REMOTE SYNTONIZATION WITHIN A FEW NANOSECONDS BY SIMULTANEOUS VIEWING OF THE 1.575 GHz GPS SATELLITE SIGNALS

Dick D. Davis, Marc Weiss, Alvin C. Clements,
and David W. Allan
Time and Frequency Division
National Bureau of Standards
325 Broadway
Boulder, CO 80303

ABSTRACT

The NBS/GPS receiver has been designed around the concept of obtaining high accuracy, low cost time and frequency comparisons between remote frequency standards and clocks with the intent to aid international time and frequency coordination. Simultaneous viewing with the USNO commercial GPS receiver at Washington, DC and the NBS constructed receiver at Boulder, CO (≃ 3000 km baseline) yielded synchronization accuracies of less than 10 ns as compared with several portable clock trips.

The hardware and software of the NBS/GPS receiver will be outlined in the text. The receiver is fully automatic under microprocessor control with a built-in 0.1 ns resolution time interval counter. The microprocessor also does data processing. Satellite signal stabilities are routinely at the 5 ns level for 15 s averages, and the internal receiver stabilities are at the 1 ns level. The second generation receiver has a built-in CRT and parallel keyboard for operator interface. Serial RS232 is provided for local hardcopy (printer) and telephone modem use.

RECEIVER BASIC FREQUENCY PLAN

The NBS/GPS receiver utilizes triple conversion, with the first IF at 75.42 MHz. This IF is wide band (25-150 MHz) and provides about 50 to 55 dB of net gain. The correlation mixer converts the IF to 10.7 MHz. The post-correlation bandwidth is set by a 12 kHz crystal filter. The 10.7 MHz IF gain of 1 to 30 dB is controlled by a microprocessor during lock-up and by coherent AGC after lockup. The third IF of 700 kHz was chosen for ease of implementation of the phase coherent detectors using CMOS switches. Approximately 40 dB of gain is provided in the 700 kHz IF. By limiting gain at each IF to less than 60 dB, we minimize stability problems. With this selection of IF frequencies we have no problems with carrier false lock due to spurious frequency interference.

CORRELATION LOOP

The correlation loop is an early-late (± 1/2 chip) non-coherent type. The locally generated clear access (C/A) sequence bi-phase modulates 86.12 MHz from the carrier loop. The resultant signal is applied to the correlation mixer and, if the local and received sequences are aligned, the resultant 10.7 MHz IF out contains only the bi-phase (50 Hz) data transitions (of course, with the early-late dither of the local code, one-half of each code chip is lost). Servo error voltage is obtained from the envelope detector during initial lock and from the in phase coherent detector through a 1 ms delay sampler when locked. Correlation loop bandwidth is set to 3 Hz during acquisition and 1 Hz while tracking.

CARRIER LOOP

The carrier loop operates as a frequency snythesizer during correlation loop acquisition and a Costas loop when tracking. The companion microprocessor computes the expected Doppler from almanac data and sets the carrier synthesizer accordingly. Range is ± 4800 Hz, in 400 Hz steps. The carrier synthesizer will therefore be within ± 200 Hz of the carrier center frequency when the track mode is initiated. Carrier acquisition follows within one second.

SOFTWARE

A measurement computation involves doing a least squares quadratic fit to 15 seconds of pseudo-range data, evaluating the mid-point estimate of the fit, computing the slant range to the space vehicle (SV) making the Sagnac correction, computing the SV clock correction and storing a value for LOCAL-SV and LOCAL-GPS. This data is also output to the video display (and) to the hard copy device if desired. A complete measurement computation sequence executes in 2.1 seconds. The main program is busy about 20-25% of the time and is in the idle loop the rest of the time.

Up to 48 track times per day may be programmed into the receiver. At the end of each track time--normally about 8 minutes--the main program then does a least squares linear fit on the 15 second data points for LOCAL-SV and LOCAL-GPS. It then stores the intercepts and slopes, along with the SV#, time at beginning of track, azimuth and elevation (AZ/EL) at the end of the track, and sigma for the fits. The sigmas vary from 2 μs to 20 μs depending on the time of day, AZ/EL and the SV.

The main program is by far the largest of the nine programs running in the machine. It receives commands to do various functions through a 16-byte circular buffer. Up to 15 commands may be queued up at one time. Normally no more than three or four commands will be queued in the buffer. At present, a total of 18 different commands are executed by the main program, but this number will ultimately grow to the mid twenties when all the planned functions are added. All precise arithmetic functions are handled through a 15-decimal digit floating point package with hex interpreter, especially developed for this system. The floating point package occupies about 2k bytes.

All of the interrupt driven programs are concerned with input/output operations. The two RS-232 programs are concerned with communications over a telephone modem, and the video and keyboard programs provide the local operator interface.

The complete software package is about 32k bytes of machine language code, with 16k of firmware and display formatting in EPROM and 16k of program in RAM to be loaded from tape, e.g., the local coordinates.

COMMON VIEW DATA ANALYSIS RESULTS

As has been shown [1] one of the main advantages of the GPS in common-view approach is the cancellation of errors that are common in both legs of the viewing path with the same GPS satellite is viewed simultaneously. Therefore, the only errors in the time and frequency measurements between two remote sites are due to changes in the differential delays. The following analysis is an effort to characterize the limitations of using GPS satellites in common-view measurements taken simultaneously at the U.S. Naval Observatory in Washington, DC with its GPS receiver, and with the NBS constructed receiver located in

Boulder, CO (a baseline of about 3,000 kilometers). We began collecting data using this mode on the 31st of May 1981 and performed the analysis over the period of June, July, August and September of 1981. Three portable clock trips were made during this period and nearly daily values were taken on NAVSTAR satellites 3, 4, 5 and 6, which correspond to space vehicle (SV) 6, 8, 5 and 9, respectively. We agreed with USNO to measure at relatively high elevation angles after upload of the SV clock and ephemeris parameters from Vandenberg Air Force Base occurs; we also agreed to change the time once a week about 28 minutes to correspond with the movement of the ephemeris. Thus the satellites were viewed at nominally constant azimuth and elevation angles at each of the two sites. The USNO receiver applies ionospheric and tropospheric corrections. The NBS receiver collects the correction data, but the corrections were not applied. The viewing time for the constellation of the above four satellites moved from nominally midnight on the 31st of May to late morning for the September data--the data being taken over about a three-hour period for the four satellites. This moved the viewing through a significantly different period in the ionospheric profile--going from midnight delays to daytime delays. The coordinates of USNO and NBS used were 38^{o} 55' 13.503" North Latitude, 282^{o} 56' 0.151" East Longitude, + 47.68 m elevation and 39^{o} 59' 43.6220" North Latitude, 254^{o} 44' 15.569" East Longitude, 1663.3 m elevation, respectively. Both sides are about the same latitude, which would make the differential delay in the ionosphere about the same.

The short-term stability has been analyzed in a previous paper [2]. Fig. 1 is a review of that stability showing the short-term white phase noise characteristics of the apparent propagation fluctuations from the satellite through the receiver, to the reference clock on the ground. If the white phase noise shown in Fig. 1 were the only limiting noise, the mean value of an 8-10 minute data set would have an uncertainty of less than one nanosecond. However, when we analyze the day-to-day fluctuations, they were of the order of 10 nanoseconds rms, which indicates that there is another random noise driving mechanism on the day-to-day fluctuations. A possible mechanism is the daily uncertainties in the emphemeris. Fortunately, in the common-view approach, the clock error goes to zero, and the ephemeris error is significantly reduced from the actual error realized in a navigation solution. Fig. 2 is a plot via the common-view approach of UTC (USNO) provisional-UTC (NBS). The circles indicate the portable clock trips made during this period. The first clock trip was simply used to calibrate the differential delay between the USNO and NBS receivers and amounted to 335 nanoseconds. The remaining two trips used that as a calibration value assuming it would remain constant. The values were compared against quadratic least-squares fits to the data over the period in which the clock trip was taken. The portable clock values agreed to within an rms of less than 10 nanoseconds--which is of the order of the portable clock trip uncertainties. Four months of data were broken up into ten-day segments where continuous data were available. For each ten-day segment and for each of the space vehicles (SV6, 8, 5, and 9) NAVSTAR 3, 4, 5, and 6, respectively, a linear-least-squares (LLS) fit to the USNO-NBS clock time differences was calculated. Each LLS fit gave an intercept and a slope. The consistancy of these intercepts and slopes are a measure of the synchronization and syntonization accuracies, respectively, taken across the four satellites and as a time series given the ten-day average. Taken as a time series, the uncertainty on the LLS fit for a single satellite was 4.7 nanoseconds and averaged across the four satellites was 2.2 nanoseconds. The uncertainty on the slope from a single satellite for the ten-day average was about 0.7 nanoseconds per day and averaged across the four satellites was 0.3 nanoseconds per day. A slight asymmetry in the intercept values was observed that seemed consistent from one ten-day interval to the next and amounted to a peak-to-peak of about seven nanoseconds, which would indicate possibly an error in the coordinates at one or both of the sites.

Fig. 3 shows a frequency stability analysis using modified $\sigma_y(\tau)$ versus the sampling time [3]. The shaded area represents range of performance of the state-of-the-art standards that are currently being studied in various timing centers. The square blocks are stability measures for Loran-C taken over the last year for comparison purposes. The circles with the x in the middle are the frequency stability analysis of the data shown in Fig. 7 for the comparisons of the time scales UTC(USNO) versus UTC(NBS). The circles with the dots in the middle are estimates of the GPS measurement limit from the previous ten-day analysis. The one-day, two-day and ten-day values were calculated by measuring the same thing with the four satellites--UTC(USNO)-UTC(NBS). It is interesting that the measures seem to follow a $\tau^{3/2}$ behavior, which would indicate white phase noise again, but at a higher level. There are not apparent indications of systematics for sample times out to ten-days, which allows us to have a frequency comparison capability over ten-day samples of about three parts in 10^{15}. It then becomes apparent that at the ten-day averaging time the GPS in common-view is about a factor of 26 times better than is Loran-C for the Washington, Boulder path. It is also interesting to note that for sample times of the order of four days and longer, the instabilities of two of the best clock ensembles in the world are measurable using the GPS in common-view approach.

ACKNOWLEDGEMENTS

The authors are deeply appreciative of the cooperation of the staff of the USNO. We are also grateful for the support of our sponsors: Air Force Space Division, Jet Propulsion Laboratories, Navy Metrology Engineering Center, and Naval Air Logistics Center. Without their support this project would most probably never have come to fruition.

REFERENCES

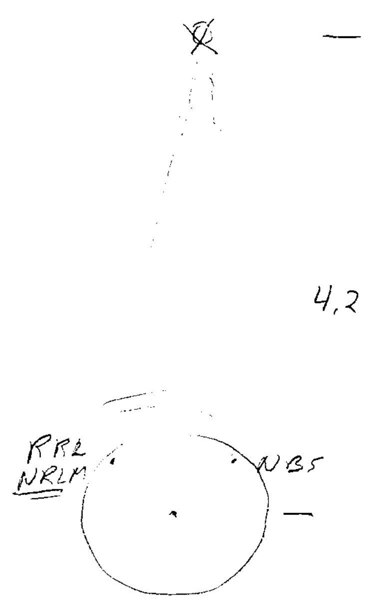
[1] D. Allan and M. Weiss, Accurate Time and Frequency Transfer During Common-View of a GPS Satellite, Proc. 34th Annual Symp. on Frequency Control (SFC), 344 (1980).

[2] Davis, et. al., Construction and Performance Characteristics of a Prototype NBS/GPS Receiver, Proc. 35th Annual Symp. on Frequency Control (SFC), 1981.

[3] D. Allan and J. Barnes, A Modified "Allan Variance" with Increased Oscillator Characterization Ability, Proc. 35th Annual Symp. on Frequency Control (SFC) 1981.

67°

12 hr. period



GPS − NRLM + D
GPS − NBS + D

NRLM − NBS ΔD

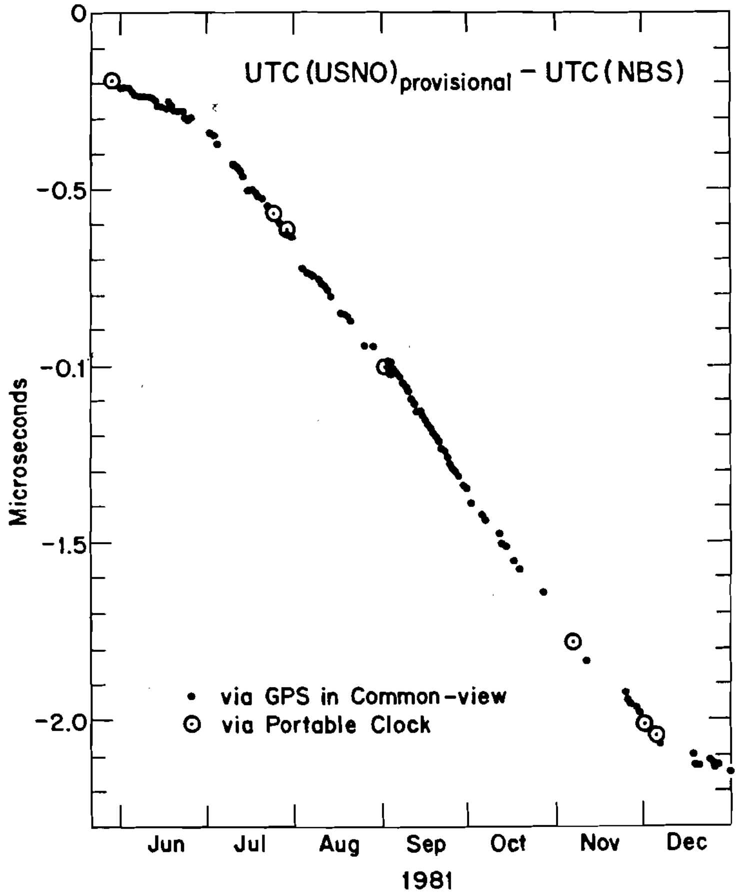


FIGURE 2

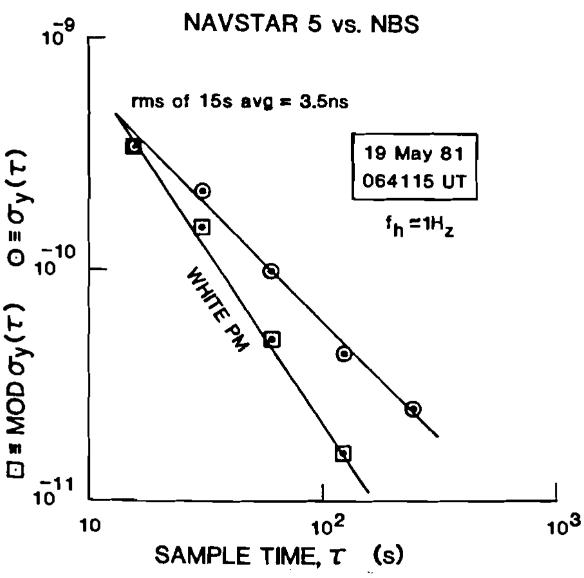


FIGURE 1

3000 km

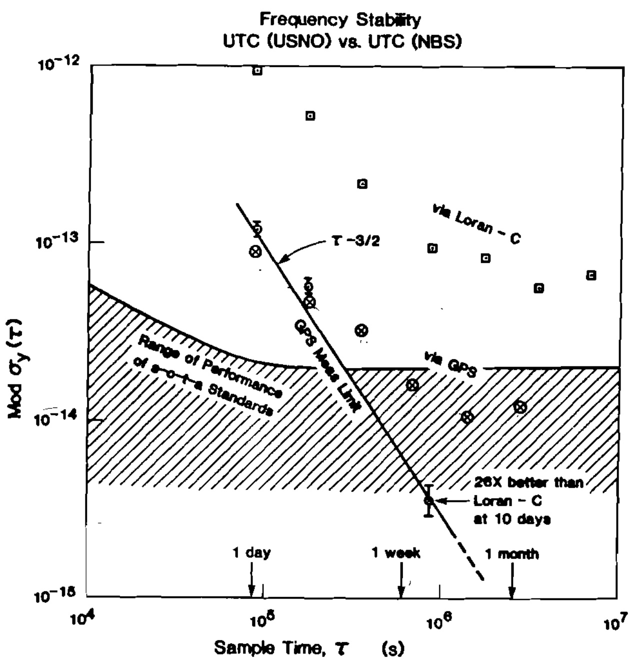


FIGURE 3