TEST RESULTS AND ANALYSIS OF A LOW COST CORE GPS RECEIVER FOR TIME TRANSFER APPLICATIONS

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Abstract

Precise timing is inherent to the operation of the Global Positioning System (GPS), enabling worldwide continuous precise time transfer at a very low-cost. Motorola's GPS receivers have been used for time synchronization and frequency control for several years. Motorola has introduced the next generation of GPS receivers for precise timing, which feature improved performance and lower cost.

Typically, the precise pulse from a GPS receiver is used to discipline a higher precision crystal or rubidium oscillator so that it can be synchronized to a common time stamp. The pulse stability from the GPS receiver is important in the disciplining process. The pulse is also used to synchronize the system to UTC, so the absolute accuracy of the precise pulse is of interest.

Most precision timing applications are at fixed base station sites. In the case of wireless telecommunications applications, many of the sites where the GPS receiver is installed are shared with other RF antennas. The GPS signal can be jammed by various RF emitters at certain frequencies and power levels. For a GPS receiver to operate under these conditions, it must be able to track the GPS signal in the presence of in-band and out-of-band interference.

The new UT Oncore™ has been tested against UTC time standards for accuracy and atomic standards for stability. This paper outlines the tests performed and the results of these tests are compared with previous generation receivers. Other performance aspects of the GPS receiver including immunity to interference signals and startup time are also presented.

Using GPS in Precise Timing Applications

GPS is best known as a worldwide positioning system. In order to provide accurate positioning, a precise timing system is used. This makes time information an integral part of GPS. Using GPS as a time base has both advantages and disadvantages.

Advantages of GPS in Precise Timing

The GPS constellation of satellites provide continuous worldwide coverage for positioning and timing applications. The system has been under deployment for several years and was declared fully operational in April of 1995. The U.S. government has committed to operating maintaining the GPS constellation well into the next century. Furthermore, GPS will continue to be available to the civilian community with no direct user costs outside the cost of the equipment. Due to the system design of GPS, there is no need for a high cost time standard within the user equipment. This enables low-cost GPS receiver designs.

GPS is deployed and operated by the U.S. Department of Defense (DoD). The DoD's track record in the operation of the constellation has been stellar. The GPS service is operated without interruptions in coverage or availability. There are several redundancies built into the satellites, the constellation, and the ground segment to ensure continued operation.

The time base of GPS is synchronized to Universal Time Coordinated (UTC), a worldwide basis for measuring time. This allows GPS users to measure UTC through solving for GPS time in the navigation equations and using the broadcast time parameters. As a result, GPS user equipment is capable of providing a precise one pulse per second (1PPS) signal synchronized to UTC.

Challenges of GPS in Precise Timing

All of these benefits of GPS do not come without associated challenges. These challenges can be addressed at both the GPS receiver module level and the timing system level.

The civilian broadcast frequency of GPS satellites is 1575.42 MHz. These spread spectrum signals are very low power at the Earth's surface; so low they are below the noise floor. Hence, GPS signals must be received by a direct line of site to the satellites without blockages due to buildings, towers, or trees. Antenna site selection and installation must be approached with

Presented at the 1997 IEEE Frequency Control Symposium in Orlando, Florida

deliberate care to ensure optimum performance. In order to mount the GPS antenna in a good location, there may be a long RF cable run to the location of the GPS receiver equipment. Cabling systems must be designed to provide adequate power to the antenna and sufficient signal to the receiver.

Since they are at such a low power level, GPS signals are susceptible to interference from external sources. To further aggravate the situation, most timing applications of GPS are at wireless infrastructure locations where there are high power RF transmitters. RF interference can cause the GPS signals to be jammed, which will cause the GPS receiver equipment to lose lock on the GPS signals. Again, care must be taken in the GPS system design and installation to mitigate jamming.

Despite the efforts to design integrity monitoring and redundancy into the GPS constellation and ground segment, failures do occur. Most of the time, satellite failures are flagged in the satellite health status, which is continually broadcast to the user equipment. From time to time, there have been unflagged failures that cause errors in the computed time and position solutions. These failures are unpredictable and can have severe effects if left unchecked.

Motorola UT Oncore™ GPS Receiver

Motorola's Oncore GPS technology has been used in precise timing applications for over five years. The UT Oncore is Motorola's latest generation of GPS receiver for precise timing applications. The UT Oncore receiver builds on the capabilities and proven reliability and performance characteristics of previous Oncore receivers.

The UT Oncore has many improvements aimed at the challenges of using GPS in precise timing applications. Improvements included added RF jamming immunity and support for longer antenna cable runs.

The remainder of this paper will discuss the main performance characteristics of the latest UT Oncore GPS receiver in the context of precise time synchronization and frequency stabilization applications.

Timing Accuracy

The precise 1PPS of the Oncore receiver is typically used to discipline a higher quality external oscillator. The external oscillator provides a more stable 1PPS signal and can be used to generate signals of other frequencies. GPS allows these signals to be calibrated and synchronized. If the GPS antenna installation is sub-optimal, there may be times when GPS is unavailable due to blockage or interference.

Figure 1 - UT Oncore 1PPS vs. Cesium

Average: 13.8 ns Std. Dev: 38.3 ns

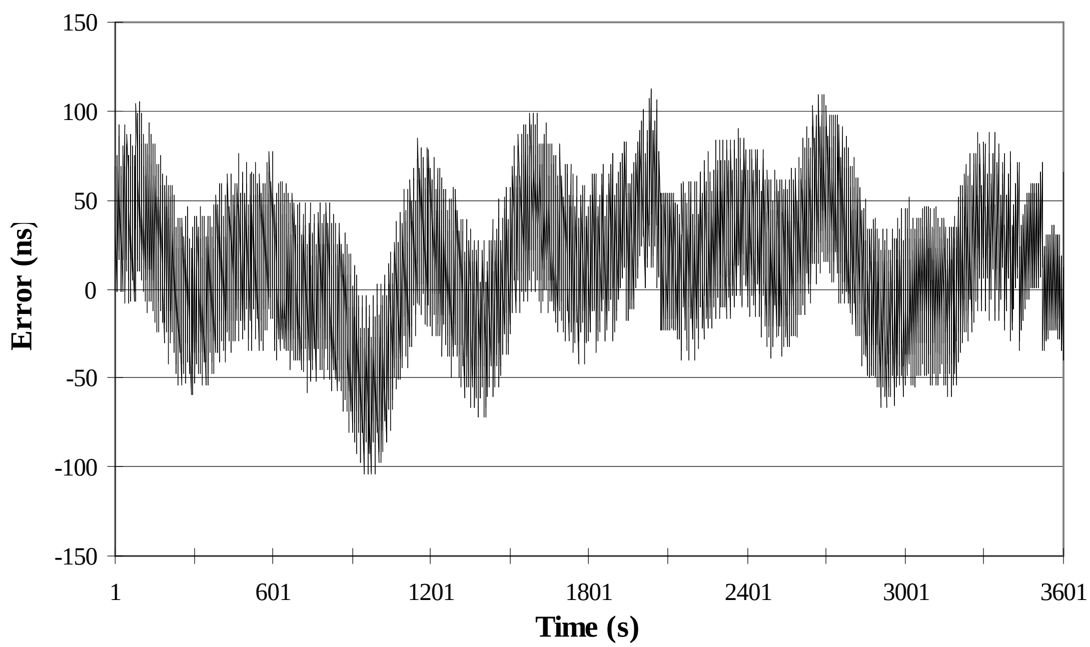
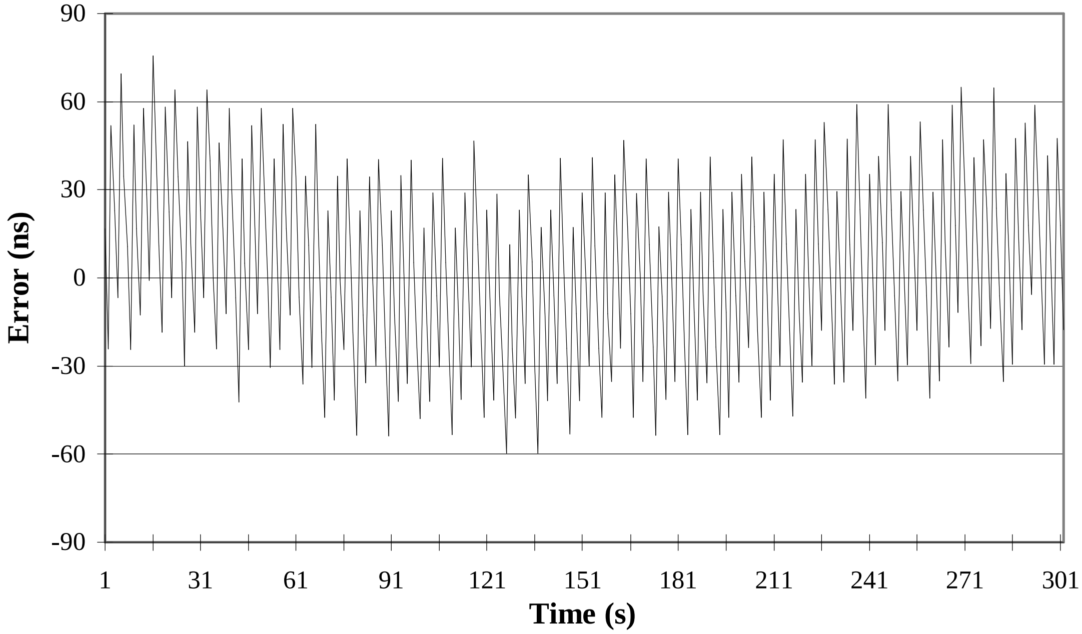


Figure 2 - UT Oncore 1PPS vs. Cesium

Average: 3.5 ns   Std. Dev: 31.9 ns



The external oscillator is used to continue the stable pulse through GPS outages.

For oscillator disciplining applications, it is important to understand the accuracy and stability characteristics of the 1PPS signal. The most effective use of a GPS derived 1PPS is to use a long term average of the pulse for disciplining. The averaging time can range from several minutes to sveral days depending on the desired system performance. Averaging the pulse output reduces the effects of receiver noise and temporal errors on the GPS time solution.

Over the years, Oncore receiver output has been compared against various atomic time standards. Previous generation Oncore receivers have been compared with U.S. Naval Observatory standards [1]. Recently, the UT Oncore was compared with Cesium and Rubidium standards.

The UT Oncore pulse output was compared with the output from a Cesium standard. The UT Oncore was put in position-hold mode at a known location for maximum pulse stability. Figure 1 is a plot of the difference between the UT Oncore 1PPS output and the Cesium standard output. Figure 2 is a small section of the data showing the sawtooth behavior of the raw GPS pulse. The test results affirm that the UT Oncore 1PPS has a standard deviation under 45 ns when in position-hold mode. The standard deviation of the pulse is a measure of the pulse stability.

The UT Oncore was also tested in position fix mode. Table 1 summarizes the results of several tests comparing the 1PPS to atomic standards. A four hour data set was broken into four one hour segments. The standard deviation and total pulse spread was computed for each one hour segment and for the entire four hour set. The table shows the minimum, maximum, and average values for both the position-hold mode test and the position fix mode test. The average standard deviation when in position-hod mode is 37.1 ns vs. 78.5 ns for position fix mode. The average spread of the pulse data is 209.0 ns for position-hold mode vs. 434.6 ns for position fix mode.

The receiver solves for the negative sawtooth residual and reports it in the serial output. A user can remove the sawtooth error to obtain a smoother output. Since the sawtooth error is Gaussian, a long term average of the pulse output is not biased by the sawtooth error. For this reason, most users do not remove the sawtooth error.

One hour segments of several long term tests were compared with the overall average as shown in Table 2. Averaging the pulse output for as little as one hour results in a time solution that is typically within 25 ns of UTC. Averaging for four hours improves the

Table 1 - UT Oncore 1PPS vs. Cesium
Summary Statistics

	Position-Hold Mode		Position Fix Mode	
	Standard deviation (ns)	Total spread (ns)	Standard deviation (ns)	Total spread (ns)
Four one hour tests				
Minimum	27.0	190.1	59.5	335.4
Maximum	51.5	236.5	92.7	538.6
Average	37.1	209.0	78.5	434.6
One four hour test	30.8	236.5	61.8	538.6

synchronization further. This precise level of synchronization to a worldwide time base enables many wireless applications that require synchronization.

Table 2 also shows the standard deviations and pulse spreads for the same data. The standard deviation of the pulse is highly repeatable at the 40 to 45 ns level. The peak to peak pulse spread is always under 300 ns.

RF Jamming Immunity

Many precise timing GPS installations require locating the GPS antenna at close range to radiating antennas such as cellular telephone, paging, or other wireless communications systems. Some of these transmitters may randomly cause the GPS receivers to lose lock on tracked satellites. This can be very disconcerting to the timing community since the system must rely on ‘clock coasting’ until the satellite signals are reacquired. Long coasting times require more expensive oscillators for the timing electronics in order to meet system specifications for holdover capability.

Improved Filtering

The GPS signal is broadcast at 1575.42 MHz with a bandwidth of +/- 1 Mhz. Experience has shown that receiver selectivity, or the ability to select only the GPS band of information and reject all other signals, is an important feature for GPS receivers, especially in cases such as those often encountered in timing applications.

To reduce the risk of unintentional jamming from high power out-of-band signals causing dropouts, additional filtering has been added to the UT Oncore. The desired result was achieved by working with various GPS L-band filter suppliers to develop filters that were small, economical and had the desired characteristics.

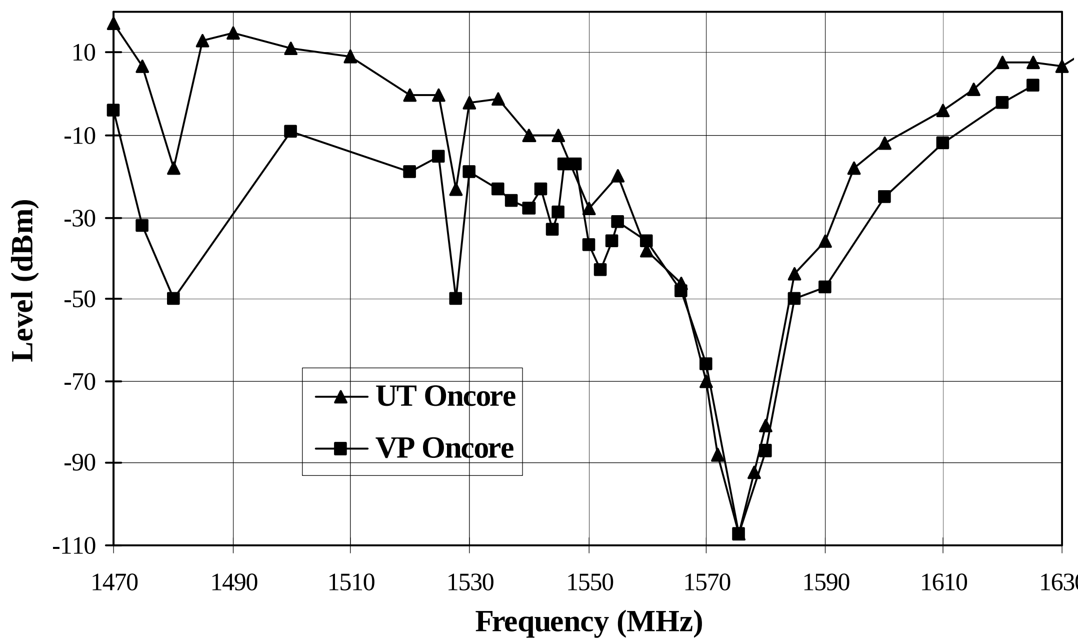
The VP Oncore (the predecessor to the UT Oncore) with the best selectivity (B4 model) uses two L-band filters and a five pole first IF filter. Experience from this model was used to design the improved UT Oncore. Although the B4 design is effective, the band width of the input filter on this model is comparatively wide and the low side roll off is not very steep. The image filter and the first IF filter are very effective and have been retained for the latest UT Oncore (R5 model). The first L-band filter has been replaced with

Table 2 - UT Oncore 1PPS vs. Cesium
Position-Hold Summary Statistics

	Average (ns)	Standard deviation (ns)	Total spread (ns)
40 one hour tests			
Minimum	-21.4	35.0	187.0
Maximum	22.3	52.3	286.9
Average	-2.5	41.2	224.4
10 four hour tests			
Minimum	-15.1	39.3	241.8
Maximum	12.8	44.2	286.9
Average	-2.5	42.0	260.0

Figure 3 - RF Jamming Immunity

Power Level vs. Frequency



one with a narrower band width and steeper low side roll off. In addition, a third L-band filter was added between the first filter and the image filter. The second IF filter has also been improved. The result is a GPS receiver with greatly improved selectivity, which is to say, better immunity to jamming signals.

Figure 3 compares the selectivity of the R5 model of the UT Oncore with the B4 model of the VP Oncore. An additional 30 dB of rejection (an improvement of 1000:1 in power) has been achieved at the first image (J/S 110 dB). The improvement is 15 dB at the second image (J/S 87 dB). The jamming immunity of the GPS receiver and antenna system will be further improved with the additional margin provided by the filtering in the active antenna.

Adaptive Tracking Loops

Motorola has developed an innovative software technique to further improve the jamming immunity of the UT Oncore receiver. The technique takes advantage of the fact that for precise timing applications, the receiver is not moving

In mobile applications of GPS, the receivers must be able to track satellites under varying dynamics. Vehicle acceleration causes an apparent frequency shift in the received signal due to Doppler shift. In order to track signals through acceleration, the tracking loops are wide enough to accommodate the maximum expected vehicle acceleration and velocity. When the GPS receiver is stationary, the tracking loops do not need to be as wide in order to track the satellites.

In the new UT Oncore GPS receiver, the satellite tracking loops are narrowed once the receiver has acquired the satellites and reached a steady state condition. This adaptive approach allows the tracking loops to be narrowed for maximum interference rejection while not unduly compromising the rapid startup and acquisition characteristics of the UT Oncore.

Test results have demonstrated that this approach is effective at providing an additional 10 dB of jamming immunity both in the GPS band and out-of-band.

The combined results of the additional filtering and the adaptive tracking loops in the new UT Oncore make it very effective at improving RF jamming immunity, thus making installation in timing applications more flexible and robust.

RF Jamming Immunity Test Procedure

Figure 4 shows the test setup for performing the RF jamming immunity tests. The first component is a

GPS satellite simulator generating a signal with a known level, usually -130 dBm. This signal is mixed with jamming signal generated by the HP8642B. The combined signal is connected to the RF input of the GPS receiver. A spectrum analyzer is used to monitor the characteristics of the signal. The GPS receiver is monitored using a PC with controller software to display the satellite signal strength data.

With the jammer signal turned off, the GPS receiver is configured to track the satellite being simulated. The signal strength of the tracked satellite is noted. A test frequency is selected on the signal generator and the cavity filter is tuned to this frequency. The power level of the jammer signal is increased until the signal strength reported by the GPS receiver drops by 2 dB. The power level is recorded for plotting. The test is repeated for each frequency across the spectrum of concern.

A jamming curve generated in this manner does not represent the absolute power level that the GPS receiver can withstand in the field. This test does not take into consideration the added benefit of an active antenna with selectivity. In addition, the data points represent the jammer level required to desense the GPS receiver by 2 dB. The receiver will continue to track the satellite with much more jamming power. The jamming plot serves as a comparison tool between different modules. For example, from the chart one can conclude that the new UT Oncore has 20 dB additional jamming immunity at 1500 MHz. It would be incorrect to state that a UT Oncore receiver in the field will lose lock on the satellites with a -10dBm jammer signal at 1500 MHz.

Antenna Power Supply

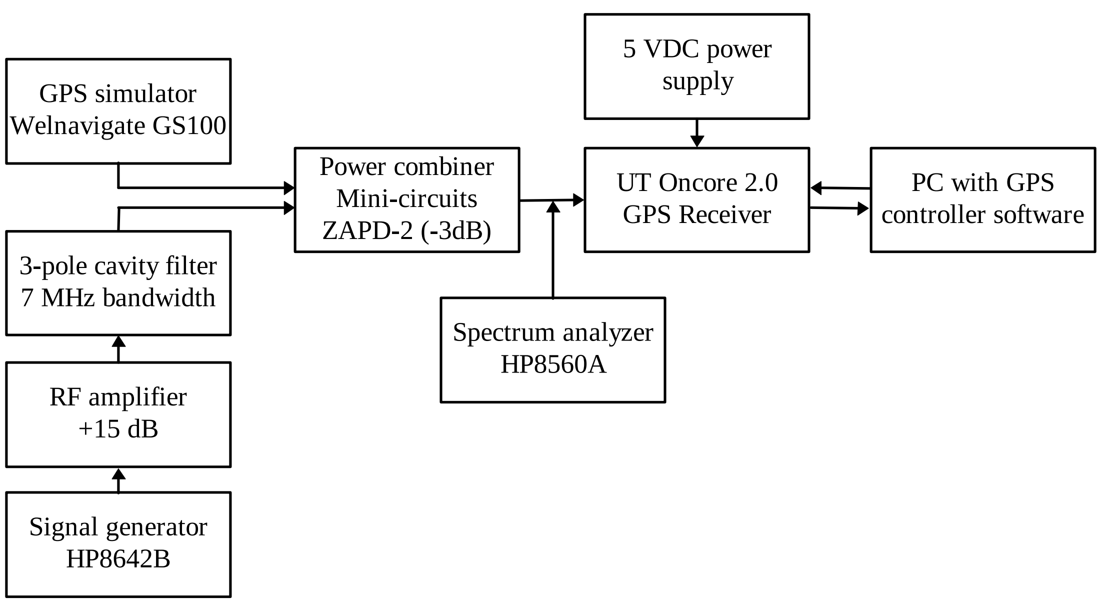
For the convenience of Motorola customers, the UT Oncore provides a means for detecting over current and open circuit conditions of the connection between it and the antenna. This allows the user a degree of confidence that the antenna is connected and drawing current. This feature can eliminate hours of trouble-shooting, especially in a new installation.

The antenna power supply circuit consists of a current sense resistor, two rail to rail operational amplifiers, a pass transistor and a voltage divider to set the upper and lower limits of the under current and over current thresholds. The operational amplifiers compare the voltage developed across the current sense resistor with these thresholds. If the antenna is drawing 5 mA or more, the first operational amplifier will produce a logic level to the digital circuits where it is monitored by the firmware. If the signal is absent, indicating an under current condition, an alarm bit is set to alert the user.

For the over current circuit, when the voltage drop across the current sense resistor is equal to the over current threshold (set at about 90 mA) the output of the amplifier starts shutting down the pass transistor. At this point, the voltage to the antenna starts to decrease and a logic level is provided for the digital circuit to trigger an alarm bit that indicates an overcurrent condition.

An additional feedback path between this output voltage and the over current operational amplifier

Figure 4 - RF Jamming Immunity Test Setup



causes a further decrease in the output current depending on the output voltage level. This action results in folding back the current such that the short circuit amount is about 45 mA, which is less than the 90 mA threshold. This prevents the over heating of the series pass transistor should the shorted coax condition occur. A chart of the typical output voltage vs. the load current is shown in Figure 5.

The output current limit is higher than previous versions of Oncore receivers. This is to support longer cable runs through the use of higher gain antennas or in-line amplifiers so that the signal does not drop below the tracking threshold when it reaches the GPS receiver.

Startup Process

When a receiver is first powered on, the acquisition and tracking process begins. The satellites selected for acquisition are based on the best estimates of date, time, and position, and a satellite almanac. If the receiver has all of this information, then the startup condition is considered warm. If the receiver also has a recent set of satellite ephemerides, then the startup condition is considered hot because the ephemerides will not need to be downloaded before positioning is started. If none of this information is available, then the startup condition is considered cold.

The UT Oncore receiver has been highly optimized for rapid startup times in all of the startup conditions. The typical time to first fix (TTFF) in a cold condition is better than 90 seconds. For warm it is 45 seconds, and for hot it is under 15 seconds. Typical TTFF is defined as the median time it takes the receiver to compute a valid position fix.

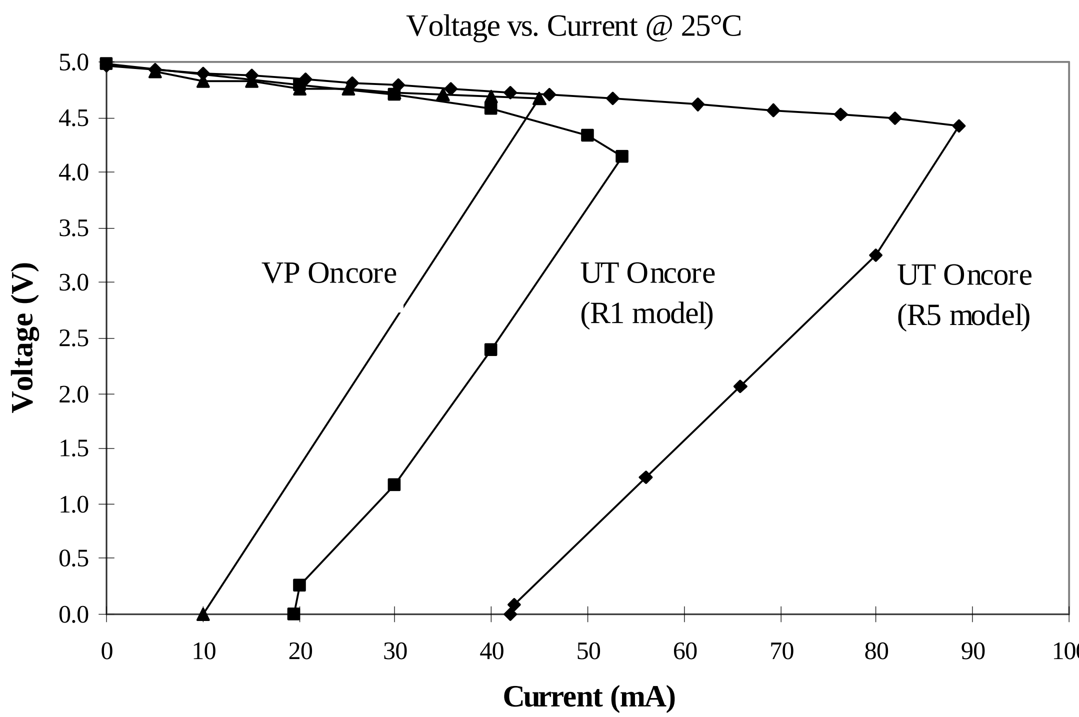
When the receiver is powered down, it will lose the date and time and all of the information stored in RAM including the position and almanac. The next time the receiver is powered on it will be in a cold start condition. If backup battery power is applied, the real-time clock (RTC) will maintain the date and time, and the RAM will maintain the satellite almanac and ephemeris information so that the next time the receiver is powered up it will be in a hot or warm start condition.

Initialization

An alternative approach to providing backup battery power is to input the date, time, position and almanac when the receiver is powered on. This will allow a warm start without the need for backup battery power. All of this information can be downloaded from the receiver while it is on so that it can be retained for the next power cycle.

The UT Oncore receiver should be put in position-hold mode for optimum timing performance [2]. The receiver is given a position rather than solving for it. A common approach to obtaining a good position for

Figure 5 - Antenna Circuit Performance



the position-hold mode is to average the position output for an extended period of time to overcome the effects of Selective Availability (SA). Experience has shown that two hours of position averaging results in a position that is typically within 20 meters of the true position. Testing has demonstrated that even a 100 meter error in the position-hold position has little effect on the timing performance of Oncore receivers [1].

Pulse Control Mode

The 1PPS output can be configured by the user. There are four settings for the pulse. The first two are off all the time and on all the time. The third mode is for the pulse to be on only when a minimum of one satellite is tracked. This ensures that the pulse will always be locked to a GPS satellite. The final mode is for the pulse to be on only when the Time RAIM algorithm confirms the integrity of the timing solution. This mode ensures that the pulse will not only be accurate, but also reliable. The disadvantage of this mode is that when only one or two satellites are tracked, the pulse will be unavailable. The various pulse control modes allow for some of the pulse validity decisions to be made by the GPS receiver rather than the timing system, simplifying the application.

Time RAIM Algorithm

Although the DoD has designed a system of satellites to operate on a continuous basis, 24 hours per day, anomalies in the satellite signal occur occasionally. As mentioned previously, the GPS satellites have had unflagged failures from time to time. The most recent such failure will be discussed in the next section. Motorola's design team has taken this into account and has developed an algorithm specifically for reliable high accuracy timing, which is capable of detecting and removing satellite timing anomalies which are not flagged by the system.

The Time Receiver Autonomous Integrity Monitoring (Time RAIM) [3] algorithm makes use of redundant satellite measurements to check the integrity of the timing solution. The technique is similar to the position RAIM approach used in the aviation community. The Time RAIM algorithm has been employed in Oncore GPS receivers for over two years with proven success.

Detect, Isolate, and Remove

When the receiver is in position-hold mode, only one satellite measurement is required to compute a time solution. If more satellites are tracked, a redundant solution is possible. The UT Oncore tracks up to eight satellites in parallel. With redundant measurements, statistical blunder detection is performed to detect measurement errors that are outside the normal measurement accuracy. If the chosen alarm threshold is exceeded, an alarm condition exists. At this point, the algorithm attempts to isolate the faulty satellite measurement causing the alarm. If identified, the satellite measurement is flagged as a blunder and it is removed from the satellite selection list. The time solution is then recomputed and the Time RAIM algorithm checks to see if the solution is below the alarm threshold.

Most of the time, satellite problems are flagged by the unhealthy bit in the satellite message. In these cases, the unhealthy satellites are automatically removed from the solution. In the cases where the unhealthy condition goes unflagged, the Time RAIM algorithm has proven very effective in protecting the integrity of the time solution.

March 18th GPS Time Anomaly

The robust Time RAIM algorithm was recently put to test when a timing anomaly was introduced into the navigation message stream, corrupting time for six seconds on one satellite. A few weeks after the occurrence, the U.S. Space Command released the following information about the GPS Timing Anomaly on the Coast Bulletin Board [4].

"On 18 Mar 97 at 00:26:36Z, GPS satellite SVN 35 (PRN 5) experienced an anomaly which caused the vehicle's time to jump forward by approximately two hours and twenty minutes. The reason for this anomaly is unknown. Six seconds later, the anomaly self corrected and the vehicle's internal time was reset. The satellite remained in standard code for the duration of the anomaly resulting in erroneous navigation and timing data being transmitted to users."

This problem manifested itself as a corrupted Z-count, causing the hand-over word (HOW) of one subframe/page of the navigation message stream to increment in time by 8400 seconds. The HOW is 30 bits long and is the second word in each subframe/page. A HOW occurs every six seconds in the data frame and the anomaly only occurred for one data frame or six seconds, then the error condition went away. The most significant bit (MSB) is transmitted first. The HOW begins with the 17 MSBs of the time-of-week (TOW) count. These 17 bits correspond to the TOW count at the 1.5 second epoch which occurs at the start (leading edge) of the next following subframe [5].

Simulation

After determining the cause of the timing anomaly, Motorola designed a test scenario for implementation using a multichannel simulator to determine the effect upon Oncore receivers. The scenario was configured to simulate normal operation for two minutes followed by six seconds of the timing anomaly, then continuing in normal operation. The Oncore GPS receiver was configured using a macro command that performed the following functions: default, load an almanac prior to 3/18/97, date 3/18/97, time 00:24:36, position, position-hold and the Time RAIM setup message. The UT Oncore was tested under two conditions.

Time RAIM Off First tests were run with the Time RAIM algorithm turned off. Observation of the clock showed a shift in time of about 20 minutes, which represents the total time error offset (8400 seconds) divided by seven, which was the number of satellites that were being tracked. During the anomaly, the 1PPS signal was pushed out of tolerance by several hundred milliseconds. Both the time solution and the 1PPS signal recovered after the six second anomaly was ended.

Time RAIM On A second set of tests were run with Time RAIM turned on with the alarm limit set to 1300 ns. Satellite SV35 (PRN 5), which contained the timing error was removed immediately from the solution and the Time RAIM status flag indicated an alarm condition for a period of two seconds. Prior to the removal of the satellite containing the clock error, there were a total of seven satellites being simulated. The 1PPS signal was only affected by the removal of one satellite, slightly effecting the average 1PPS time by a factor of 1/n statistically. The receiver will reintroduce the removed satellite to the list of available satellites at the top of the hour.

Field reports indicate that Oncore receivers with the Time RAIM algorithm in operation were successful in detecting the March 18th timing anomaly. Similar anomalies have occurred three other times since 1993. The U.S. Space Command is taking measures to reduce the probability of such anomalies occurring.

The Time RAIM algorithm is an essential component when operating equipment which is dependent upon precise time. The ability of Motorola's Time RAIM algorithm to detect, isolate, and remove timing anomalies such as this enables the system user to utilize GPS precise timing with a high confidence factor.

Conclusions

Using GPS is a cost effective method for obtaining time in precise timing applications. The susceptibility of GPS to jamming and satellite anomalies pose system challenges. Motorola’s UT Oncore technology addresses the weaknesses inherent in GPS technology with strong jamming immunity and Time RAIM. The latest Oncore enhancements improve GPS reliability and ease of use in timing applications.

Acknowledgments

The authors wish to thank Johann Heinzl at Hewlett Packard’s Santa Clara Division and Monte Variakojis at Odetics Telecom who have provided test data for use in this report.

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