GLOBAL POSITIONING SYSTEM

FOR

TIME AND FREQUENCY MEASUREMENTS

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ABSTRACT

The Global Positioning System (GPS) has been used for time synchronization among major national time-keeping facilities for nearly ten years. Its reliability and accuracy are well documented. While older GPS equipment has operated well in a laboratory environment, more advanced receivers now on the market provide enhanced performance at a lower cost while expanding GPS time accuracies to new applications. The Collins Air Transport Division of Rockwell International has developed a commercial GPS sensor known as the NAVCORE® I which derives position, velocity, and time data from GPS satellite signals. Digital data outputs are updated at the rate of one complete solution per second, making the sensor function applicable to a wide range of dynamic and static time and navigation applications. This paper describes time performance of the NAVCORE receiver and the design of a time and frequency system based on NAVCORE.

INTRODUCTION

The Global Positioning system, developed and deployed by the United States Department of Defense, is a universal, all-weather, worldwide positioning system that provides position and velocity and time. GPS requires the tight interplay of three essential elements: The satellites, the ground monitoring and control system, and the user's receiver. When fully operational in 1990, the satellite constellation (figure 1) will consists of 24 satellites in orbits 12,000 miles above the earth. The satellites are solar powered by two steerable solar panel wings to maintain continuous sun tracking. Battery back-up for short periods of darkness is provided. A minimum of four GPS satellites will be visible anywhere in the world 24 hours per day. Currently, a test constellation of seven satellites provides 5-8 hours per day of coverage.

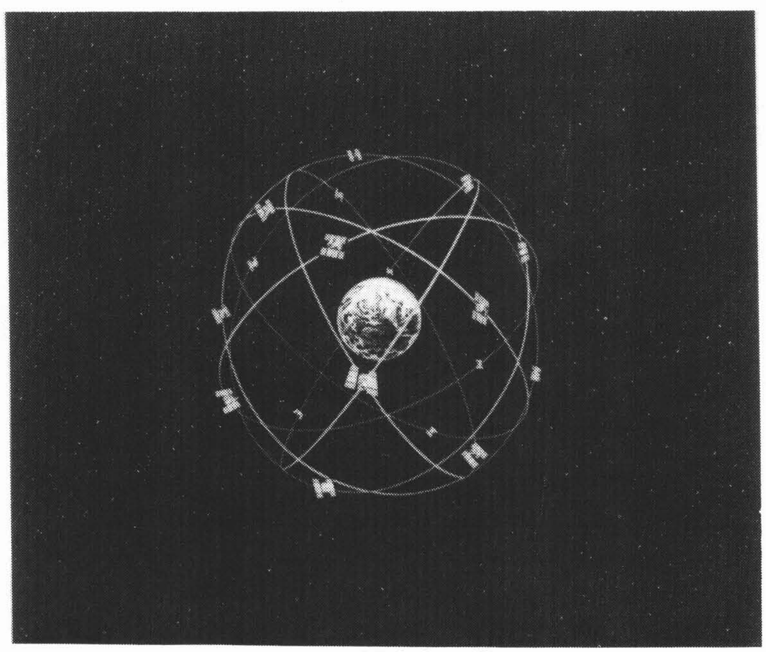

Figure 1. GPS Satellites.

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The ground control segment consists of a master control station and a number of monitoring stations. The control center daily uplinks ephemeris correction and other system data, such as the time difference between the GPS system and UTC (USNO), for storage and subsequent transmission to the user segment.

GPS is a one-way system. The satellites transmit the navigation information while users only receive information which allows an unlimited number of users. The United States Department of Defense and the Department of Transportation have a published policy of making the GPS C/A signal available free of charge on an international basis "with an accuracy commensurate with national security."

The system operates on the principle that the user determines his (pseudo) range and range rate to a number of GPS satellites (with precisely known ephemerides) by measuring the transit time of the navigation signal between each satellite and himself and scaling it by the velocity of light. Since the user clock is not directly synchronized to the satellite clocks, this pseudorange measurement is in error by the amount of user clock offset (figure 2). Acquisition of at least four satellites will permit the user to determine his position coordinates and obtain a user clock correction. When position coordinates are precisely known, one satellite measurement is sufficient to determine the user clock correction.

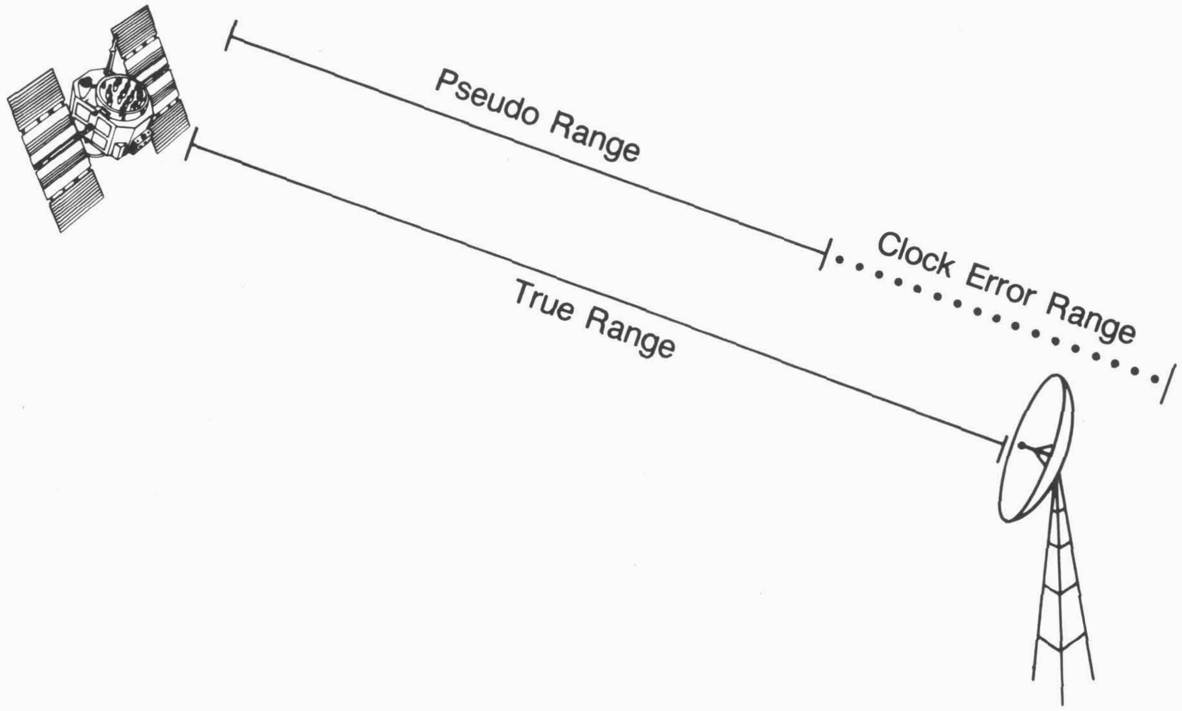


Figure 2. Clock Error.

NAVCORE OPERATION

Since its inception, the NAVCORE® I receiver (shown in figures 3 and 4) has been designed to be a low-cost black-box GPS sensor. In addition to a 1-Hertz analog timing pulse, the set has two RS-232 input/output ports. One is bidirectional for control and display functions and the second is for outputting time and navigation data. The analog timing pulse is synchronized to UTC (USNO).

Figure 3. NAVCORE.

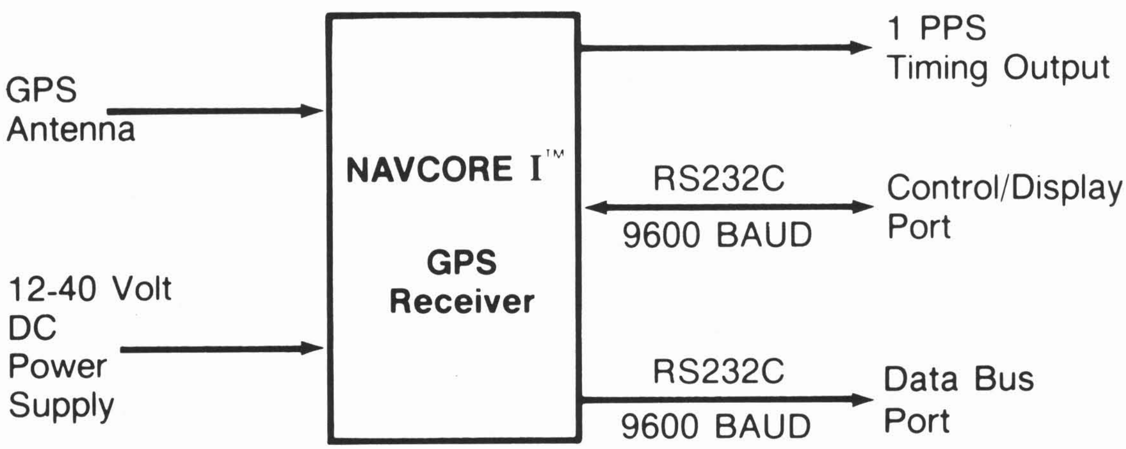


Figure 4. NAVCORE Block Diagram.

In its simplest form, the receiver provides a timing pulse derived from the internal temperature compensated crystal oscillator (TCXO). A TCXO was chosen for its small size and low power and for its lack of warm-up requirements. While the receiver is tracking one or more satellites in the stationary mode or four or more satellites in the dynamic mode, NAVCORE easily achieves time accuracies of better than 100 nanoseconds with respect to UTC (USNO). When the full constellation of GPS satellites is in place, a GPS receiver using a TCXO will be capable of providing accurate time to all but the most exacting requirements.

PERFORMANCE

Figures 5 and 6 are a photograph and block diagram, respectively, of the equipment which was used for over a year to verify time performance of the NAVCORE GPS receiver. In addition to the NAVCORE with power supply and control display unit, the equipment consists of a GPS time transfer receiver leased from the

National Bureau of Standards, an Efratom FRK rubidium oscillator, a Hewlett Packard model 5335A time interval counter and an IBM personal computer. Data from the GPS receiver at the Naval Observatory is also used.

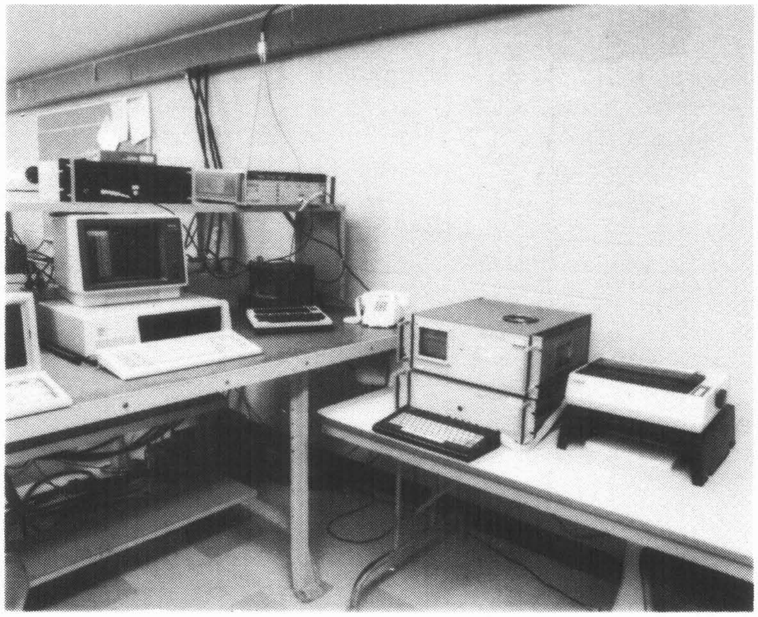


Figure 5. Lab.

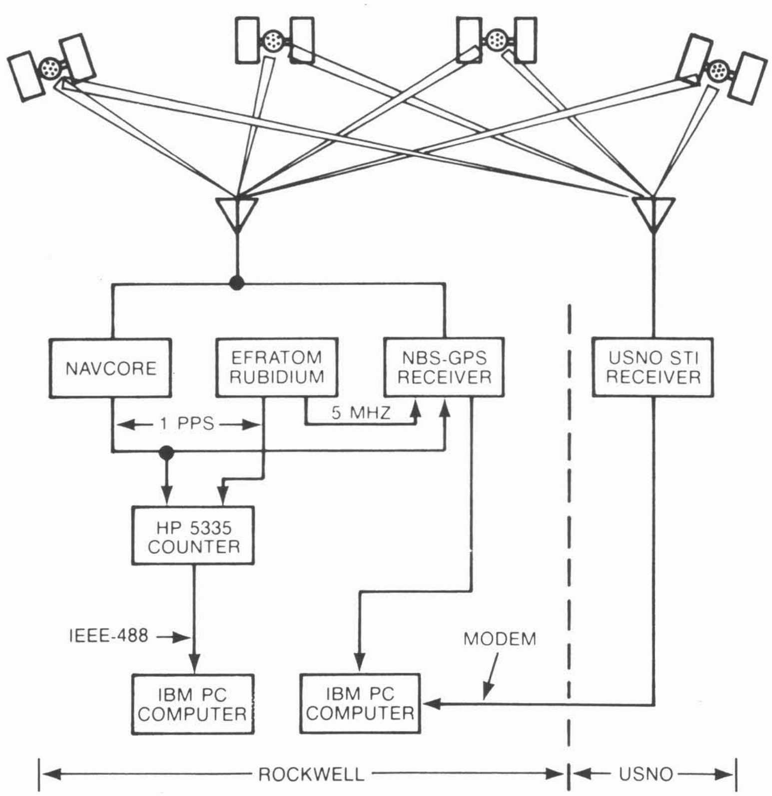


Figure 6. NAVCORE Time Accuracy Test Setup.

NAVCORE tracks up to four satellites simultaneously and derives position information and GPS time. GPS time is then corrected in the receiver to UTC (USNO) using down-link data from the satellites. The 1-Hertz timing pulse is output on the UTC 1-second mark, followed by digital data on the RS-232 bus to describe time, date and receiver tracking status. Operation of the NAVCORE is completely automatic, including selection of the optimum satellite constellation.

At five predetermined times each day, the 1-Hertz output form NAVCORE was compared to GPS time using the NBS time transfer receiver. At the same time, the receiver at the Naval Observatory is tracking the same satellite in "common view" and comparing UTC (USNO) to GPS time. Accuracy of this common view measurement technique has been demonstrated to be better than 10 nanoseconds.

Performance of NAVCORE over an 8½ month period is summarized in figure 7. Curve A shows the relationship of NAVCORE's time mark pulse and GPS time as measured by the NBS receiver. Curve B is the relationship between UTC (USNO) and GPS time as obtained from the GPS receiver at the Naval Observatory and curve C, the difference between curves A and B, is the comparison of the time derived by NAVCORE and UTC (USNO). The plot contains 1185 data points with a mean error of 42 nanoseconds and a standard deviation of 38 nanoseconds.

While it is possible to obtain greater accuracy using common view techniques, it must be remembered that this type of performance is obtained without knowing the precise location, can be obtained within five minutes after applying power to the receiver and can be obtained while moving. In fact one of the most significant uses of GPS in the future may be to bring precise time to moving platforms, such as calibration of atomic clocks used on research vessels.

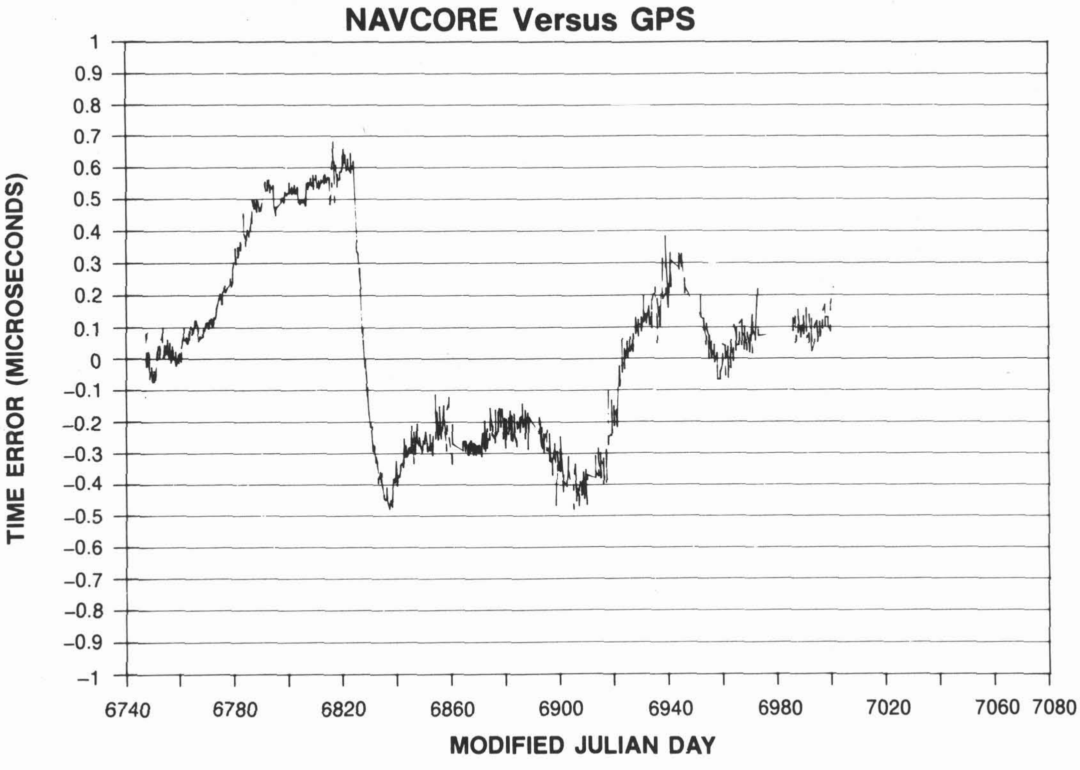
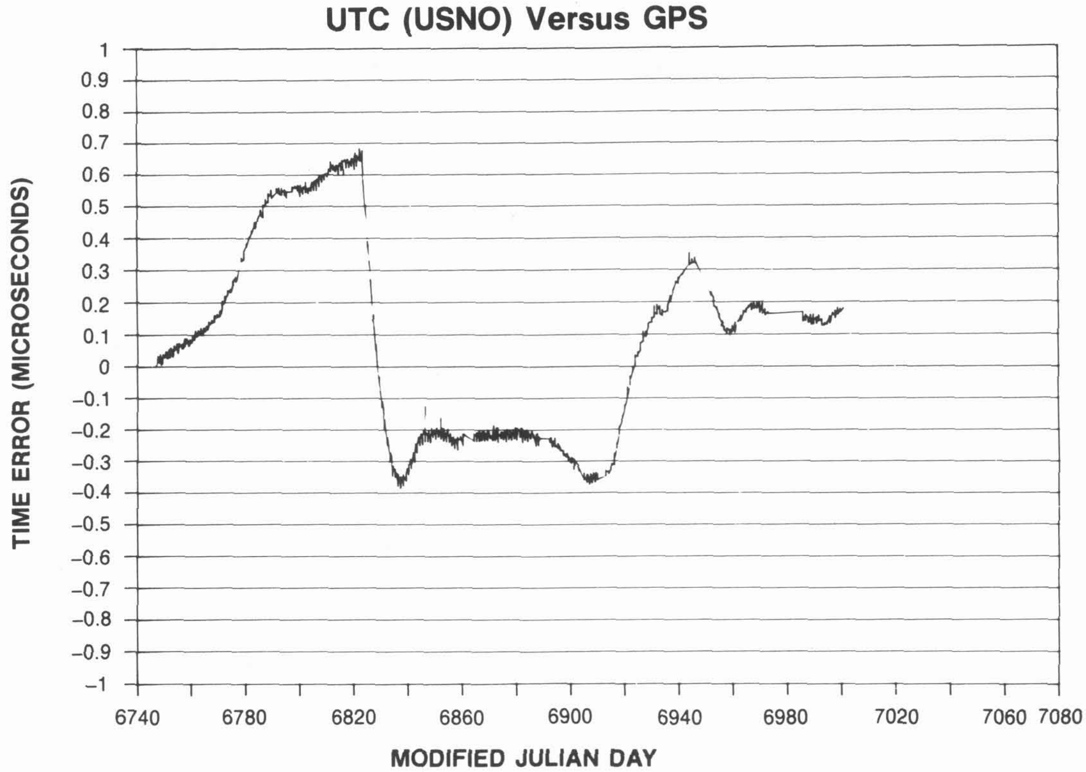


Figure 7. NAVCORE GPS Timing Data (Sheet 1 of 2).



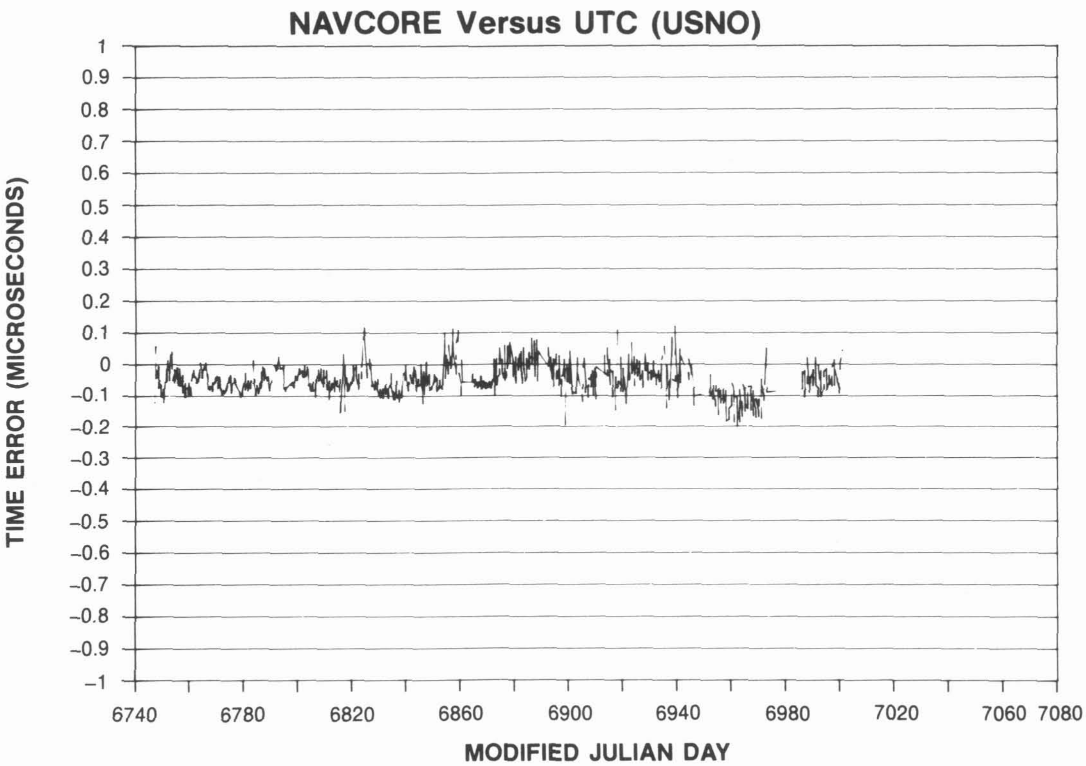


Figure 7. NAVCORE GPS Timing Data (Sheet 2 of 2).

While tracking satellites, NAVCORE continuously measures the frequency error of the oscillator and compensates for this error when outputting the 1-Hertz pulse. In absence of satellites, the receiver continues to output time based on the TCXO and the last measured frequency error before satellites were lost. Figure 8 is a plot of four days operation, sampled at a rate of once every 100 seconds. This data is collected by the HP 4335A counter (see figure 6) which compares the 1-Hertz output of NAVCORE with a pulse derived from the rubidium oscillator. Periods of no satellites are obvious from the plot by the divergence from the nominal drift of the rubidium oscillator. In this case, the worse case error during the eight hours when satellites are not visible approach 300 microseconds. This represents an error of 1 part in 10^8. From a single plot, it is not obvious whether the error results from drift in the TCXO or errors in calibration of the TCXO frequency.

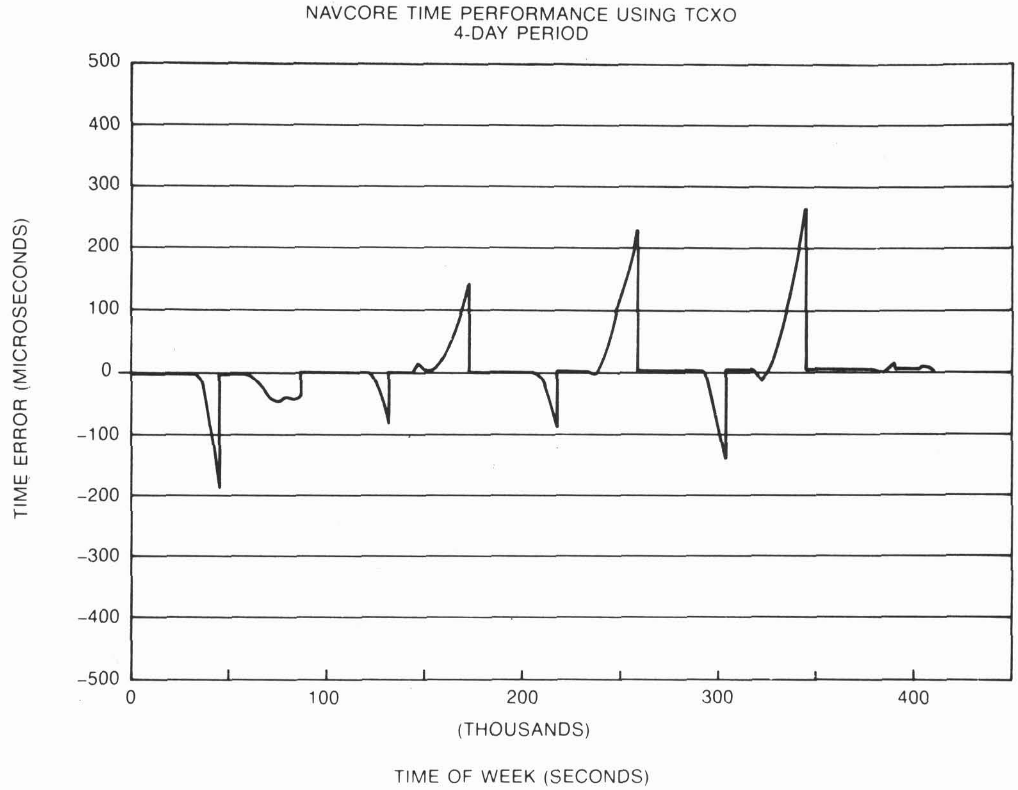


Figure 8. NAVCORE Time Performance Using TCXO.

For comparison, figure 9 shows four days of equivalent data when NAVCORE's internal oscillator is locked to the rubidium oscillator. By calculating a linear fit to the data to remove the rubidium drift, the scale can be expanded as shown in figures 10 and 11. Figure 10 shows that, during eight hours without tracking satellites, the maximum time error was approximately 7 microseconds or 2.4 parts in 10^{10}. Of particular interest is how quickly NAVCORE resynchronizes time after the satellites are reacquired. Figure 11 expands the scale further during an eight-hour period when ssatellites were tracked. A significant portion of the noise is associated with the plus or minus 50 nanosecond resolution of NAVCORE's 1-Hertz output.

ENHANCEMENTS

While locking NAVCORE's internal oscillator to an external source will improve accuracy, further enhancements can be obtained by combining NAVCORE with a rubidium oscillator into a system referred to as a disciplined oscillator. The system shown in figure 12 consists of the rubidium frequency standard, a microprocessor, digital-to-analog converter, frequency divider and phase shifter, time interval counter and the GPS

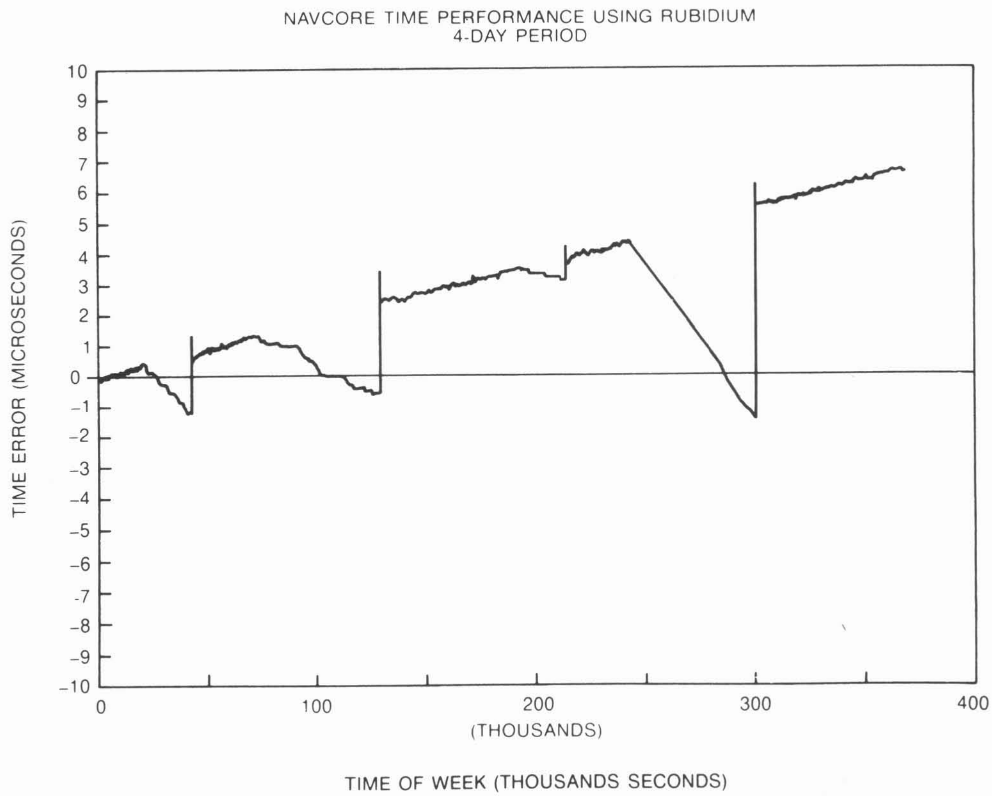


Figure 9. Rubidium Time.

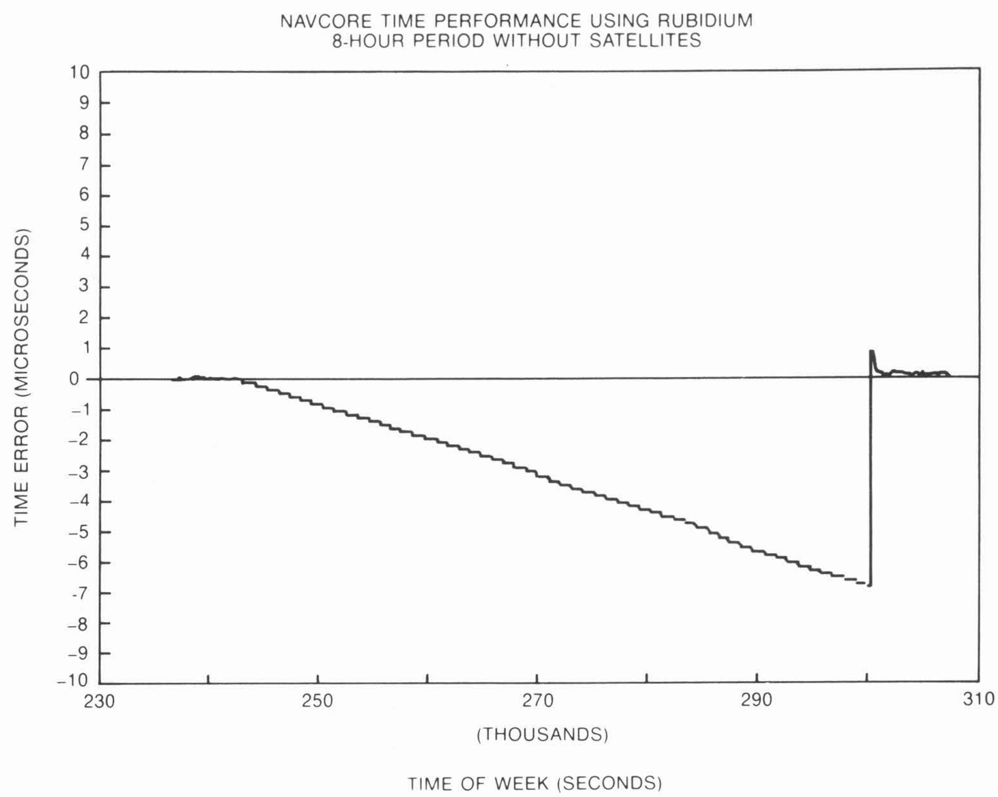


Figure 10. Performance Without Satellites.

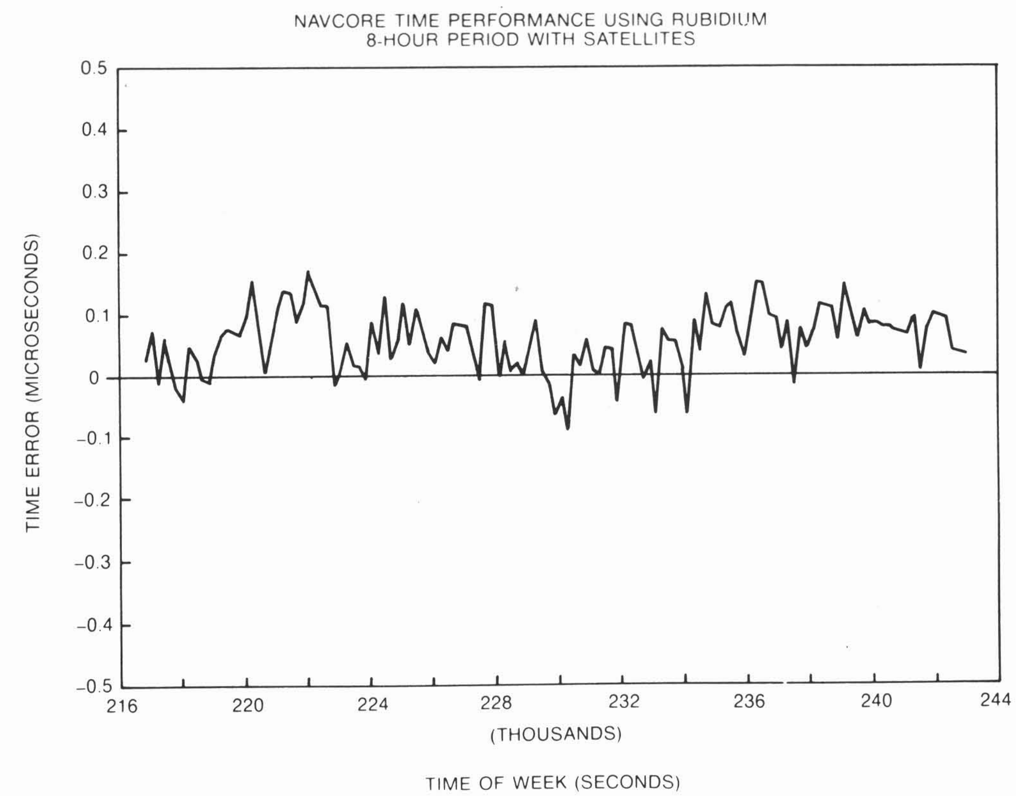


Figure 11. Performance With Satellites.

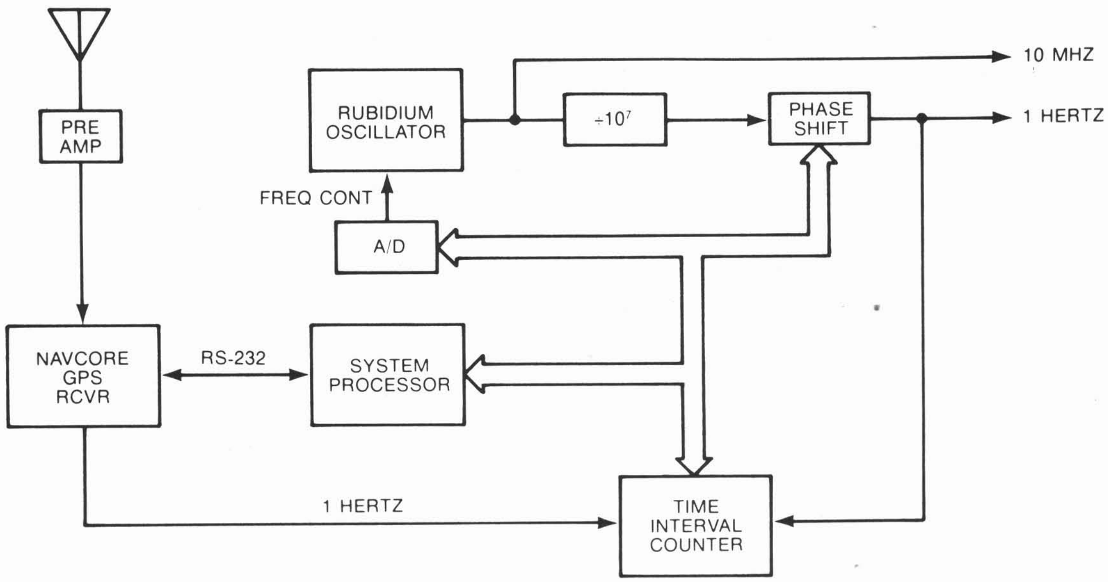


Figure 12. Disciplined Oscillator, Block Diagram.

receiver. The control loop which adjusts the oscillator frequency and 1-Hertz signal to the GPS reference can use conventional phase and frequency lock techniques, but with extremely long time constants. During initial lock-up, any time error exceeding 100 ns can be removed by phase shifting the output pulse rather than frequency tuning. After initial phase alignment of the 1-Hertz pulses, the frequency error of the rubidium is corrected by comparing the 1-Hertz pulses from the frequency divider and the 1-Hertz pulses from NAVCORE. Analysis of GPS data indicates that for sampling intervals from 1 second to 800 seconds white phase noise dominates. Consequently, optimum estimates of phase and frequency in this measurement region are obtained from the intercept and slope, respectively, of the straight line obtained from a linear least squares fit to 800 seconds of data. After initial frequency calibration is complete, a single 800-second measurement of day during the period of satellite visibility is sufficient to maintain the closed loop system with a frequency error of 5 parts in 10-12 and within a time error of no greater than 200 ns with respect to UTC (USNO). A similar system can be designed with a crystal oscillator except that shorter time constants would be required.

CONCLUSIONS

GPS receivers can now provide a cost-effective method of providing time synchronizing anywhere in the world even with a limited satellite constellation. Applications on moving platforms and in situations where time synchronization is required in minimum time are particularly attractive. Frequency performance which rivals that of a high quality Cesium and time synchronized to UTC (USNO) can be obtained by disciplining a rubidium oscillator with the GPS receiver.

QUESTIONS AND ANSWERS

Dave Allan, National Bureau of Standards: This was just an L1 channnel receiver, wasn't it? The question has come to me several times as to what this means for a common view time transfer in the future. As Colonel Green pointed out earlier, there is a civilian Users effort going forward in order to give a post–ephemeris, and thus, in a common view sense, the GPS clock errors cancel to the first order completely. We should have very good time transfer still, with that post–ephemeris. That would be a matter of two days or so after the fact. Time transfer should not be impacted, in fact if the post–ephemeris is better, it should give improved time transfer accuracy. I suppose that you will be taking advantage of the same techniques in the Navcor system?

Mr. Knoernschild: The emphasis here was for the real time performance of the system so the degradation of the system would affect this type of system.

Mr. Allan: You would not be capable of doing post analysis?

Mr. Knoernschild: We are capable of doing post analysis, but it does degrade the real time performance.