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Motion Effects on GPS Receiver Time Accuracy

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A little background

It is well known that the Global Positioning System (GPS) can be used as a source of highly accurate synchronization and time transfer. Complex algorithms are used to estimate position employing the signals received from a multiplicity of GPS satellites in the "view" of the GPS receiver. As seen from the ground, all of the GPS satellites, the GPS Constellation[1], are in constant motion. Each satellite furnishes the time tick along with other identifying information most importantly ephemeris[2] data. The satellite motion with respect to the receiver (on the ground) also imparts a Doppler shift. The Doppler shift is used to determine whether the satellites are heading toward and away from the receiver. Combined, these signals make it possible to estimate position (latitude, longitude and altitude), time and speed to varying degrees of accuracy. The receiver also employs an EEPROM to maintain almanac[3] data. Having a fresh almanac speeds the acquisition time to find and track satellites, provided the GPS has not moved much since the last time it was powered up.

The GPS satellites are synchronized with on-board Cesium or Rubidium atomic clocks that are in turn synchronized to each other and that time (GPS time) has a direct relationship to Coordinated Universal Time (UTC). The result is that all GPS satellites are all phase-coherent which makes the GPS a highly accurate synchronization resource for systems that can be on opposite sides of the globe. Similarly, highly accurate time transfer can be achieved with the GPS system.

Standard Timing Directed GPS Receivers (Dynamics Mode 1)

In general GPS receivers targeted at generating accurate time assume that the receiver is not moving. In fact, when the receiver is not moving the most accurate time is calculated. If the receiver assumes it is in a fixed location, changes in satellite distances will be very predictable as they are solely due to earth's rotation and satellite orbital motion prescribed in its ephemeris. The ITS GPS receiver module in Dynamics Mode 1 (a setting that tells the receiver that a fixed location can be assumed) uses specialized firmware that is designed specifically for GPS time

[1] Nominally, there is a 24 satellite constellation where 4 satellites each are spaced in 6 orbital planes. The orbital planes are at a 55 degree angle to the equator, and have 60 degree separation. The current constellation is 31 satellites. The additional satellites improve the precision of the GPS receiver calculations by providing redundant measurements.

[2] An ephemeris is a table of values that gives the positions of astronomical objects in the sky at a given time. In the case of GPS navigation, satellites transmit electronic ephemeris data consisting of satellite health and information about where the satellite is and prediction of where it will be at a specific time. GPS receivers then use (together with the signal's elapsed travel time to the receiver) to calculate their own location on Earth using trilateration. Trilateration is a method of determining the relative positions of objects using the geometry of triangles similar to triangulation. Unlike triangulation, trilateration uses the known locations of two or more reference points (satellites), and the measured distance between the subject (GPS receiver) and each reference point (a tracked satellite). The measured distance is determined by multiplying the speed of light and the time (estimated by the receiver) it took for the tick signal to travel from the satellite to the receiver.

[3] The almanac serves several purposes. The first is to assist in the acquisition of satellites at power-up by allowing the receiver to generate a list of visible satellites based on stored position and time, while an ephemeris from each satellite is needed to compute position fixes using that satellite. In older hardware, lack of an almanac would cause long delays before providing a valid position. The second purpose is for relating time derived from the GPS (called GPS time) to the international time standard of UTC. Finally, the almanac allows a single frequency receiver to correct for ionospheric error by using a global ionospheric model.

synchronization. It will automatically enter a self survey[4] mode on power up. The self survey mode causes the receiver to continuously calculate its geographic position for a period of 20[5] minutes.

After the self survey period, the receiver will automatically calculate an average of the geographical position and fix this value in the receiver firmware. With a stored known "fix" (position) the receiver no longer has to calculate a positional fix to update the 1PPS phase. This in turn facilitates rapid and accurate control of the phase error with respect to the GPS time mark (tick) of the output frequency internally used to synchronize the IRIG and 1PPS output signals of ITS products. Typically this phase error (the difference between the real GPS tick and our equipment tick) is less than 25 nanoseconds (nS). This can be achieved when few satellites, even down to one satellite, are being tracked. This feature means that the receiver would have to completely lose sight of all GPS satellites to stop from being synchronized to GPS.

Even in this situation (no satellites in view) our system uses a real-time phase error correction algorithm to discipline the internal crystal to correct for frequency error (tick rate), phase error (when ticks occur) and crystal drift (age component). With sufficient history acquired by the disciplining algorithm, at a constant ambient temperature, free run (no GPS satellites in view) time ticks will be able to maintain low phase error for short intervals of time (typically 0.1 parts per million which translates to less than a 10 millisecond error in a 24 hour day.

The calculations[6] to achieve all of this are rather complex. When this calculation is complete for four satellites the data can be correlated to estimate the on-board time of the satellites and local position. With each combination of four satellites, a geometric dilution of precision (GDOP) vector is calculated, based on the relative sky positions of the satellites used. Multiple channel GPS receivers can track and use data from as many satellites as it has channels, so the more satellites the better the results. That is, the more satellites that can be tracked (assuming they are in view to the GPS receiver) the more four-satellite combinations, GDOP values, can be generated. The final time and position result is based on an RMS of GDOP for each four satellite combination available at the time. The ITS receiver is a 12-channel device so it can use data from as many as twelve satellites simultaneously.

The data are discrete digital signals coming from multiple sources (many satellites) and perhaps multiple paths (multi-path RF). The data samples are processed through a Kalman[7] filter. The Kalman filter has two distinct phases: predict and update. The predict phase uses the time delay estimate from the previous time-step to produce an estimate of the time delay at the current time-step from each satellite. In the update phase, measurement information at the current time-step is used to refine this prediction to arrive at a new, presumably more accurate time delay estimate, again for the current time-step. The "slower" the solution rate setting of the filter, the more integration (smoothing) of the data stream results. These three elements of the Kalman filter are important concepts when trying to understand what happens when the GPS receiver is moving.

What if the receiver is moving?

When the receiver or the antenna is actually not stationary, the measurements are constantly changing and the self survey fix can no longer be relied upon to generate low phase error to the time mark (1PPS). In fact the more quickly the receiver moves in space the greater the error would be. Acceleration is most critical. Each sample is assumed to

[4] The survey consists of 600 3D points (x, y and z) at 100 meter or better accuracy. A "cold start" survey should take 10-20 minutes or less depending on the number of satellites in view.

[5] As described in Note 2, the receiver maintains an almanac in EEPROM which, when the receiver has not been moved since power down, gives the receiver a starting point to look for and acquire satellites. Having such a starting point can reduce time to lock from 10-20 minutes to 3 to 5 seconds. Having such a starting point at power up is often referred to as a "warm start".

[6] The receiver uses the time delay estimate (speed of light time from satellite to receiver) to calculate the distance of the receiver from the satellite and the ephemeris data to calculate the position of the satellite in the sky.

[7] The Kalman filter is an efficient recursive filter that estimates the state of a dynamic system from a series of incomplete and noisy measurements. This means that only the estimated state from the previous time step and the current measurement are needed to compute the estimate for the current state. It is used in a wide range of engineering applications from radar to GPS. An application example would be providing accurate continuously-updated information about the position and velocity of an object (position data from a GPS receiver) given only a sequence of observations about its position (estimated position relative to the satellites tracked), each of which includes some error.

be received at the surveyed location. When the time delay is estimated the satellite position will seem wrong compared to where receiver expected it to be. That is, the measurement values will differ greatly from the values predicted by the Kalman filter. In our receiver, the Kalman filter tracks rates of change in the various parameters, and attempts to get a convergent solution based on all measurements which haven't been excluded. Measurements excluded are those that exceed or do not track anticipated values. An estimated confidence is assigned to measurements (code, phase, etc) that have remained locked for a period of time. As the number of measurements discarded grows, too few samples will remain to result in a valid solution. This is “absolute unlock”. However, before absolute unlock, measurements will present greater and greater errors from the predicted, resulting in a larger and larger GDOP. Unlock will be declared once the RMS value of GDOP fall outside the acceptable measurement error of 5 meters[8] or 5-30 meters and up for a range of motion scenarios.

The dynamics modes of the ITS GPS receiver changes the configuration of the Kalman filter and discards the survey fix data for predicting measurement results. Instead, a prediction is made based on the previous velocity and acceleration solution. The range of new measured values would fit inside the error criteria set for the dynamics selected. Measurements that fall outside these dynamic ranges are eliminated. As described for a stationary position, if too many measurements are eliminated or the RMS value of error falls outside the error criteria for the dynamics expected (dynamics selected by the use) an unlock condition is declared or absolute unlock occurs.

The solution rate is also a critical parameter. If a slow solution rate is used (high integration) high dynamics will be filtered too much resulting in very large solution errors. The most accurate solutions are achieved when the solution rate and expected range of dynamics are well matched to what is physically happening from the receiver’s perspective. To that end, the ITS receiver incorporates the ability to set dynamics modes that set the system parameters and algorithms to maximize accuracy of the solution for several bands of operations, fixed (1), man walking (2), land vehicle (3), marine (4), aircraft (5).

Dynamics Mode for Timing Applications

As described earlier, generating an accurate estimate of time is a complex calculation derived from estimating the distance of the straight-line distance of the receiver from the satellites and determining the position in the sky of each satellite being tracked. If the GPS receiver is moving, satellite distance estimates would have to be adjusted to compensate for x, y and z motion of the GPS receiver itself. If the GPS receiver doesn’t know how to do this, or has no range of motion expected, compensation would become less and less accurate. In fact, it may be unable to achieve a GDOP solution at any point in time. Failure to achieve a GDOP is an “unlock” condition.

The ITS GPS receiver can accommodate motion within certain ranges with some degradation in time accuracy. Dynamic settings constrain changes in velocity/direction/acceleration with respect to their anticipated changes. We are able to measure the estimated time accuracy at a one-second by one-second sample rate and can tell the GPS receiver what type of motions to expect and therefore what type of adjustments and compensations to attempt to achieve a solution. This feature is called ***DYNAMICS MODE***.   The user selectable ITS GPS receiver modes are:

Mode Number	Dynamics Anticipated	Time Accuracy
1	Fixed base station, maximum time and frequency accuracy.	< 25nS >
2	Man pack / Walking	
3	Automotive / Land Vehicle	
4	Marine	
5	Airborne, Low dynamics (<1g)	< 100 nS> DEFAULT SETTING

[8] Although position accuracies are cited here for error evaluation, one should be reminded that the uncertainty of position is directly related to uncertainty in the time measurement. Therefore as position uncertainty grows, time phase uncertainty grows.

Selecting the highest dynamics expected is important. Simulation testing revealed that if aircraft dynamics in the range of 0.8g are experienced, but the dynamics mode selected were 1 (stationary) timing errors would exceed 1 mS and the receiver could not reliably maintain a fix (know exactly where it was). If a fix can not be maintained or the number of samples discarded grows, the receiver will declare an unlocked condition or may, in fact, truly lose lock and have to restart the survey process.

On the other hand, as the dynamics mode is set higher and higher the prediction error allowed grows with it. As a consequence the time error will grow as well. So setting for aircraft (dynamics 5) for a man walking situation (dynamics 2) would result in a larger than necessary allowable time phase error. The exact time phase error will depend on what is actually going on. Unlock states in this scenario would not likely ever occur unless all of the satellites were out of view of the receiver. Unlock states in this scenario would not likely occur unless all of the satellites were out of view, but the time phase error band would be much wider than necessary.

With firmware changes to our products having serial control interface capable of reporting time and position to a remote, it would be possible to dynamically report the RMS time error in nanoseconds. If there were a user application that would benefit from that, it could be done. It is not currently available on any version of ITS product.

For special applications it is possible to extend beyond these dynamics to low missile profiles (less than 16g accelerations). This capability is not presently in our system, but is possible at a higher price and with a non-recurring fee (not yet determined). Further, there are ITAR restrictions for export that may place a ceiling on what can be offered (unless the end-user can get/facilitate the proper export license) to 8 g accelerations, 515 meter/second maximum velocity and altitudes below 18,000 meters.

ITS products such as the 6115G series of IRIG time code generators and the 6055B-xG video inserters all offer Dynamic Mode settings for the GPS receiver to ensure time accuracy is maintained, even in mobile settings.

Instrumentation Technology Systems is a leading supplier of GPS synchronized time standards, IRIG time code generators readers and displays and video insertion products. All of our products are designed and manufactured in the United States. The company serves aerospace and military customers world-wide. To learn more about ITS and its products, see the company's website at www.ITSamerica.com.

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