BRIEF INTRODUCTION TO GPS

GPS is a satellite navigation system conceived, designed and operated by the US DoD. Originally intended to be used for precise positioning through the determination of pseudoranges from the satellites (of which there are ~28 in low earth orbit) to the (normally ground based) receiver. The key idea is that by measuring the time of flight of a radio signal from 4 or more satellites to the receiver, the position of the receiver may be accurately determined. In addition the time offset of the receiver (from composite clock GPS time) may be calculated from information within the orbit data (modulated onto carrier). By taking the time differential of these two quantities, the velocity of the receiver and the frequency offset of the receiver may be ascertained.

SATELLITE SIGNALS

The satellites transmit two L-Band (390-1600 MHz) carrier signals, L1 and L2. The carrier frequencies of L1 and L2 are 1575.42 and 1227.6 MHz respectively. Each carrier is turn modulated (phase shifted by a wave of lower freq. to convey signal) with one or more binary codes.

L1 is modulated with first the C/A (Coarse/Acquisition) code, which is the basis of the standard positioning service (civilian GPS provision). This is a pseudo-random (i.e. random like but actually not) but regularly repeating noise-like code. It has a chipping rate (rate at which binary digits are produced) of 1.023 MHz. The code modulation effectively spreads the spectrum of the carrier signal (i.e. over a far a wider frequency band than is actually required by the quantity of information sent). This gives it high resistance to interference and non- authorised jamming. The code length is limited to 1023 bits, giving a refresh rate (or duration of the code) of 1ms. The C/A code has a fast acquisition time and is easy for users to lock onto. Each of the ~26 active satellites modulates their L1 carrier with a satellite characteristic C/A code, enabling easy satellite identification through C/A code demodulation.

L1 is also modulated with a 50Hz navigation message, which provides GPS satellite orbits, clock corrections etc.

The Precise (P) code modulates both the L1 and L2 carriers, and has a far longer (7-day) duration than the C/A code. It has a chipping rate of 10.23 MHz. C/A code was designed partly to help users acquire the P code. Through a method called anti-spoofing (AS) the P-code is encrypted to form the user-restricted P(Y) code, available only to US military authorised users, through the use decryption keys.

The normal civilian users can all but forget about the P-code due to its encryption. Unfortunately the situation was made worse still in the 1990's through the introduction of Selective Availability (SA); a deliberate distortion of the satellite signals, preventing civilian users from fully utilising the full capabilities of even C/A code. SA is a time varying bias involving either manipulation of the data message (epsilon) and/or clock frequency, with the SA bias being different for each satellite. Just as the pseudoranges are combined, so must the SA biases from each satellite being tracked at a particular time be combined to form the navigational solution. The real problem for SA users is that SA is a time varying bias with low freq. terms in excess of a few hours. This makes averaging of individual pseudoranges (to effectively average away the SA effects) impossible for times less than a few hours. Fortunately for many time and frequency applications, a technique known as static positioning may be used. This allows for position determination using a stationary receiver, allowing implementation of averaging techniques, which greatly improved accuracy.

One of the advantages of the GPS system and indeed an essential feature of operation is that despite deliberate degradation of, and partial restriction to, the carrier and codes, the carrier and data modulating frequencies are held to very precise tolerances.

PURE C/A CODE RECEIVERS

Many low cost receivers track the low frequency (wrt. the carrier frequency) 1 MHz code phase. Internal synthesisers (to the receiver) produce SV specific PRN codes, which are then correlated, with the C/A code as received from each SV (with unique PRN) at the antenna. This method enables this arriving code phase to be evaluated (to within a 1ms ambiguity) using the auto correlation to within 10ns within an observation time of about 1s. By using the time tagged data within the navigation message it is possible to remove the final 1ms ambiguity.

The auto-correlation method (auto correlation is the method by which a signal is compared with itself to find the extent of correspondence between the signals) measures the difference between the propagation time as expected according to the orbital data and the propagation delay as actually measured at the receiver. This gives the time offset of the internal receiver clock relative to the (apparent) GPS time as realised using the satellites in view. It can be calculated that the 10ns code phase evaluation in 1s translates to a frequency determination capability between two successive code phase measurements 1 s apart of 10^{-8}. A pure code phase receiver is therefore only able to discipline an oscillator (say an OCXO) to within 10^{-8} of its nameplate frequency. This is simply not good enough for modern daytime and frequency applications.

Receiver noise limits this accuracy and this may be partially overcome by using averaging. The problem with averaging is that, as always, short-term frequency fluctuation detection is delayed according to the averaging time (similar to τ in the Allan deviation) used. This will mean that the receiver will have a slow response time to any frequency errors in the oscillator that it is disciplining. Therefore using only a pure C/A code receiver, only oscillators, which have a good inherent stability, are capable of being disciplined.

CARRIER PHASE

The C/A code correlation length of 1µs limits dramatically the resolution of the C/A measurement. The substantially higher frequency of the L1 carrier (as compared to the C/A code), and the resulting shorter cycle of 635 ps, will reduce its sensitivity to jamming and also improve the resolution 10000 fold over C/A code measurement. A 1-% noise induced change in the carrier and code signal amplitude results in a phase shift of 10ns and 1ps in the code and carrier respectively.

The advantage of carrier phase tracking is that frequency measurements are achievable with almost no receiver noise contribution. This enables relative frequency determination with uncertainties of a few 10^{-11} within fractions of a second. The short dwell times (on each satellite signal) enable a single time multiplexing channel (tracking of multiple satellite signals by using a rapid sequencing process) instead of the costly multichannel method, with better results

CARRIER AND CODE PHASE

The problem of the carrier phase evaluation method is that different cycles are incapable of being distinguished from each other. This makes it impossible to determine the propagation time of the signal. In a normal time and frequency oriented (i.e. not a costly geodetic receiver where different techniques are often used) receiver the modulated coded sequence must be utilised to determine the propagation time (from which all other properties are derived). The advantage with measuring the carrier phase is that it yields a very precise calculation of the rate of change of the time of flight (i.e. the time differential of the propagation time). Integration of carrier phase gives you a very accurate propagation time.

Therefore the ideal solution is to somehow combine the code and carrier phase measurements so that you get the absolute but noisy information from the C/A code and the extreme (relative) precision from the carrier phase. This will give you the smoothed propagation time without time delay (which results from averaging). This method reduces the receiver noise to nearly zero, making the accuracy of the evaluation not receiver dependent but signal dependant.

The receiver actually performs several independent carrier phase measurements once a second dwelling on each satellite for approximately 80 to 640 ms (quasi simultaneous satellite tracking), the results from which are averaged. By performing an Allan deviation on this measurement method the limiting effect seems to be white frequency modulated noise and not some systematic error. As stated earlier this method enables you to get away with one time multiplexed channel with parallel evaluation.

DIFFERENTIAL GPS

However good you make your receiver, if you operate it in stand-alone mode (i.e. as a single receiver) the accuracy available to you, as a user will always be limited by certain systematic factors, such as SA and ionosphere delays. The effects of SA can be partially or almost totally removed through static positioning and averaging techniques. Whilst this will improve the long-term performance, the short-term stability will still be affected (on the most basic of levels, without correction factors). The effects of the delay due to the ionosphere may be partially eliminated by modelling the local conditions, but in stand-alone receiver this will never be completely removed. Therefore the user interested in top end time and frequency GPS usage must resort to differential GPS, the referencing of the users GPS to a local atomic clock synchronised GPS receiver. This GPS receiver will measure the clock offsets of all satellites in view (remember it's clock offset is zero due to its synchronisation to a local atomic clock, which is not subject to the delays like SA and the ionosphere). This useful data can then be made available to the user interested in quantifying his systematic delays. This can then be used to calibrate out the contribution of SA and the ionosphere (i.e. errors which are –roughly- the same magnitude at the reference and user positions). This necessitates the reference position being ‘quite’ nearby for this technique to be of any use.

One test of the accuracy of your receivers is not their absolute accuracy, rather the ability of two co-located (i.e. subject to the same systematic delays like SA and ionosphere) to agree. Each receiver is assumed to be independent (which in a sense it is not because each is subject to the same systematic errors) and tracks a satellite with SA activated. The resulting plots of the time development of the internal clock offset of each receiver clearly show the results of the SA perturbation of the signals. This is apparent for each receiver. Taking a closer look at the difference between the code phase measurements made by each receiver, reveals that whilst a certain common factor is removed (i.e. each receiver suffers from similar though not identical delays and perturbations) the remaining amount does not show noise-type characteristics. It is probably due to multipath reflections (i.e. the signal can be received at the antenna after reflecting off an object not by the direct route), which differ between receivers. This illustrates the importance of carefully selecting antenna positions for timing applications and the use of quad helix antennas.

This problem can be partially eliminated if carrier phase measurements are taken into account. The higher frequency of the carrier c.f. the code reduces the effect of reflections and improves the accuracy between two co-located receivers to ~5-10ns wrt apparent GPS time. This is an excellent demonstration of the ability of combined carrier and code phase evaluation to deliver high accuracy (agreement between two co-located receivers) in short observation times.