A CODELESS IONOSPHERIC CALIBRATOR FOR TIME TRANSFER APPLICATIONS

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BIOGRAPHY

Dick Davis has been an electronics engineer with the National Institute of Standards and Technology (formerly NBS) Time and Frequency Division since 1968. During that time he has been principal design engineer on several systems for time-frequency dissemination including TV-Time, for which he received the first Applied Research Award of the NBS in 1975, the GOES satellite time dissemination system, the ACTS (Automated Computer Time Service) and the NBS/GPS time transfer receiver for which he (along with Allan, Clements and Weiss) received the Applied Research Award of the NIST in 1983.

Marc Weiss received his B.S. degree from Valparaiso University, Valparaiso, Indiana in 1973. He received his M.S. degree in Mathematics in 1975, and his Ph.D. in Mathematical-Physics in 1981, both from the University of Colorado, Boulder, Colorado. He has been with the Time and Frequency Division of the National Institute of Standards and Technology (formerly NBS) in Boulder Colorado since 1978. He wrote the software for the NBS/GPS Time Transfer System for which he received the Applied Research Award of the NBS in 1983, along with the other principals. More recently he has been developing methods to better utilize the Global Positioning System for common view time transfer. Dr. Weiss is also currently working on new time scale algorithms.

Matjaz Vidmar received his degree in electrical engineering from the University of Ljubljani, Ljubljana, Yugoslavia. He designed the RF and analog portion of our ionospheric calibrator while on a six month Fulbright scholarship at the University of Colorado. He returned to Yugoslavia in May of 1989 and is currently in the institute of advanced studies at the University of Ljubljani.

ABSTRACT

With solar activity near maximum, the single largest error in the use of GPS for "common view" time transfer is correction for ionospheric delay. This paper describes the hardware and software development of a "codeless" ionospheric calibration receiver that recovers the P code clock on L1 and L2 and uses the phase difference to compute the L1 ionospheric delay. Major features of the hardware include dual-volute antennas on a choke-ring ground plane, very low-noise-front end, and alternate L1--L2 phase sampling through a common IF channel. S/N of the recovered P code clocks is typically positive by several decibels in a 100 Hz bandwidth. Signals are processed as 8 bit data, with all satellites in view individually (and simultaneously) tracked in real time to recover the ionospheric delay values. All processing is with an internal 8 bit CMOS microprocessor. The normal mode of operation of the ionospheric calibration receiver is in parallel with a GPS C/A time transfer receiver, with the measured ionospheric data automatically replacing the modeled ionospheric data transmitted by the SV. In this way, the ionospheric calibrator operation is transparent to the time-transfer user. Data will show that the performance of the ionospheric calibrator is 1-4 ns for 15 s averages, with the ultimate limitation being multi path.

INTRODUCTION

For most of the decade, solar activity has been low and the contribution of ionospheric delay to the error budget for common view [1] time transfer has been tolerable. However, now that we are approaching a maximum in the approximately 11 year sunspot cycle, the L1 ionospheric delays are approaching 100 ns for the low angles used for intercontinental time transfer. We therefore need to be able to measure the ionospheric delay rather than use the transmitted model which can be substantially in error. Cost and security dictate that we consider only a codeless type receiver, as opposed to a "full-up" P code unit. Some features that are required are that the unit be self contained and have battery backup, make continuous real time measurements of L1 ionospheric delay for all satellites in view, directly interface with a time transfer receiver, and be relatively inexpensive (no more than $5K).

The calibrator can also be used as a stand-alone unit for ionospheric measurements, with values of L1 delay for all satellites in view sent to one of the two serial ports as often as every 15 s. In this mode, the calibrator must be set "on time" within +- 1 min and requires a copy of the GPS almanac, updated every 1 to 4 weeks. A stable source of 5 MHz power is required, preferably from a cesium or rubidium standard; however a crystal oscillator with a drift rate of parts in 10^{-9} per day is satisfactory.

DESCRIPTION OF IMPLEMENTATION

Figure 1 shows the major elements of the calibrator in simplified form. Based on the original idea of MacDoran, the objective is to recover the 10.23 MHz P code clocks for L1 and L2 through a delay-and-multiply operation [2,3,4,] and then measure the difference in delay for the L2 and L1 clocks for each satellite. Another interesting implementation of the codeless technique was developed by Imae, while working in cooperation with the BIPM [5]. These phases of the clocks are recovered by multiplying the composite signal by sin(-ωp) and cos(-ωp) and summing the sin and cos components for 7.5 s. A 4 quadrant atn(ssum/csum) yields the clock phase. Phase difference from one L1 measurement to the next is used to compute frequency error in (ωp) and close the tracking loop. Measurement on L1 and L2 is carried out sequentially, that is L1 is measured for 7.5 s followed by a 7.5 s measurement of L2. This is analogous to the "tau-dither" loop in a GPS receiver and provides similar advantages and disadvantages. The major disadvantage is a degradation by S/N by 3 dβ. Advantages include greater simplicity; since the same narrow-band IF is used for both L1 and L2, the potential for errors due to unequal phase shifts through separate channels is minimized.

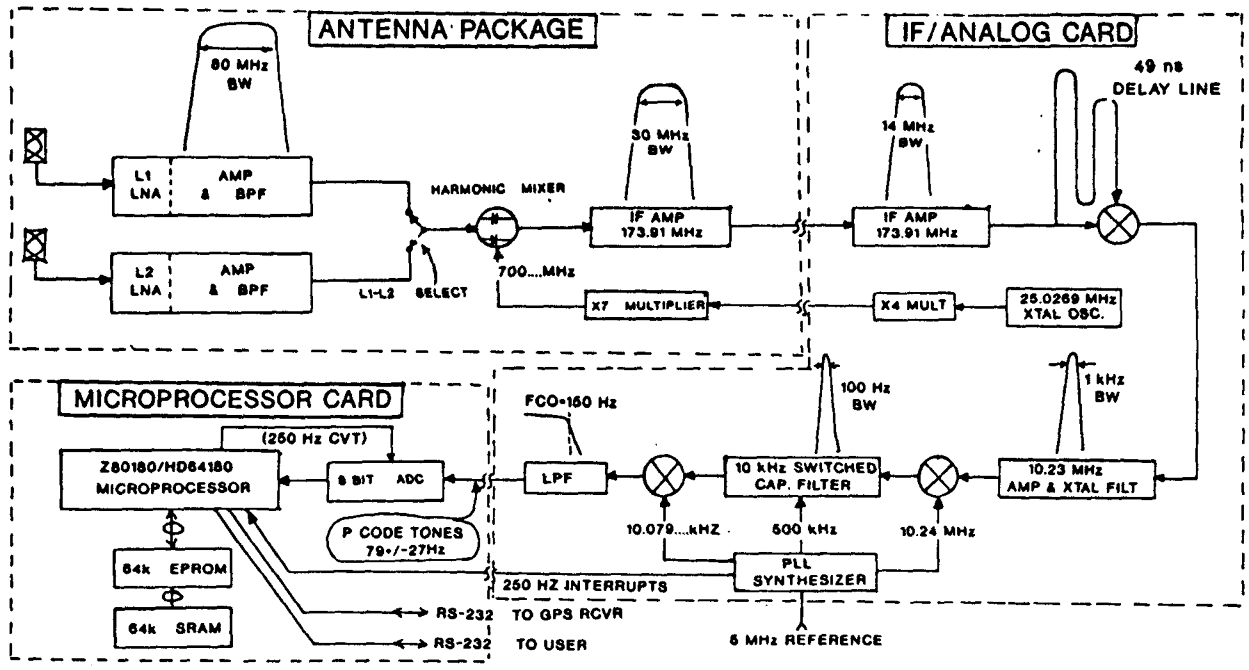

Figure 1- Block diagram of NIST ionospheric calibrator

ANTENNA PACKAGE

The antenna package for the calibrator uses separate L1-L2 antennas and low noise amplifiers. All components except the antennas and low noise amplifiers (LNA) are mounted on a single printed circuit board approximately 25 cm square. Microstrip bandpass filters and monolithic amplifiers are included on the board for L1 and L2. The amplifier chains for L1 and L2 are switched on alternately for 7.5 s and the resultant output signals are applied to a harmonic mixer with the effective local injection frequency halfway between L1 and L2. This results in the same IF frequency for each L band signal, except for Doppler shifts. The 173.91 MHz IF amplifier in the antenna package provides about 30 dB gain with a bandwidth of 30 MHz. Total gain in the antenna package is approximately 85 dB.

Design of the antenna package was patterned after the NBS/GPS time transfer receiver antenna, where simplicity, reliability, and cost were major concerns. The circuit board used is Fiberglass epoxy, and all RF/IF gain elements except the GaAs FETS are inexpensive monolithic amplifiers. The times 7 multiplier from 100....to 700....MHz uses a 1N4148 switching diode. The LNA's were constructed using a "C" band GaAs FET followed by a monolithic amplifier. Although the price of the antenna package is relatively modest, performance does not suffer. Measured noise figures for both L1 and L2 are less than 1 dB.

INDOOR UNIT

The indoor portion of the calibrator is housed in a standard rack mount case. Primary parts are the analog card and the microprocessor card. Also included but not shown, are a 110/220V switching power supply and a starved electrolyte lead-acid battery capable of powering the microprocessor and memory for up to 24 h. Although the unit will not continue measurements during a primary power outage, it does not lose stored tracking data or the time-of-day clock.

IF/ANALOG CARD

The IF/analog card includes additional gain at 173....MHz followed by the delay and multiply mixer for recovering the 10.23 MHz P code clocks. A crystal filter and amplifier with a 1 kHz bandwidth is followed by an additional down-conversion, so the recovered P code clocks are centered at 10 kHz. The signals are further amplified and band limited to 10 kHz +-50 Hz in a cascaded switched capacitor filter. The final down-conversion centers the P code clocks at 79....Hz, with Doppler extending from 52 to 106 Hz. Three precise frequencies are synthesized on the card using a 5 MHz reference. Two of these are the local oscillator injection frequencies for down-converting the P clocks and the third is the 500 kHz reference to the switched capacitor filter. The 25....MHz for the first LO is generated from a crystal oscillator, since the normal frequency error in such an oscillator do not compromise measurement accuracy. (Offsets in the LO injection frequency of 50 kHz result in less than 0.5 ns shift in the measured L1 ionospheric delay.)

MICROPROCESSOR CARD

The microprocessor card includes the 8 bit A/D converter, a Z80180/HD64180 microprocessor, and support circuitry. Our decision to use the Z80180/HD-64180 microprocessor was influenced by the fact that we had used the Z80 as the processor in the NBS/GPS time transfer receiver and the 64180 is code compatible with the Z80. This meant that we could move large portions of the code from the time transfer receiver in the calibrator, including the routines used to compute satellite Doppler shift and azimuth/elevation. The newer microprocessor has several advantages over the Z80, including low power CMOS design, up to 10 MHz clock, 2 on-board UARTS, 2 DMA channels, and a segmented memory management unit capable of addressing 512 k of memory. In this application we have included 64 k bytes each of EPROM and SRAM.

CHOKE-RING GROUND PLANE

Several months ago, we equipped three of our on-site GPS receivers with choke ring ground planes and noted a decrease of the rms noise for individual 13 min tracks from original values of 6-10 ns down to 2-5 ns. This reduction of 6 dB to 10 dB in noise is the result of a reduction in noise temperature of the antenna system due to attenuation of the side lobes that are in the direction of the hot earth, and simultaneous attenuation of multipath signals at low elevation angles.

The L1 radiation patterns of three ground planes were measured on the antenna test range. Included were a 122 cm, a 76 cm and a 51 cm ground plane and the volute antenna without ground plane. The ground planes provided at least 7 dB additional attenuation at 0° elevation, compared to the bare helix. Up to 15 dB of additional attenuation can be achieved by lowering the helix into the choke rings an additional 2 cm. Naturally, there is a price to be paid in reduced gain at angles below 30°.

Until now, we have not determined whether noise figure or multipath reduction is predominant in the measured noise reduction; however since both a good noise figure and reduced multipath effects are desirable, we have equipped the calibrators with choke-ring ground planes. Our first units have ground planes that are approximately 60 cm in diameter. They are fabricated using a base plate of 1.57 mm aluminum with five concentric choke rings riveted to the base plate with aluminum pop rivets. Height of the choke rings is approximately a quarter wavelength at L2 and spacing is about one-sixth wavelength, although the exact spacing does not appear to be critical. Diameter of the innermost ring is 28 cm. As time permits, we will characterize the multipath reduction by operating the calibrators with and without the ground planes and plotting the phase variations. Multipath causes cyclic patterns that are easily recognized in a phase plot [6].

SOFTWARE IMPLEMENTATION

The analog signal, sampled 250 times per second, is converted to 8 bit digital form and processed to recover the phase difference of the L1 and L2 P clocks. Using stored almanac data, we first determine when a satellite is above the set elevation mask, and if so, to begin (or) continue the tracking operation. Doppler shift values and Az/El values are computed using the time transfer receiver program segments.

Every 15 min, the microprocessor computes the Azimuth/Elevation for every satellite in the constellation. For satellites that are above the elevation mask and are not already being tracked, it initiates a frequency-vs-amplitude search using 7.5 s of data, centered about the Doppler shift value predicted from the almanac and extending up to +-1 Hz either side. The search range is truncated any time another satellite has either a measured Doppler shift (while tracking) or a predicted Doppler shift (from the almanac) that is less than 2 Hz away. An initial search is made at 0.1 Hz intervals, with a second search made in steps of 0.05 Hz. The second search is bounded by the 50% points relative to the maximum amplitude found in the first search.

The frequency bin containing the largest amplitude is then used to further refine the doppler frequency estimate. The 7.5 s data sample is then broken into 4 intervals of 1.75 s and the change in signal phase for these 4 segments is used to compute a linear least squares frequency offset from the frequency estimate. At this point, the frequency estimate or Doppler should be within 10 mHz of the correct value. This Doppler value, along with the estimate of Doppler rate obtained from almanac data, is used to initiate tracking.

All of the software is written in assembly language; however it was originally developed in C programming language on a PC. Algorithms were tested using real data from the calibrator. Originally it was our intent to use 1 bit sampled data in order to minimize the processing time for the microprocessor. However we found that it was difficult to lock on satellites at elevation angles below 30°, especially when 3 or more satellites were at elevation angles above 50°. Simulations in Figure 2 show that the weaker signals are masked by noise and signals from the other satellites with 1 bit sampling, whereas with 8 bit sampling, signals even with negative S/N in a 100 Hz bandwidth are recoverable. An actual amplitude spectral plot of PRN's 8,6,11 & 9 using 8 bit data are shown in Figure 3. These were the only satellites in view at the time the plots were made. Note that the amplitude spectra are plotted with precision of only +- 1 Hz around the frequency value predicted by the almanac.

With very tight coding of the 250 Hz data loop, we can complete all the 8 bit processing required to generate the sin and cos sums for 10 satellites in 1.2 ms when running with a 9.2 mHz processor clock. This represents only 30% of the total processor time. Other time sensitive processing is required only every 7.5 s and adds only a few percent to the processor load.

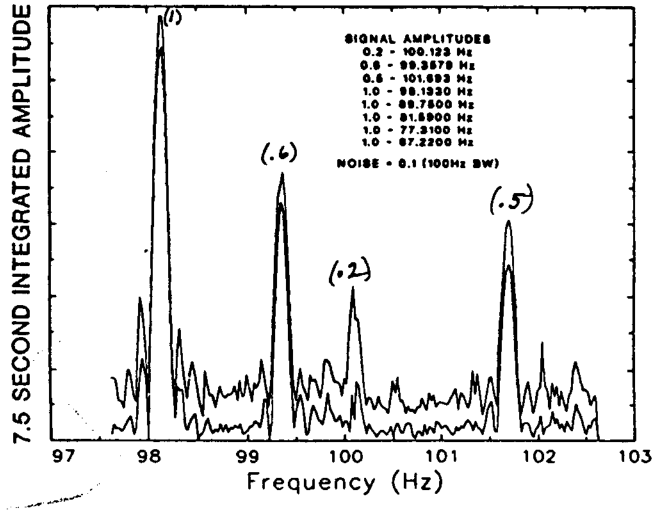

Figure 2. Simulated 1 bit data

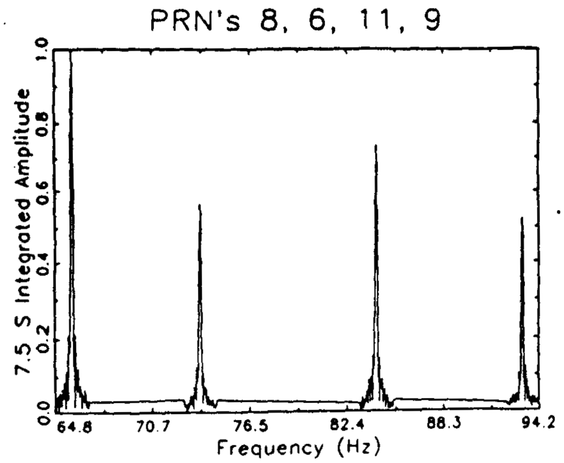

Figure 3. 8 bit-data-measured amplitudes

All of the real-time tasks are interrupt-driven, with full context switching between tasks. The background "number crunching" program supports the real time tasks through a command queue. Background operations that require more than a second of computation time are segmented and call themselves to completion through the command queue. This insures that no task gets too far behind the real-time requirements.

USER INTERFACE

Two RS-232 serial ports are available for communications. Normally, one of the ports is dedicated to communication between the calibrator and the companion GPS receiver (if there is one). Data transferred over this interface would include almanac updates provided by the GPS receiver, 15 s tracking data, and time-of-day information. The data rate is 1200 Baud.

The direct user serial port provides GPS-satellite tracking data with the ionospheric model data replaced by measured data. Up to 2 weeks of time transfer tracking data are stored in the calibrator in this mode.

When the calibrator is used in the stand-alone mode, the user is required to provide occasional (1 month maximum) updates of the almanac data, along with verification that the internal clock is maintained on time within better than 1 minute. At least 3 types of data can be provided to the user in the stand-alone mode: First are the "raw" 250 s^{-1}, 8 bit data measurements. Second are the 15 s ionospheric values for all satellites in view, formatted and time tagged. Third is the 15 min average ionospheric value for each satellite in view, with up to 1 week of data being stored for retrieval on command.

SIGNAL SIMULATOR - L1-L2 DELAY BIAS

Any difference in the group delay in the L1-L2 rf bandpass filters and amplifiers in the antenna package will result in a bias in the measured L1 ionospheric delay, equal to approximately 1.6 times the difference in group delay. We therefore needed a signal simulator to measure the L1-L2 antenna package delay. The simulator generates a pseudo-P code that is in phase for both L1 and L2, within 1 ns. Measurements of several antenna packages indicate L1 ionospheric delay bias of 4 ns to 7 ns. Once we have characterized the value, the bias should remain constant with temperature and time.

The test setup in Figure 4 was used to measure the group delay bias stability of two antenna packages. Each antenna package was placed in an environmental chamber and cycled from -20 to +50°C while continuous measurements of L1 delay were made. The measured L1 bias changed by less than 2 ns over this temperature range on both units, as shown in Figure 5. These measurements do not characterize the change in delay of the volute antennas; however their contribution to the delay instability is small compared to the bandpass filters.

Biases in the calibrator are not a significant problem for differential time transfer as long as the value indeed remains constant. In fact, the L1-L2 delay biases in the SV's are also not a problem, since in common-view time transfer, we are looking at the same SV and any bias within the SV will be common to all participating users, and will drop out when the differences of the time transfer measurements is taken.

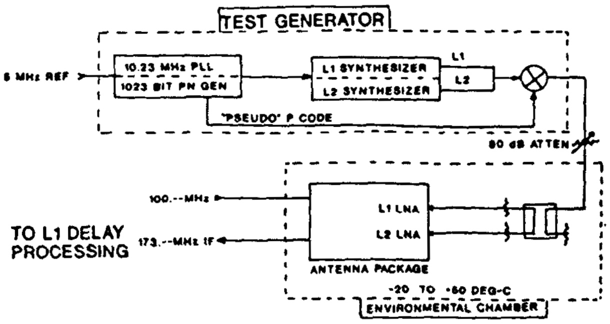

Figure 4. Test setup for measuring delay bias vs temperature

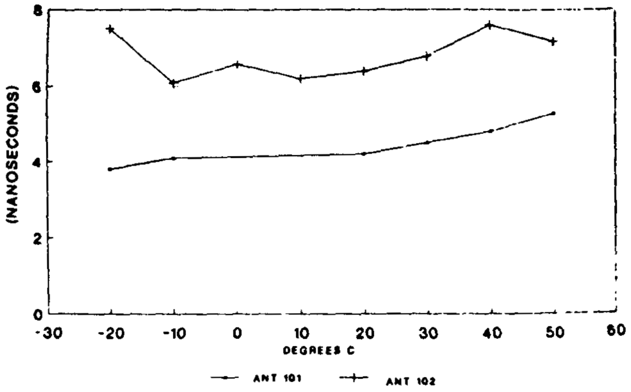

Figure 5. Measured delay bias vs temperature

MEASURED RESULTS

Our estimate of the time required to complete and debug all of the software was optimistic. The first version of the complete program was assembled and linked less than 2 weeks ago. Several bugs have prevented the continuous tracking of all satellites in view. We had to make a decision whether to process data for this paper or devote most of our efforts to solving the software problems permanently. As a result, we have processed only a limited amount of real time data. Figure 6 shows one SV track for several hours, ending at less than 10° elevation. Granularity of the plot is 1 ns, but can be reduced to 0.5 ns with minor software changes. In any case, the 15 second rms noise is less than 1 ns, including the contribution of granularity. Sigma-tau plots indicate the noise averages down as 1/tau out to about 16 min.

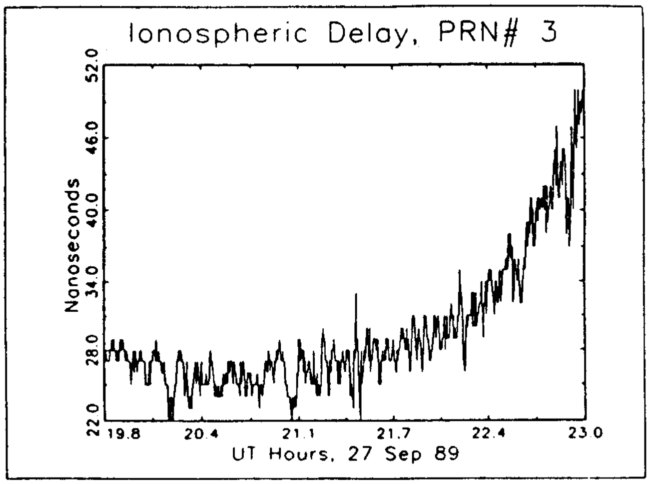

Figure 6. Measured ionospheric delay for PRN 3

CONCLUSIONS

The ionospheric calibrator described will shortly be in use for improving international common view time transfer results. Since it will function as a continuous monitor of ionospheric delay with minimum operator interaction required, it should also be useful for any application requiring measurement of ionospheric delay at the 1-2 ns level.

ACKNOWLEDGEMENTS

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