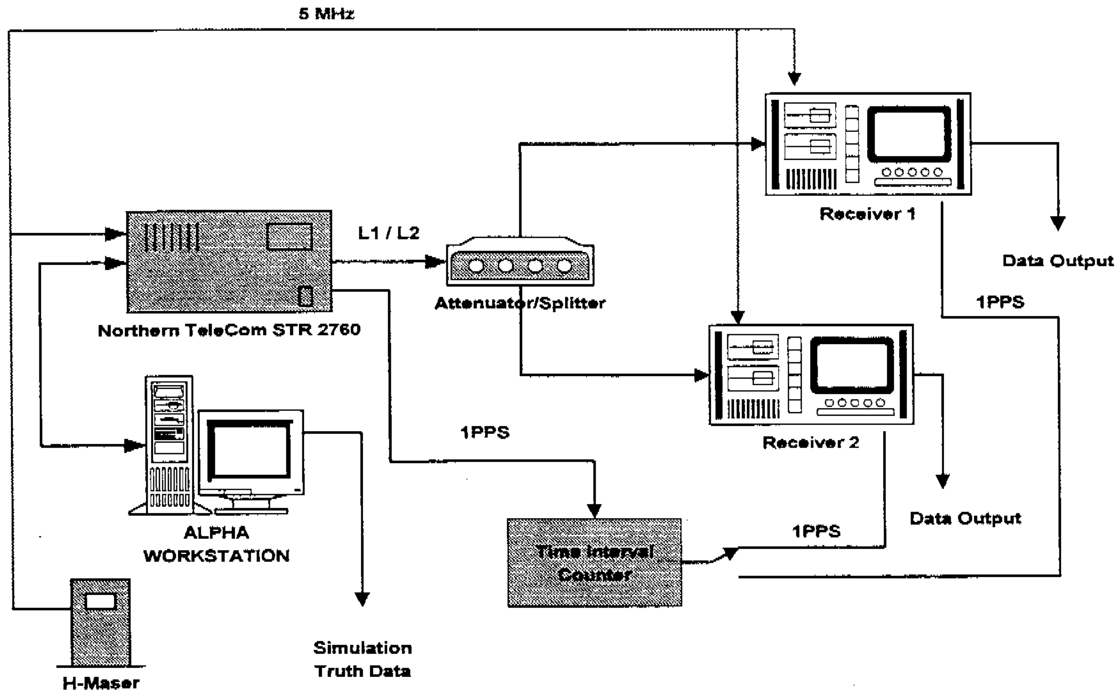

Figure 1. Simulation Configuration

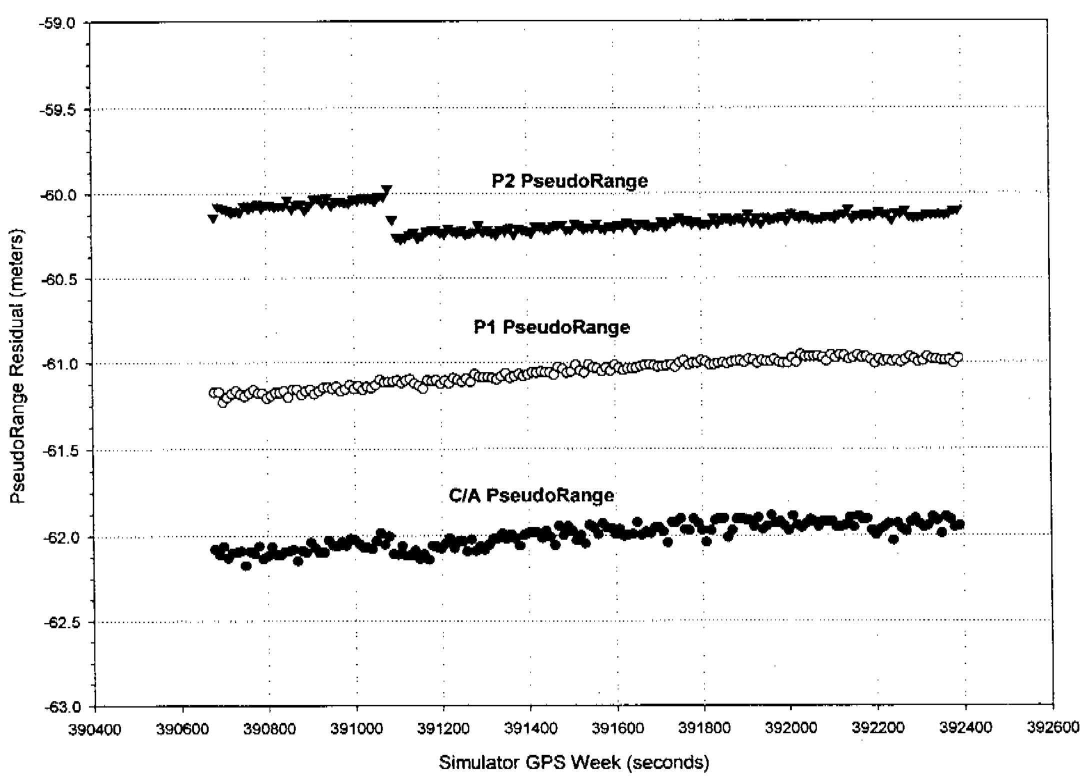

Figure 2. Receiver One PRN 01

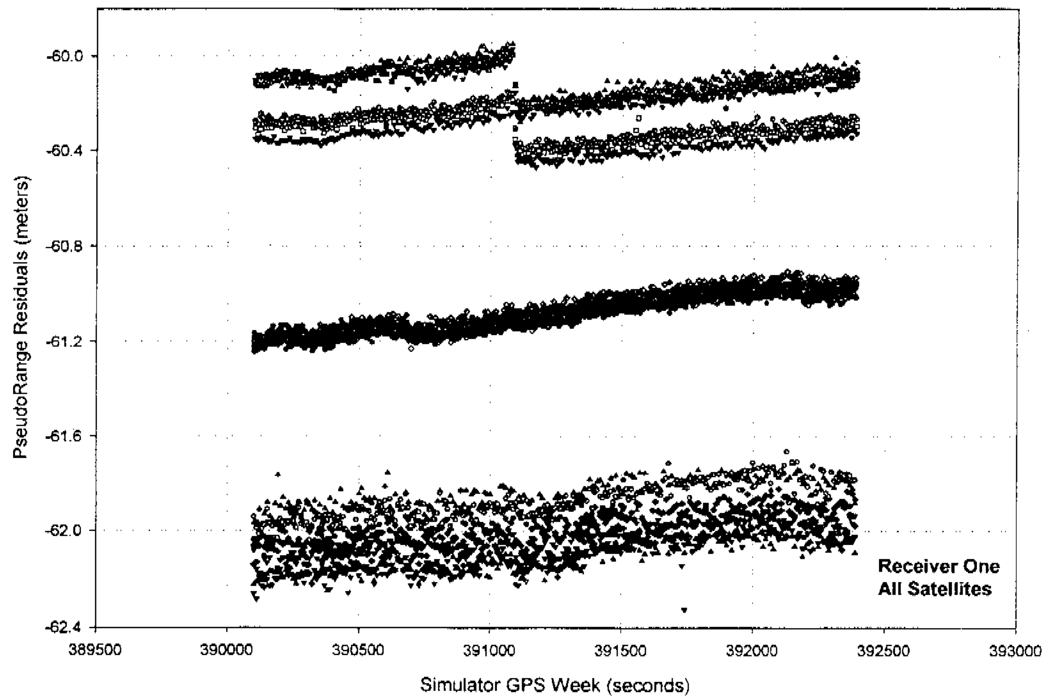

Figure 3. Receiver One All Satellites

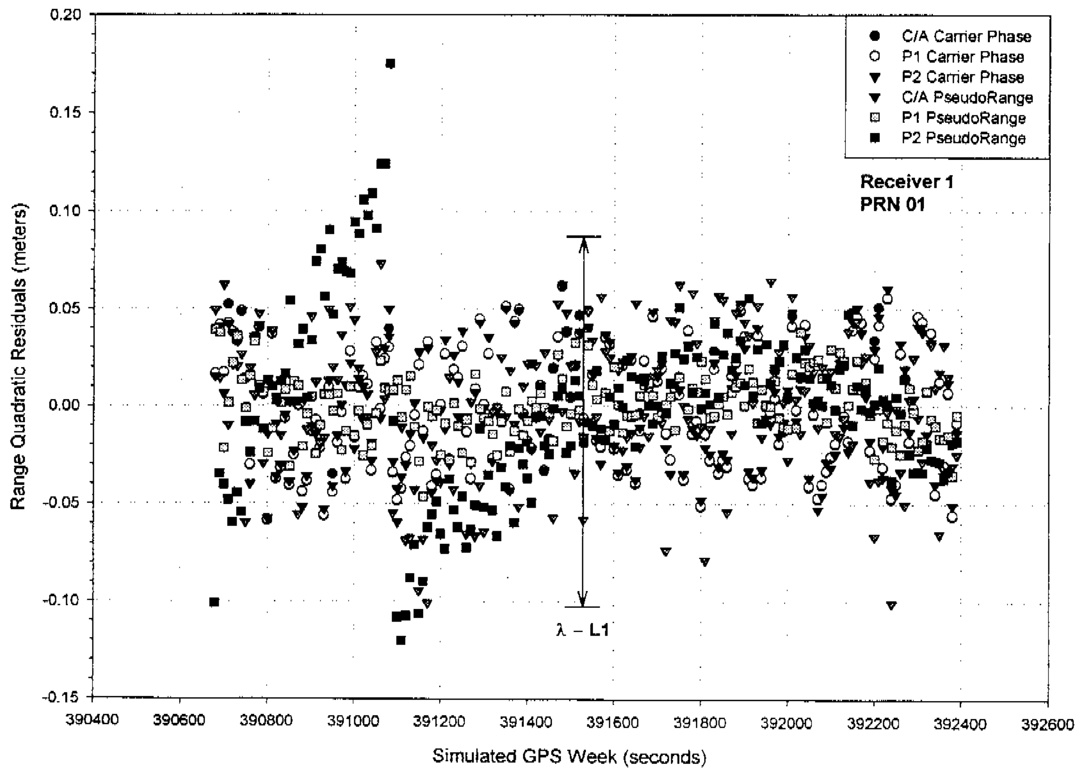

Figure 4. Receiver One, PRN 01 Residuals

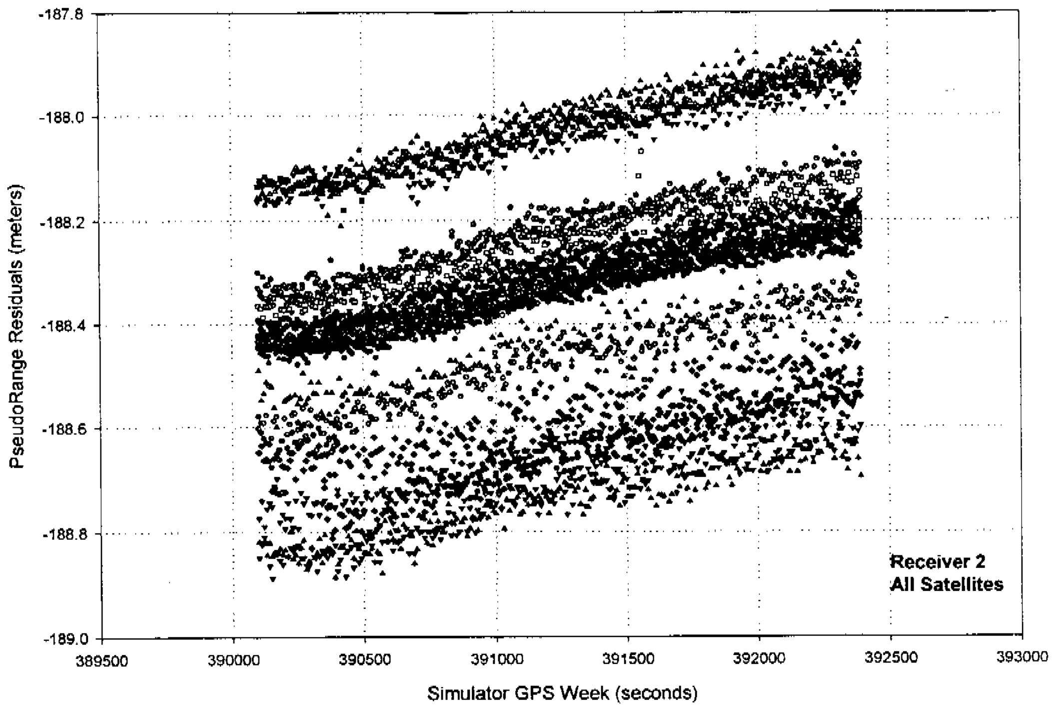

Figure 5. Receiver Two All Satellites

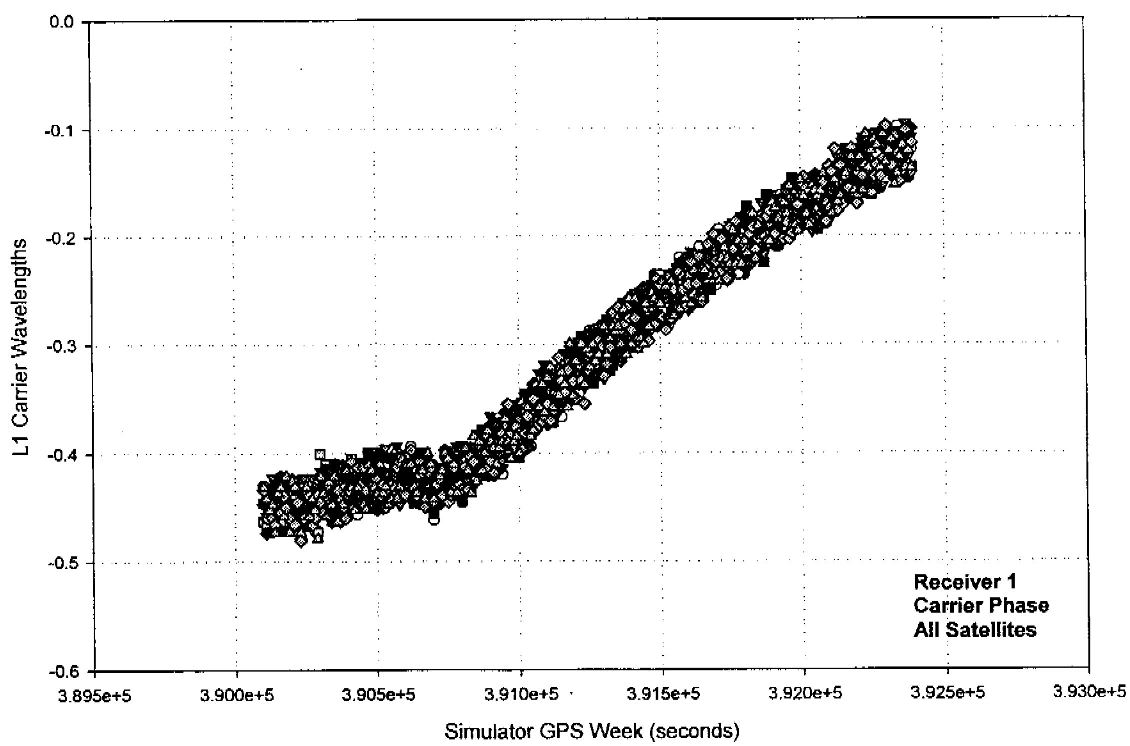

Figure 6. Receiver One Carrier Phase All Satellites

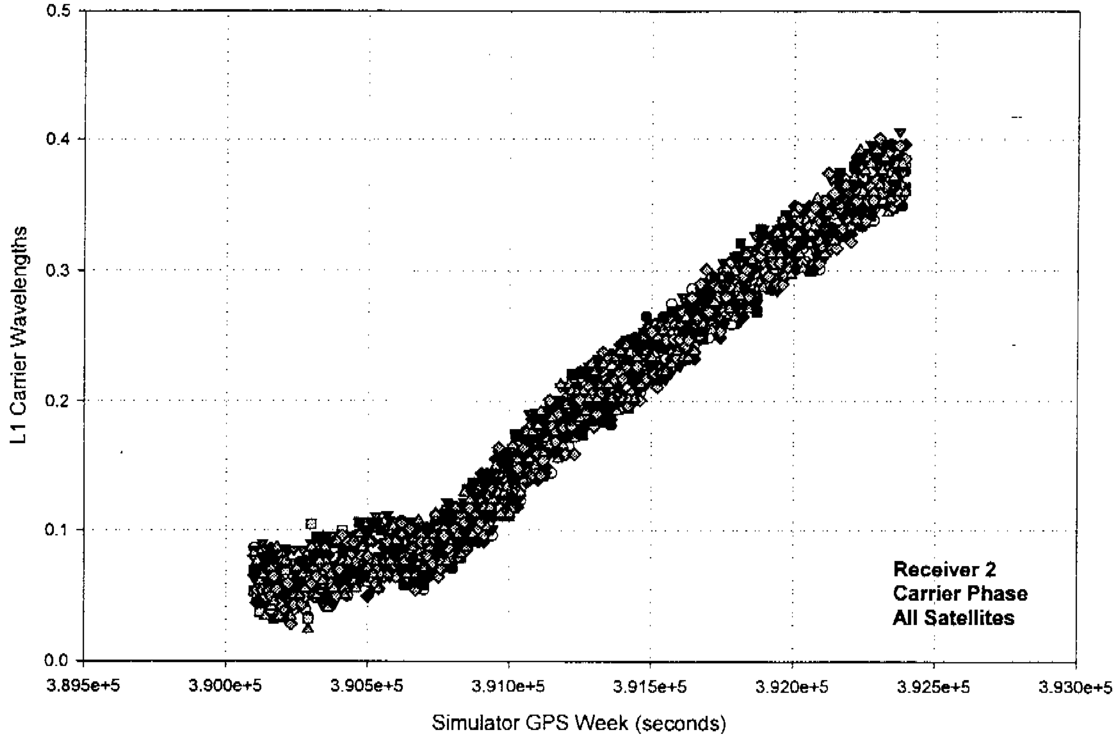

Figure 7. Receiver Two Carrier Phase All Satellites

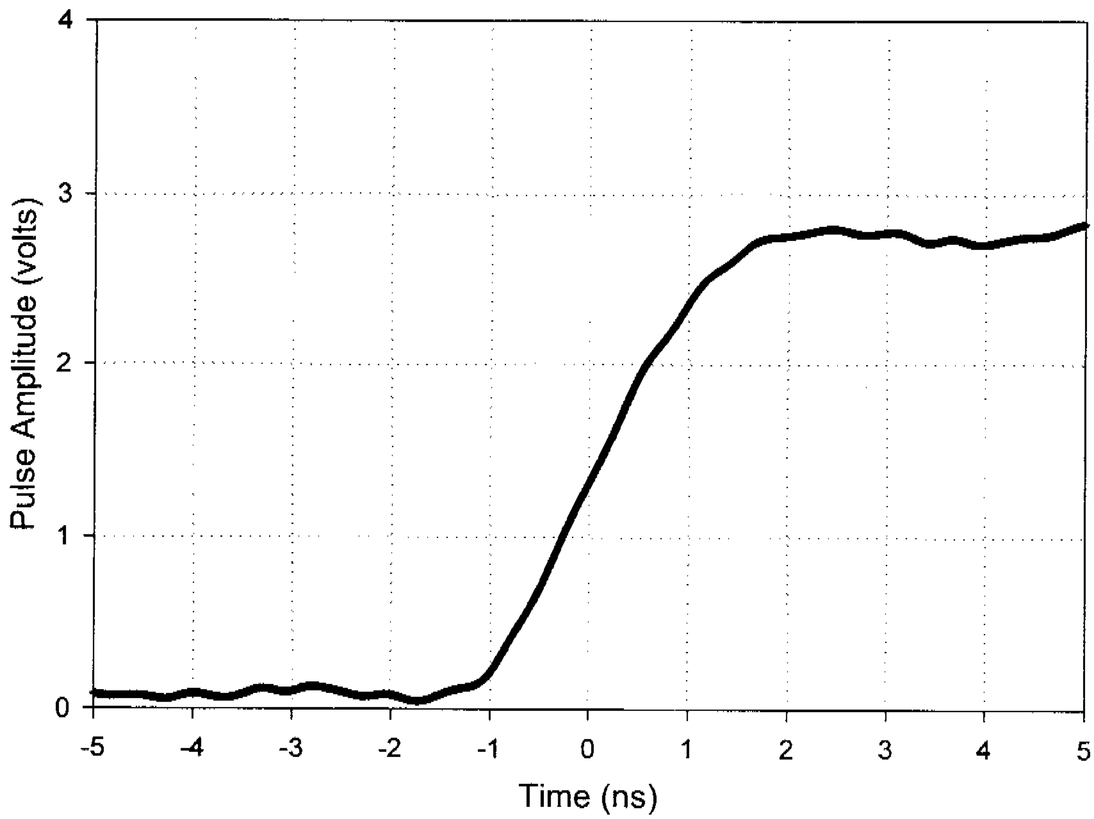

Figure 8. 1PPS Reference from Simulator

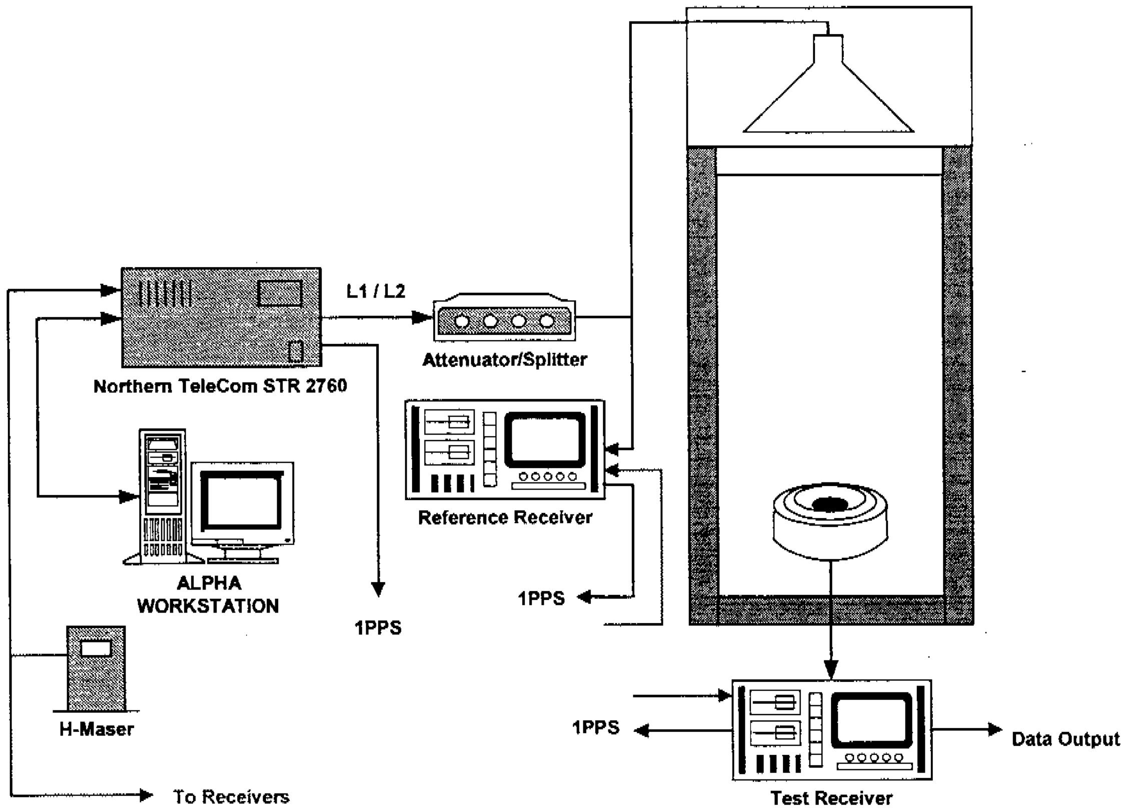

Figure 9. Final Simulation Configuration

Questions and Answers

JIM RAY (USNO): May I ask what you would hazard as a guess for the end-to-end absolute calibration?

JOE WHITE (NRL): I do not think I would really like to hazard one. There are so many variables that we have not looked at thoroughly. I think it would be difficult. I believe that we probably, within our ability to simulate signals, could get to the hundred picosecond level. Whether we can really get everything all together and continue it, and find a receiver that is stable enough is the question. I think that probably everybody who is going to show data today is going to show some receiver hops. We have to decide which side of the hop is truth.

JIM RAY: It looks like great work.