An Off-Air Observatory Time Service

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Abstract

When the decision was taken to severely reduce the funding for the Greenwich Time Service, an alternative precision time service had to be found, so that the Satellite Laser Ranger could continue to operate.

There were certain constraints on the alternative such as, high precision, highly reliable, not labour intensive, physically small and inexpensive.

This paper shows how this was achieved. It is considered to be a unique solution not achieved before and provides an elegant solution to an inherently complex problem. Great reliance is put upon external agencies to provide the infrastructure to maintain their equipment. Use is made of the LORAN-C chain of stations for the frequency references and the Global Positioning System satellite for the Time of Day and traceability.

This is a one rack complete observatory time service and the results compare very favourably with the remaining standards on site.

Introduction

Until the summer of 1987 the RGO had always generated its own independent time. In the best years we had 8 operational Caesium standards (Cs Stds). Our operating conditions provided us with one of the best available time scales.

However, that has now all changed and the RGO now is dependent upon other agencies to provide us with frequency references and Time of Day (TOD). We are now a user of the system which we were influential in setting up.

Part of our work was involved with the monitoring of the LORAN-C stations around us in Germany, Iceland and the Mediterranean.

It is no longer necessary to refer to the stars in order to get TOD. Today very few places do this, others merely switch on a black box and wait a while and out comes the answer. It is not even essential to know where you are on the surface of the earth.

Requirement

The astronomical work at the RGO in Herstmonceux today is now primarily involved with Satellite observations. We have a Satellite Laser Ranger (SLR) which is our main instrument. All other large telescope work is done on the Canary Islands.

The requirements for the SLR time service was such that it wanted a frequency at 5MHZ with a stability around 1×10^{-11} and TOD presentation with resolution to 1μs, and traceability to BIH. A 1 pps on time was also required for the timing of the laser.

The equipment had to be housed in the telescope building, must be protected against short mains failure, inexpensive, and because of the reduction of staff - non-labour intensive (automatic).

Solution

Back in 1985 I proposed that we used a disciplined frequency standard as our "local" standard, with LORAN-C as its frequency reference and GPS satellites as the TOD reference (1). This proposal was only based upon the specifications of the equipment (2) (3) and not upon experiments done.

In spring of 1986, Austron, who were aware of my problem of dying Cs Stds and severe financial restrictions, came to the rescue. They donated a Global Positioning System (GPS) receiver, the single most expensive item in my system.

Whilst we still had some life in the Cs Stds on site the GPS receiver was to be used to check the stability of the received TOD. The results were very encouraging and gave me enough solid argument to manage to get the funds for a Discipline Frequency Standard (DFS).

The LORAN-C receivers were available from our monitoring service, and so I had the equipment to establish an "Off-Air Time Service". Fig 1 shows the basic arrangement.

The system had to be self sufficient and so the power supply to the rack went via a Uninterruptable Power Supply (UPS) which would protect us against outages of up to 30 mins.

Practical Realisation

The traditional way of using LORAN-C and GPS in the Time comparison field is to use them as a receiving means.

Here we are not only using them as a comparison but are using them to set up the system.

The LORAN-C and the DFS are in a closed loop and the DFS and the GPS are in an open loop.

The received LORAN-C signal directly influences the frequency output of the DFS.

The GPS receiver having once synchronised the DFS is then only used for comparison.

Two LORAN-C stations can be monitored and the best signal is used as the Primary reference for the DFS whilst the second, less consistent signal, is used as the Secondary reference.

Freqency Reference

From Fig 1 it can be seen that the DFS and LORAN-C receiver are in a closed loop.

Initially the DFS is used as the reference frequency for the LORAN-C receiver. Once tracking the LORAN-C receiver will produce an error signal, which is proportional to the difference between its local reference and the station being received.

This phase shifted 1MHZ is then fed back into the reference input of the DFS. The DFS then reduces this error by adjusting its crystal oscillator output frequency until there is a minimum difference.

The DFS now has an output frequency closely locked to the Cs Stds at the LORAN-C Station being monitored. This is now the local "off-air Cs Std" giving frequency and Time Interval.

Time of day reference

To enable the system to be used as an "Off-Air Time Service" it is necessary to obtain TOD information. The GPS satellites give this information to ± 100nS and so by using the GPS receiver (4) and synchronising the output of the DFS to one of the satellites we then have TOD.

By continuing to monitor the difference between the DFS 1PPS and the received 1PPS it is possible to get details of the local 1PPS error on UTC (BIH) very quickly.

Operational Results

The Map Fig 2 shows the sites of LORAN-C stations used, and the future coverage. This gives an idea of the long distances used in this experiment. Sylt is about 400 miles, over mainly water and Estartit is more like 600 miles over land. Neither of these signals are free from the multitude of interfering signals present in Europe. The most consistent interfering signal is the local (less than 100 miles) French station at Lessay. This station would have been used as the frequency reference had it been fully operational. But as this was not the case, then Sylt was used, the best available to us.

When eventually the LORAN-C/DFS combination settled to around $\pm$ 1 x 10^{-12} per day then the GPS receiver was brought into the system. All available satellites were monitored and quickly enabled us to synchronise the 1PPS and TOD of the DFS to an acceptable offset from UTC (GPS). The outputs then available were 5MHZ $\pm$ 1 x 10^{-12}, 1PPS to $\pm$ 100 ns/day and TOD to better than $\pm$ 100 nS. This was within the acceptable limits set by the Satellite Laser Ranger specification and meant that we now had an observatory clock system without the expense of the Cs Stds, monitoring equipment, and an expensive large installation.

Fig 3 shows the quality of lock of the LORAN-C receiver/DFS combination, over an eight hour period. Alongside for direct comparison Fig 4, is the output of the DFS compared with CsS an HP5061 Supertube Cs Std. The variations of the locking are much reduced in the DFS output remaining better than $\pm$ 1 x 10^{-12}.

To check the GPS received pulse, another Cs Std (CsV) was used with a second GPS receiver. Fig 5 shows how the 1PPS pulse from CsV compared with the 1PPS of the DFS. The slope is due to the rate of CsV. The comparison of the DFS against GPS Fig 7, shows the level of uncertainty of about $\pm$ 100nS. The DFS output is therefore shown as around the acceptable level of stability for the system. The slope this time is due to LORAN-C Sylt.

The short term results of the DFS against a local good supertube Cs Std however has show up some sudden unexplained perturbations of the order of several parts in 10^{-11} which are still being investigated and are thought to be problems with the reception of LORAN-C signals.

For some time the two input statistical mode of operation of the DFS was used and this showed some strange effects around sunrise and sunset. Perhaps there is a diurnal effect on the signals we receive. But never before have we monitored them so closely with 1μS full scale.

Future Trends

With the results so far obtained it gives sufficient confidence to say that the limiting factor is the reception of the LORAN-C signal.

When the expansion of the LORAN-C network in Europe is complete then the system described in this paper will be even more stable. It will enable observatories and others interested in precise time of day to obtain this quickly and cheaply and by using the navigational results from the GPS anywhere without even the need to know where you are. The latest LORAN-C receivers are capable of selecting the station and automatically locking on to it.

The DFS can monitor up to two stations and if either fails it will continue on the other. Should both fail then it will continue to apply the corrections that it had calculated before the failure, and give a couple of days of protection before the system starts to drift off.

This all goes to make up a very good automatic system relatively inexpensive and all fitted into one 19" rack.

Conclusions

For over 300 years the RGO has had its own independent time service based upon local observations of the stars. However, the work that we started at Greenwich, the Prime Meridian, has been overtaken by technology.

We still have the Prime Meridian at the Old Observatory in Greenwich Park, London, but no longer will we have our own independent time service. We are now operating a dependent time service, off-air. Radio now provides us with more than a method of intercomparison, it provides us with our references.

We now rely upon the Cs Stds at the LORAN-C stations being looked after in the way we looked after ours. We rely upon the GPS timing stations ensuring that the TOD from the GPS system is within acceptable limits. We now have a fairly straight forward system of two radio receivers and an intelligent crystal oscillator to provide us with our time.

Acknowledgements

I should like to express my sincere thanks to all those individuals and organisations who have shown an interest and given valuable assistance to the RGO in its hour of need. Most especially Austron who donated the GPS receiver and have sponsored my attendance at this conference.

References

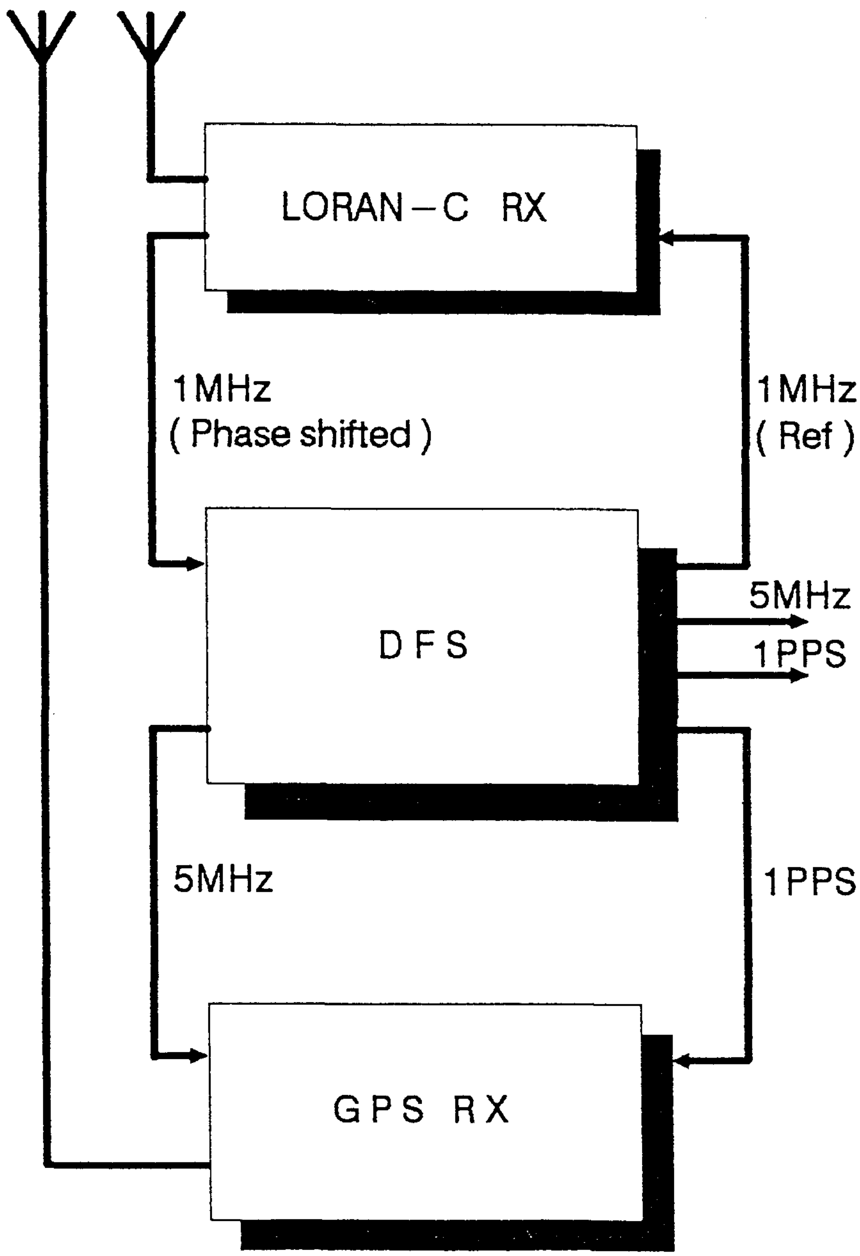
(1) Second proposal for an SLR Time Service November 1985 (RGO).

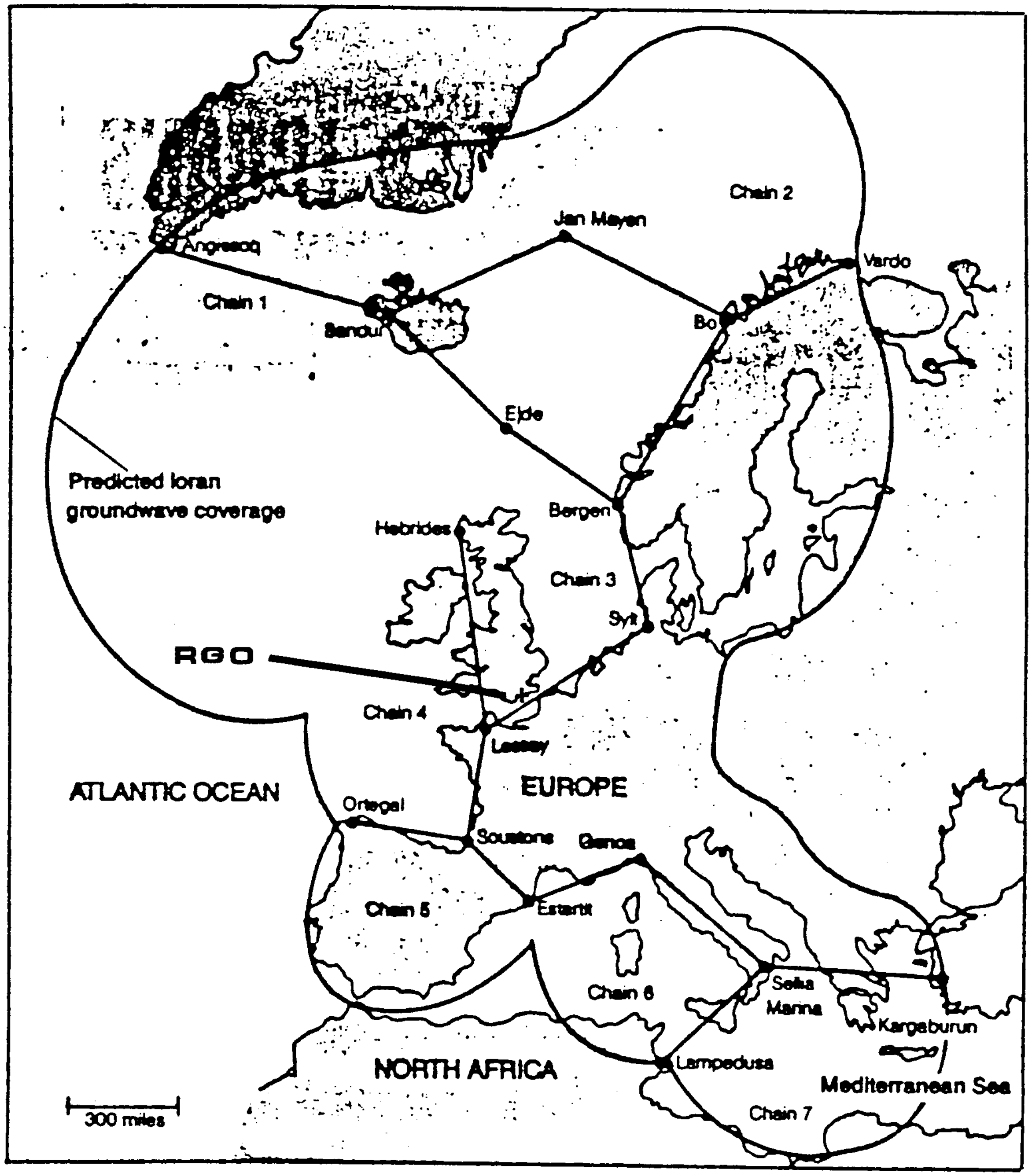
(2) Austron 2000C specifiction LORAN-C receiver.

(3) Austron 2110 specification Disciplined frequency standard.

(4) Austron 2101 specification GPS receiver.

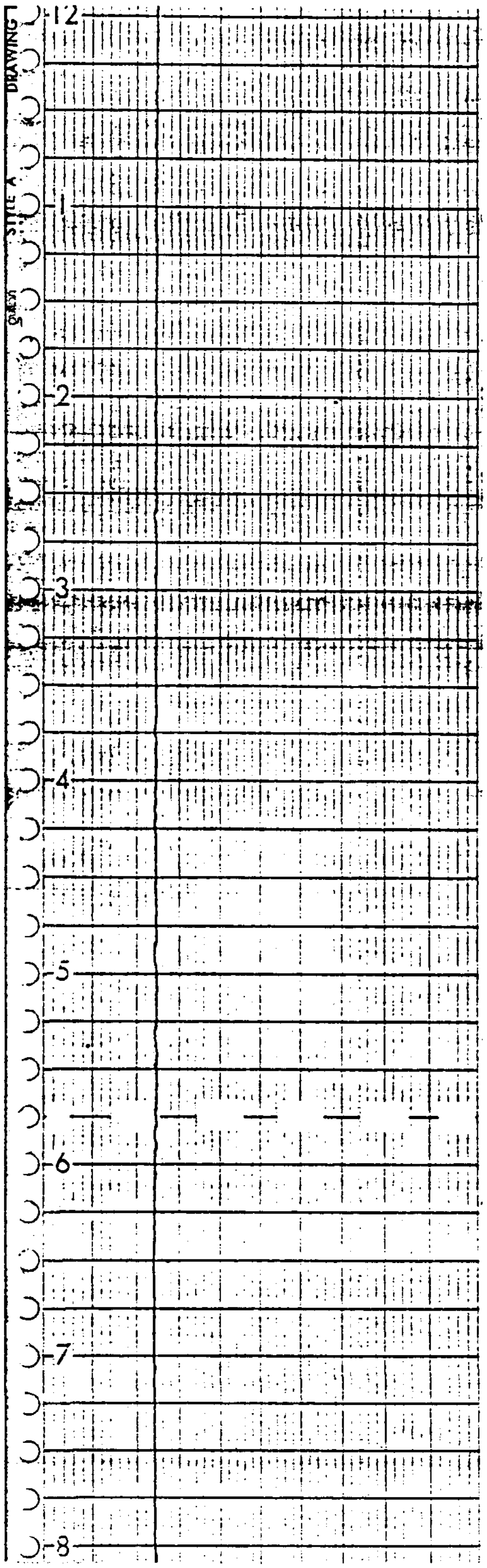
Fig. 1


LORAN – C RX
1MHz
(Phase shifted)
1MHz
(Ref)
DFS
5MHz
1PPS
5MHz
1PPS
GPS RX

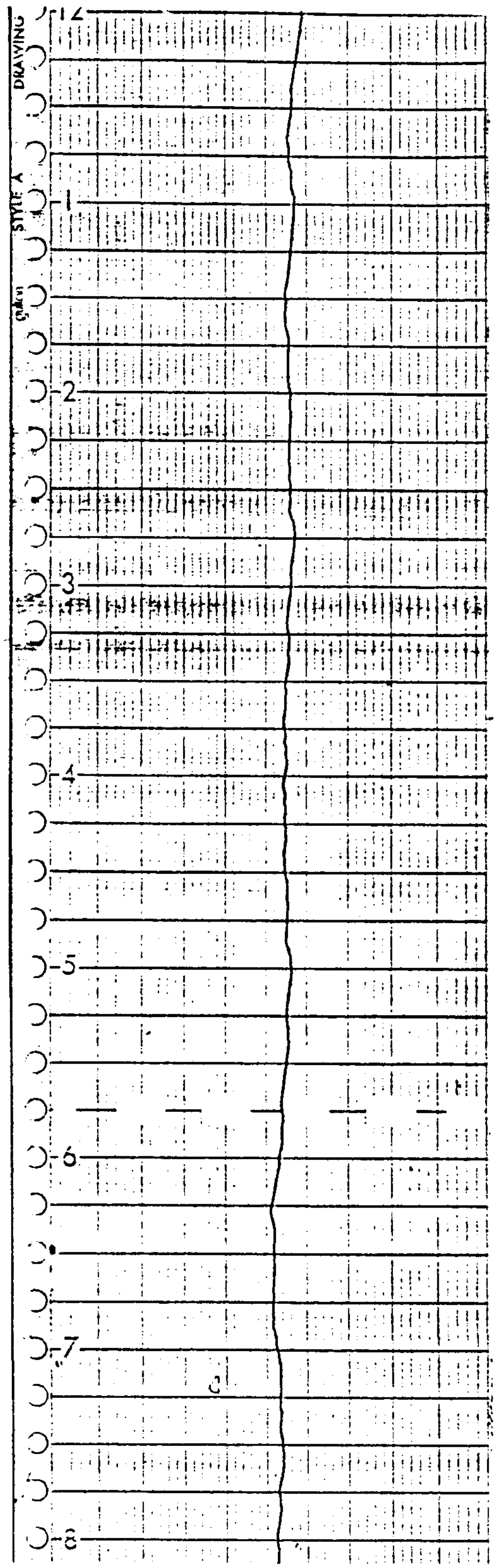


Proposed new European loran coverage shown by solid line

FIG. 2



10 µS
DFS - SYLT
Fig. 3



1 µS
Cs.S - DFS
Fig. 4

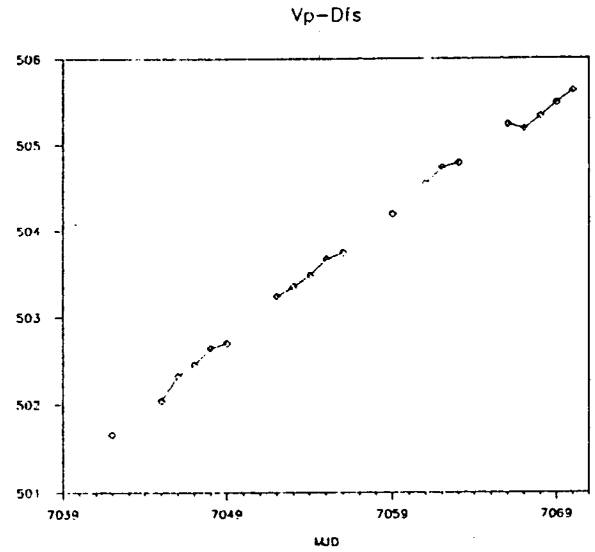


FIG. 5

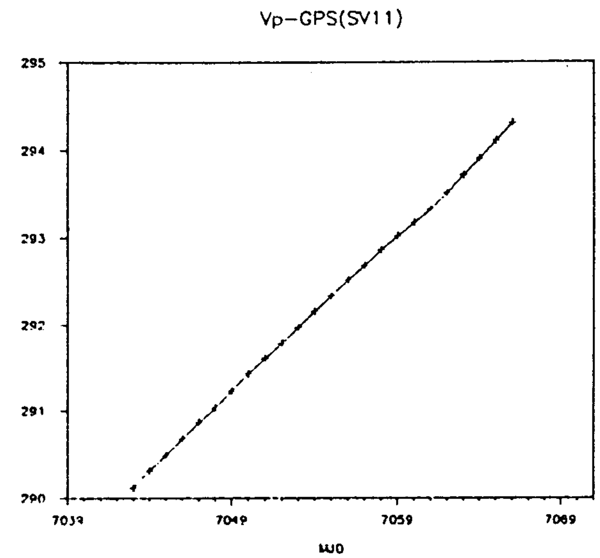


FIG. 6

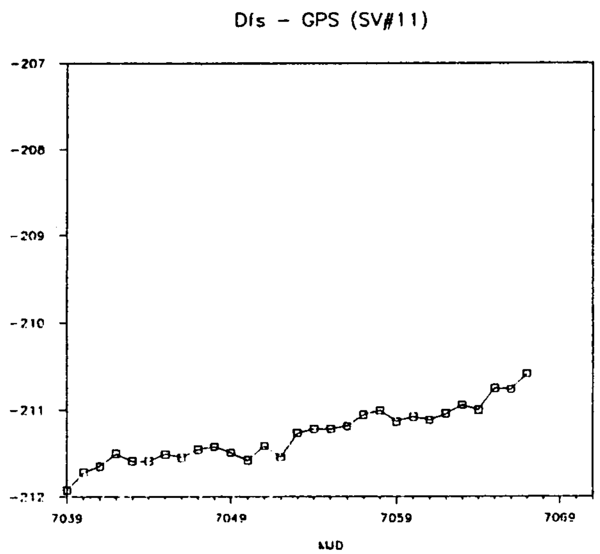


FIG. 7

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 timekeeping 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.

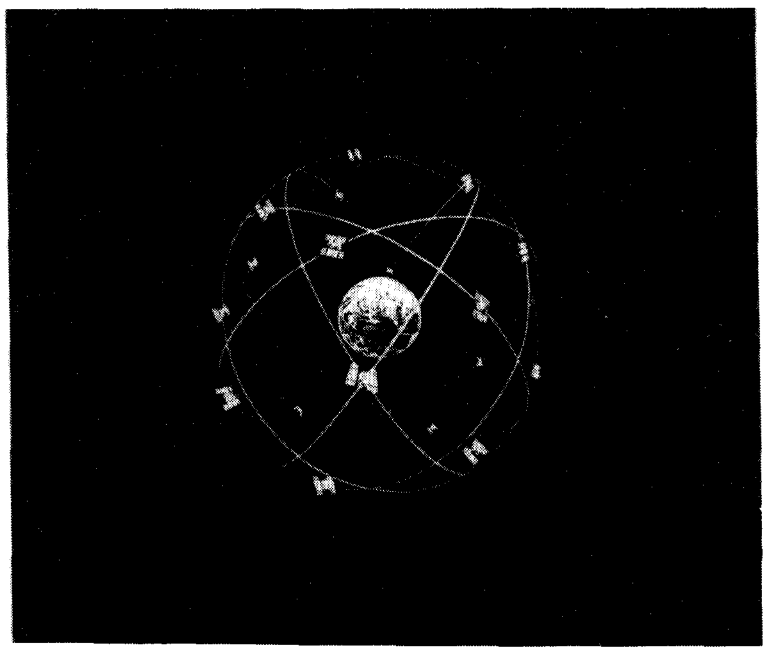


Figure 1. GPS Satellites.

NAVCORE® is a registered trademark of the Collins Air Transport Division of Rockwell Intternational

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.

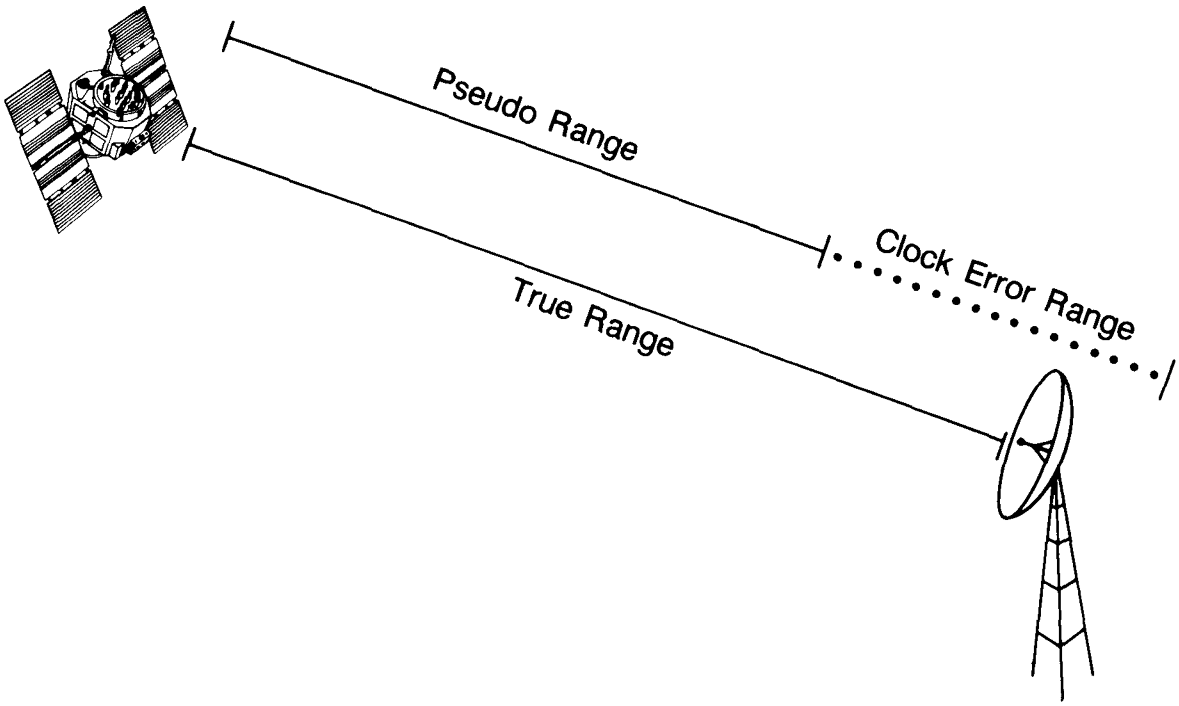


Figure 2. Clock Error.

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).

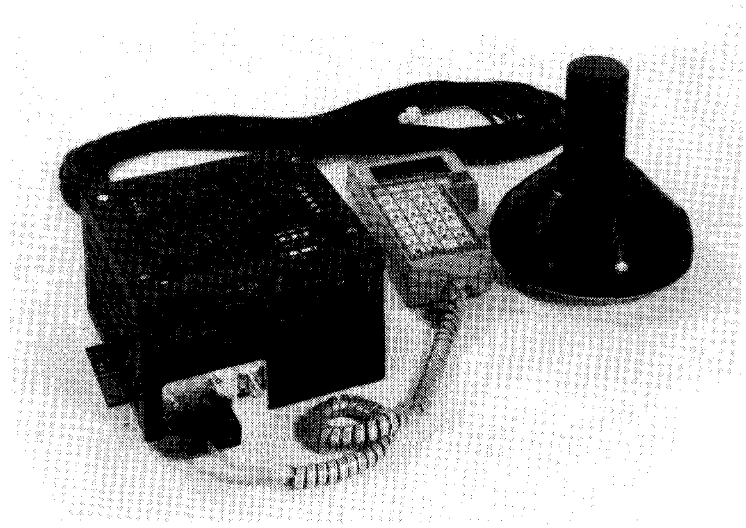


Figure 3. NAVCORE.

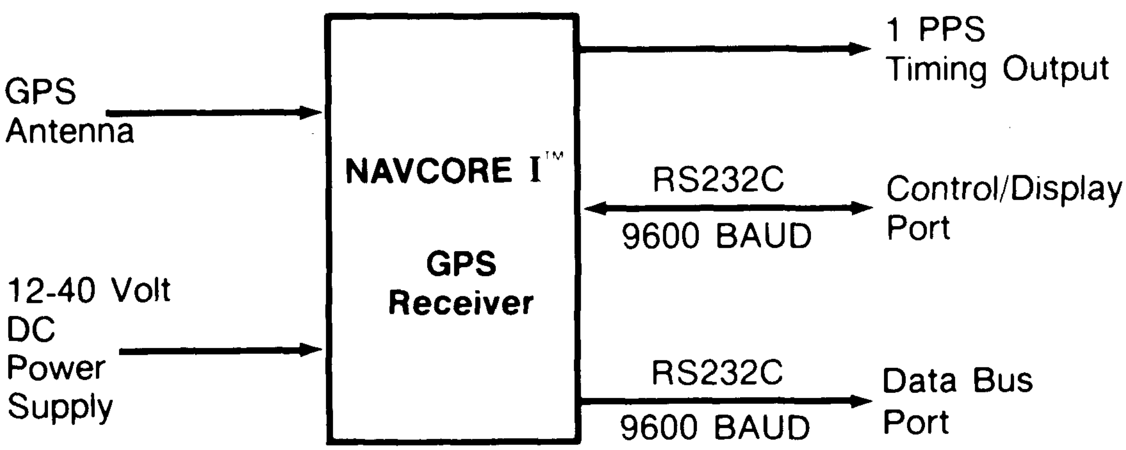


Figure 4. NAVCORE Block Diagram.

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.

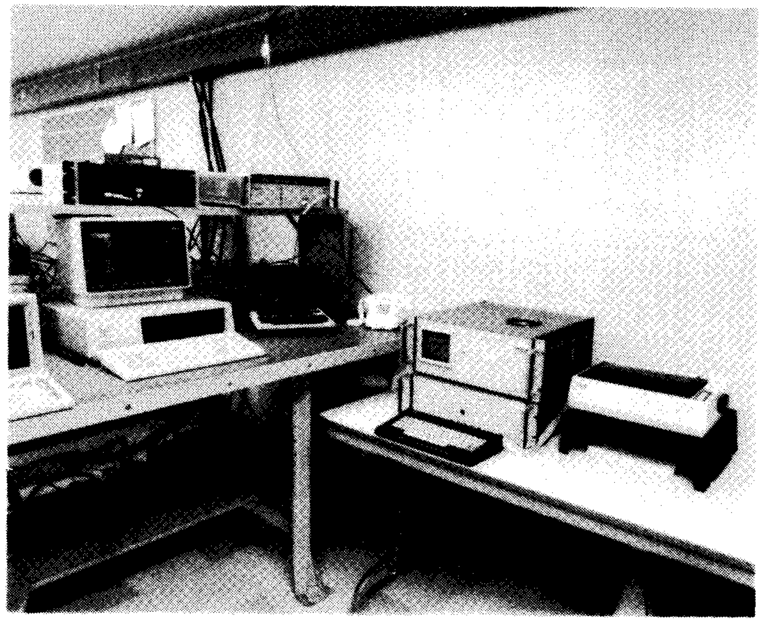


Figure 5. Lab.

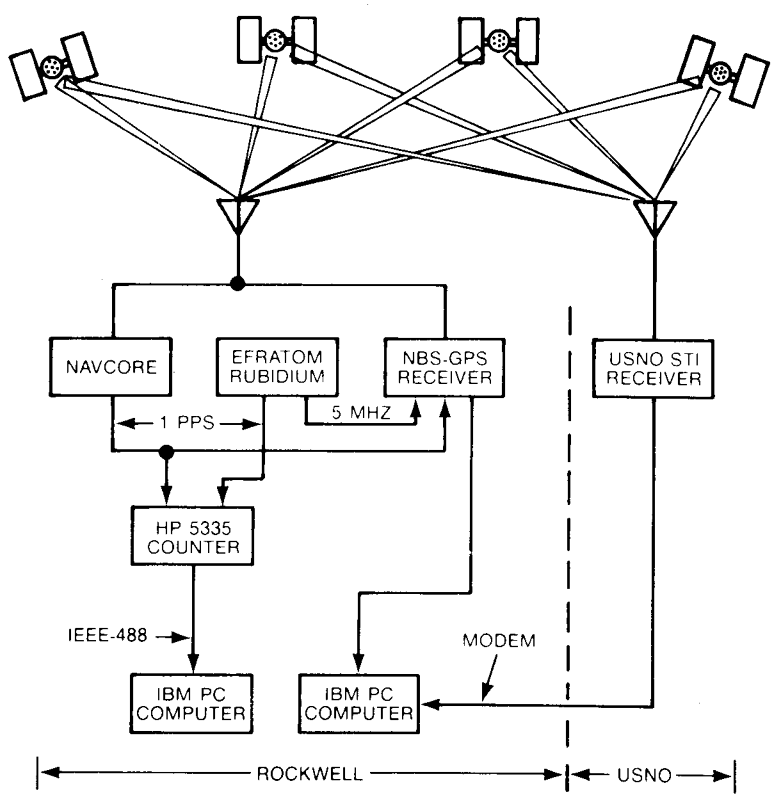


Figure 6. NAVCORE Time Accuracy Test Setup.

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.

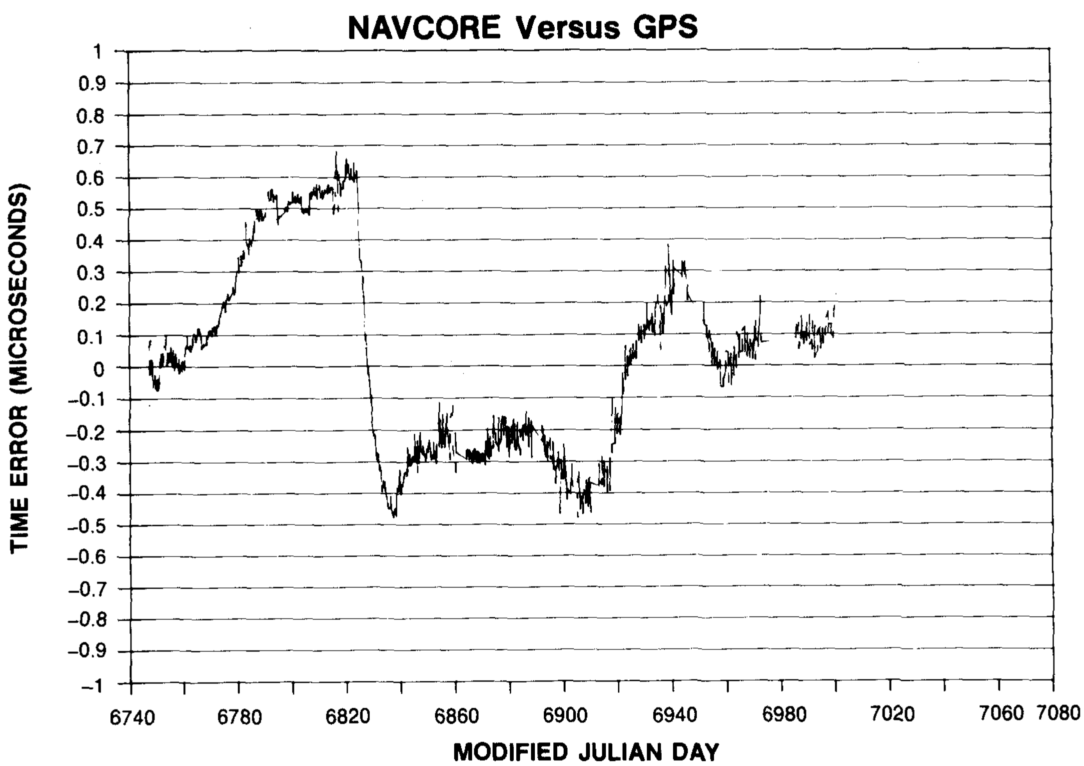
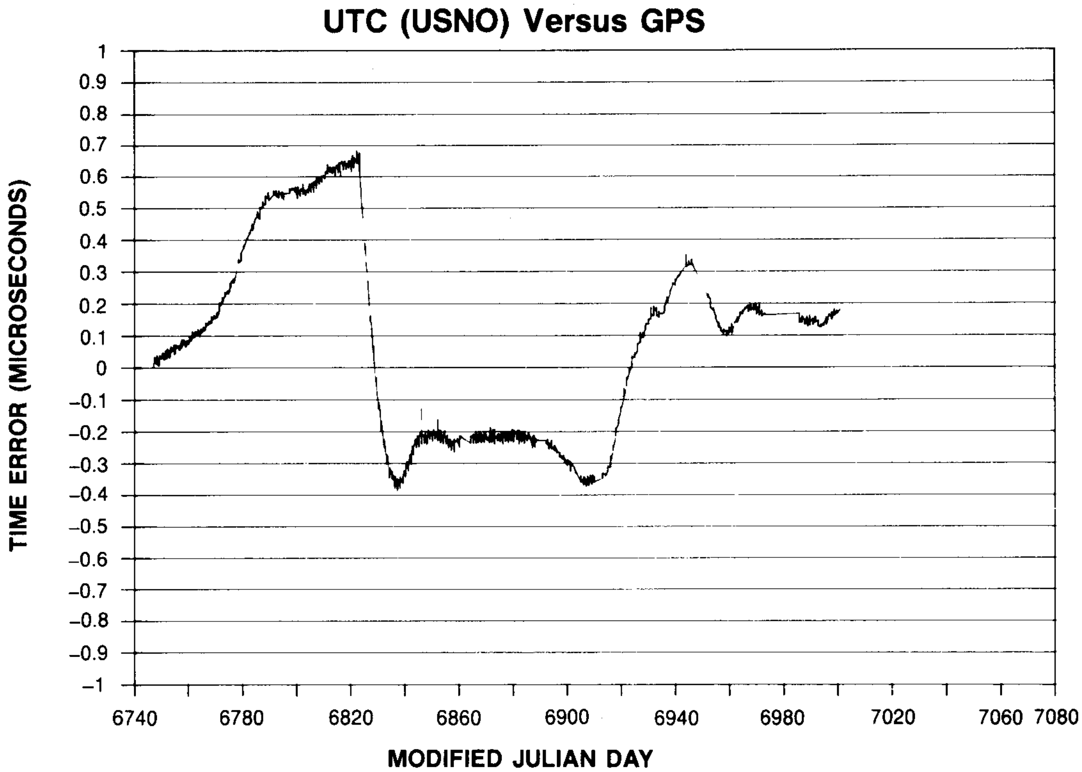


Figure 7. NAVCORE GPS Timing Data (Sheet 1 of 2).



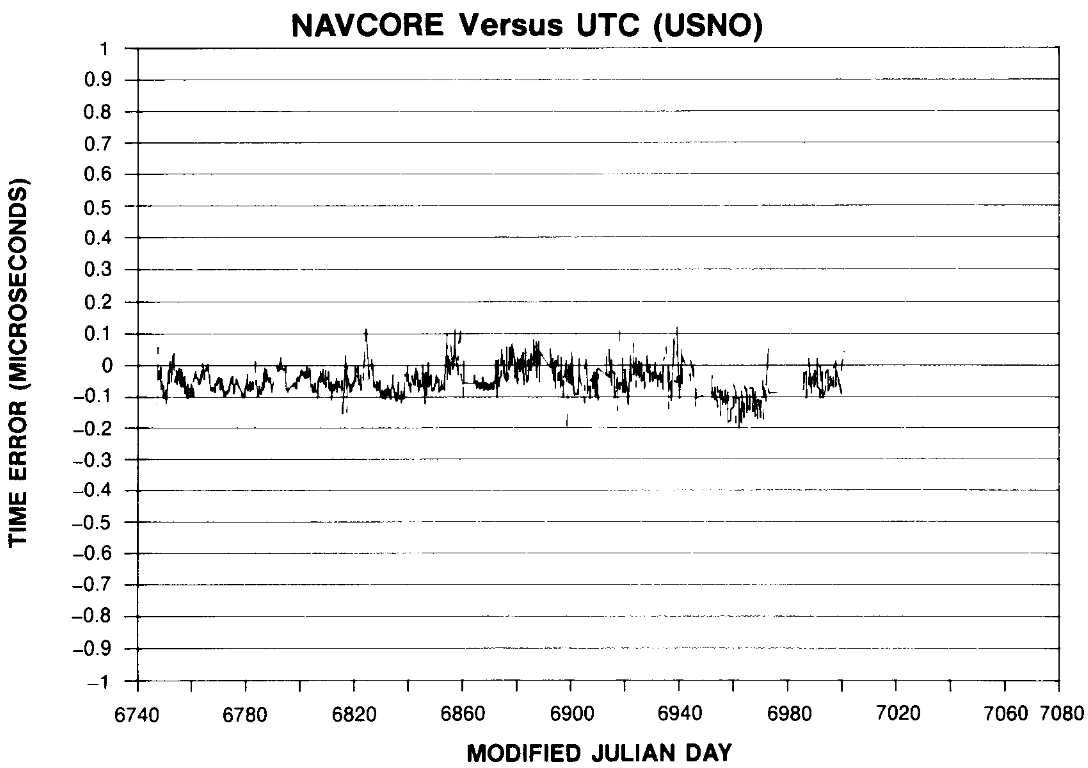


Figure 7. NAVCORE GPS Timing Data (Sheet 2 of 2).

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.

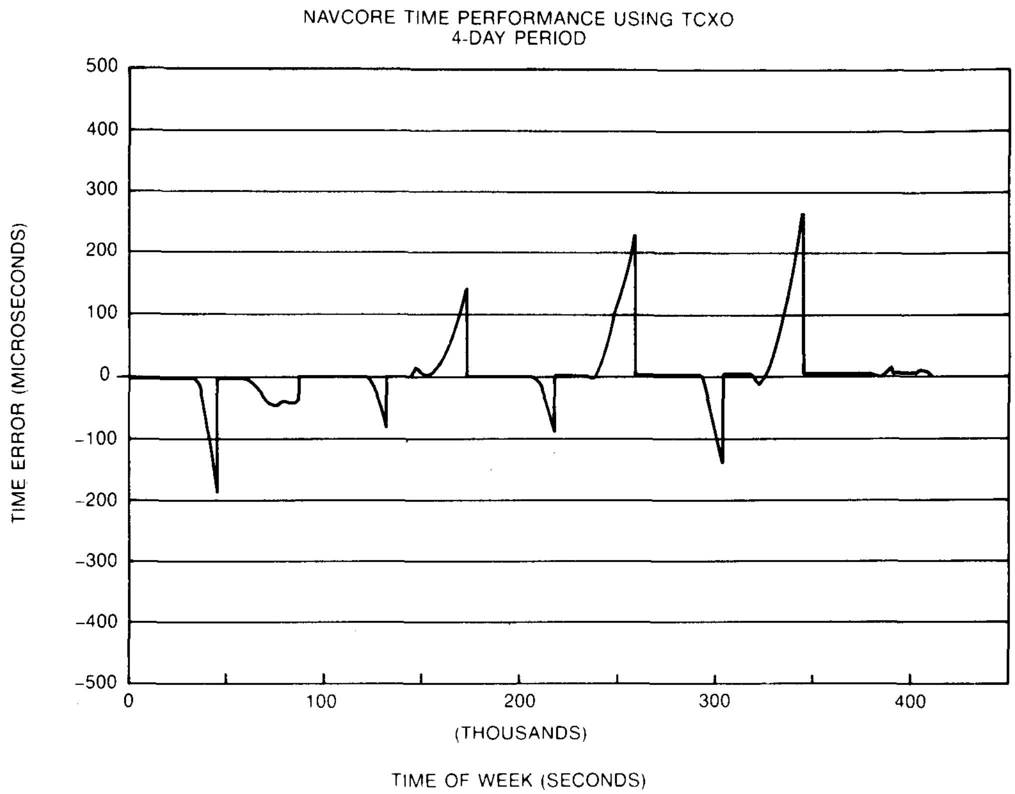


Figure 8. NAVCORE Time Performance Using TCXO.

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

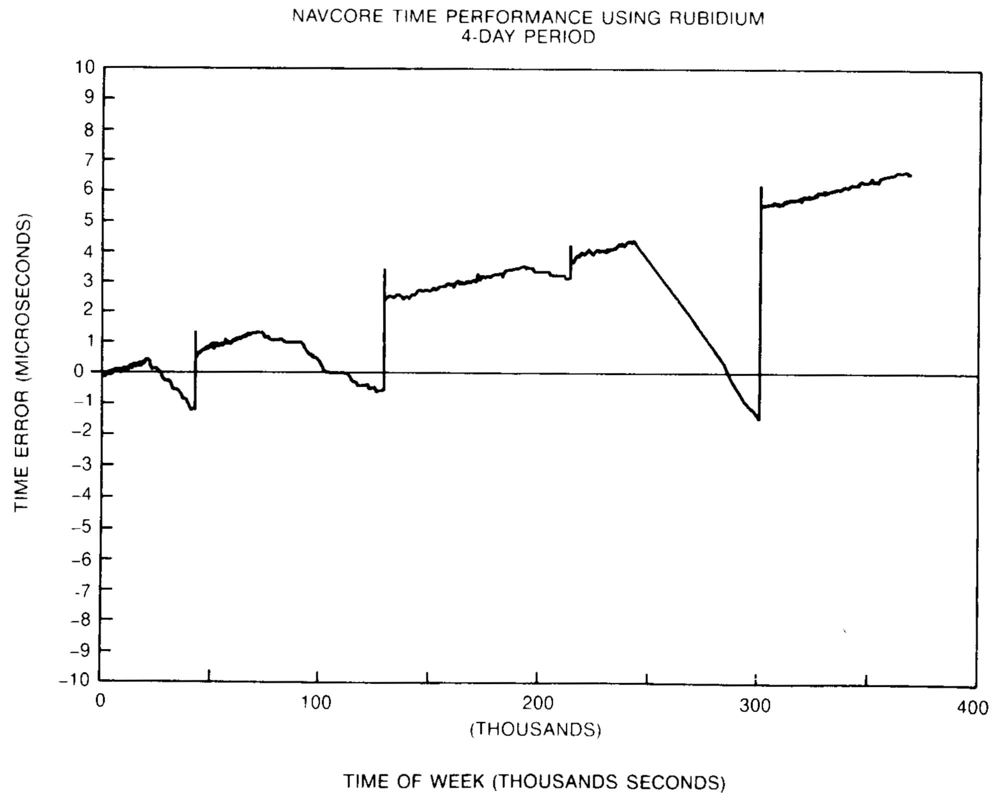


Figure 9. Rubidium Time.

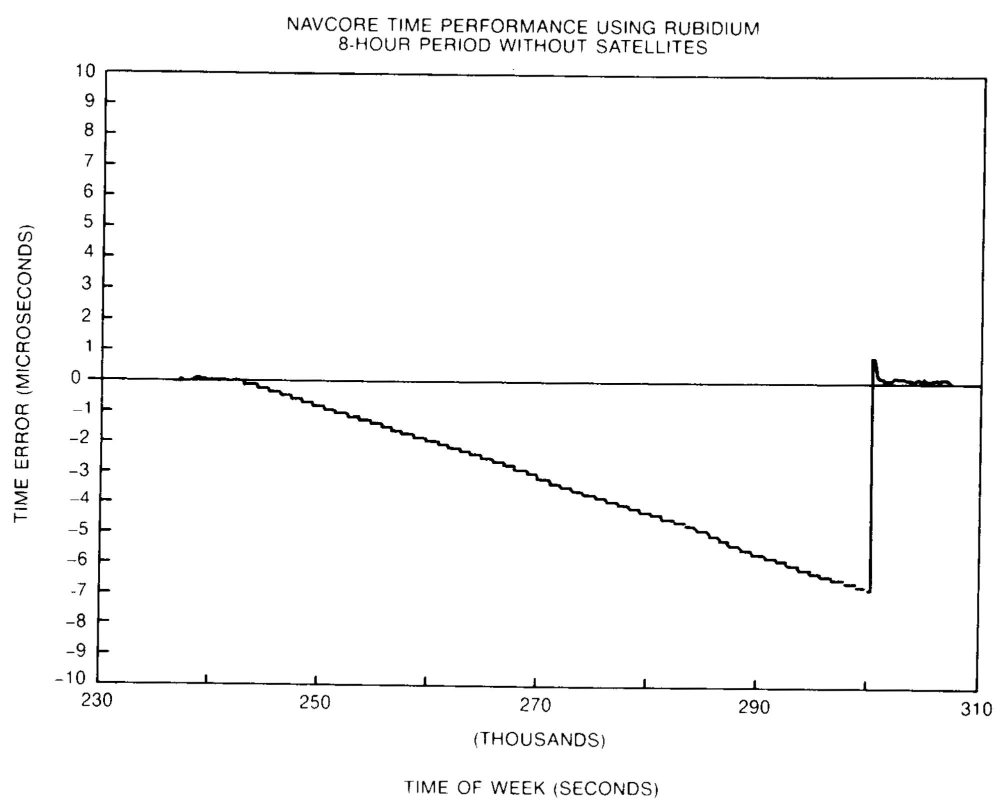


Figure 10. Performance Without Satellites.

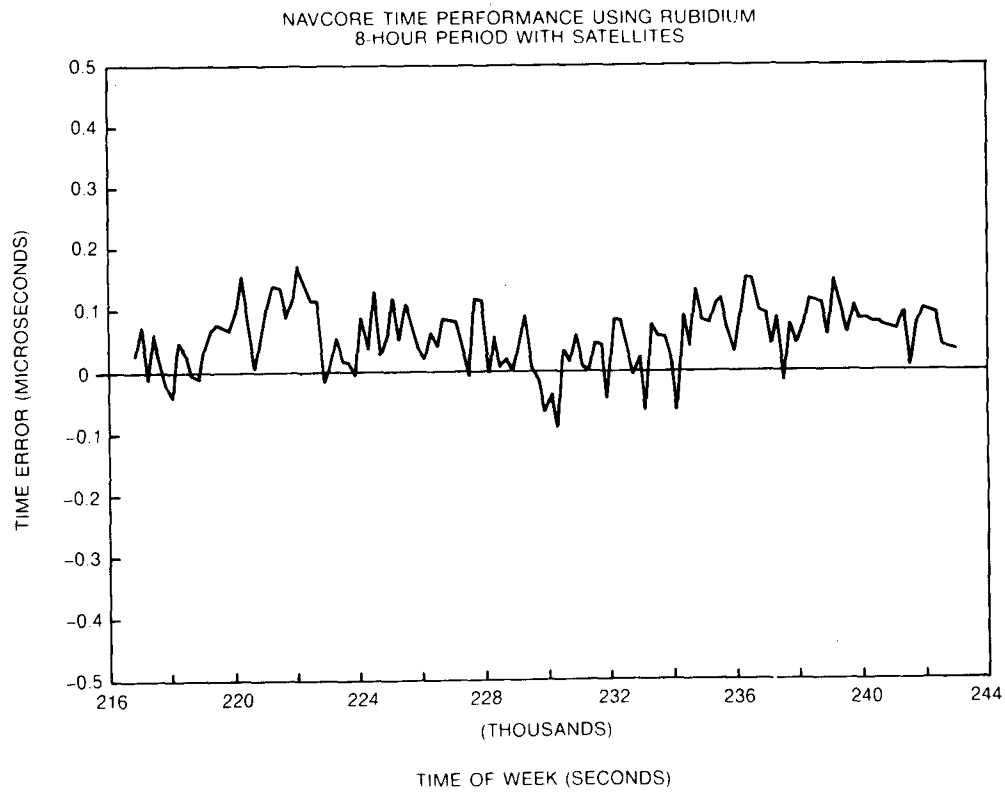


Figure 11. Performance With Satellites.

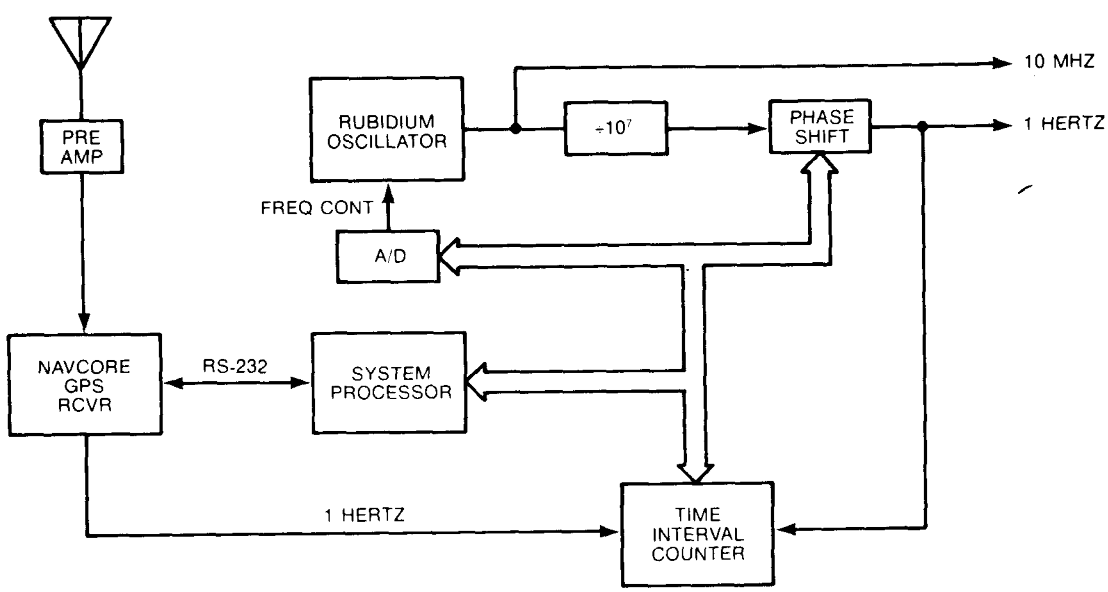


Figure 12. Disciplined Oscillator, Block Diagram.

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.