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DIRECT-Y: FAST ACQUISITION OF THE GPS PPS SIGNAL

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Abstract

The NAVSTAR Global Positioning System (GPS) provides positioning and time information to military users via the Precise Positioning Service (PPS), which typically allows users a significant margin of precision over the commercially available Standard Positioning Service (SPS). Military sets that rely on first acquiring the SPS Coarse Acquisition (C/A) code, read from the data message the handover word (HOW) that provides the time-of-signal transmission needed to acquire and lock onto the PPS Y-code. Under extreme battlefield conditions, the use of GPS would be denied to the warfighter who cannot pick up the un-encrypted C/A code. Studies are underway at the GPS Joint Program Office (JPO) at the Space and Missile Center, Los Angeles Air Force Base that are aimed at developing the capability to directly acquire Y-Code without first acquiring C/A code. This paper briefly outlines current efforts to develop "direct-Y" acquisition, and various approaches to solving this problem. The potential ramifications of direct-Y to military users are also discussed.

INTRODUCTION

At the most basic level, GPS is a system that allows users to calculate their position and time by triangulating from multiple reference points (GPS satellites that are in view), whose positions are known at any given time. Twenty-four satellites form the current full constellation. These space vehicles (SVs) are distributed into six orbital planes, with four SVs per plane in circular orbits about 20,000 km above the earth's surface.

The GPS signals and codes were designed very carefully to enable user sets to operate autonomously, to acquire and track GPS satellite signals, and to compute accurate navigation and time solution even when the user equipment (UE) does not have valid almanac and ephemeris prior to start. In addition, the signals were designed to provide two levels of service, the Standard Positioning Service (SPS) or civilian service, which is available to all users, and the Precise Positioning Service (PPS), available only to military users. To prevent unauthorized users from utilizing or spoofing PPS, the military ranging signals were encoded. This encoding and spoof prevention mechanism is termed Anti-Spoofing (AS). To limit accuracy to SPS users, artificial ranging errors are introduced into the ranging signals. The existence of these errors in the GPS signal is referred to as Selective Availability (SA). Military UE are equipped with cryptokeys which allow the removal of SA errors and allow the tracking of the encrypted precise ranging signals.

The ranging signals take the form of Pseudorandom (PRN) codes. Each satellite transmits a unique Coarse Acquisition (C/A) code for SPS and Precise (P) Code for PPS. The precise code is normally replaced by its encrypted equivalent Y-code. GPS user sets obtain ranging measurements by acquiring and tracking a SV PRN code. Some military UE first acquire the C/A code and then acquire a time mark to allow transition to Y-code track. In the event that those UE are denied access to the C/A code, they would not be able to utilize PPS either. A solution to this problem is to upgrade those UE to allow the direct acquisition of the Y-code without first acquiring C/A code. In the following sections, we discuss the PRN codes and UE acquisition and track functions to explain why direct-Y acquisition is not as simple as it sounds. Details about technology enhancements required to support direct-Y and tradeoffs between technology and Concept of Operations (CONOPS) are also discussed.

SIGNAL IN SPACE AND CODE STRUCTURE[1]

Each satellite transmits unique C/A and P(Y) PRN codes. These codes appear to be random but actually are exactly reproducible in much the same way as a sequence of outputs from a random number generator when supplied with an initial seed. Each C/A code is a Gold code with bit rate (or chipping rate) of 1.023 MHz and repetition period of 1023 bits. The C/A code thus repeats every 1 ms.

The GPS UE forms a pseudo-range (PR) measurement by locking on to the code corresponding to one of the SVs. This is done by correlating a replica of the code generated within the UE with the received, down-converted satellite signal. All satellites broadcast C/A code using the L1 carrier frequency of 1.57542 GHz. The UE's antenna receives signals from all satellites in view. However, the orthogonality property of the codes allows a channel of the UE to track an individual satellite signal. This method of communication is termed code-multiplexing. PR measurements made by receiver channels tracking four or more satellites can then be used to calculate a navigation solution and GPS time.

When generating the signal, the SV adds to each code, in modulo two fashion, a 50 Hz navigation message (referred to as the NAV message). The resulting bit sequence is used to phase shift the L1 carrier (phase-shift keying), which is then broadcast. The PRN code itself provides no information. Its function is to provide a mechanism for the UE to lock on to the phase of the satellite signals so that signal times of transit can be measured. The times of transit, relative to the UE clock, when multiplied by the speed of light, are the PR measurements. GPS UE typically have two tracking loops, one that tracks the code and provides the PR measurements, and one that tracks the carrier, which provides delta range (DR) or Doppler-like measurements. A typical measurement frequency is 1 Hz.

The 50 Hz NAV message is demodulated once the loops begin track. Included in the NAV message is the entire satellite constellation almanac, ephemeris for that particular satellite, and satellite clock offset relative to the GPS time standard. This data are needed, along with four or more PR measurements, in order for the user set to compute position and time. The C/A code signal component nominal power specification is -160 dBW.

Another property of the C/A PRN codes is that the signal frequency spectrum is spread out over a 2 MHz bandwidth (about twice the chipping rate) centered at the carrier frequency. This enables the signal to be more robust to interference and jamming.

The PPS P(Y) codes have a chipping rate of 10.23 MHz. Because of the higher rate compared to C/A code, they tend to provide more accurate PR. Similar to the C/A codes, there is a unique P(Y) code for each SV. Normally, each SV can broadcast either the un-encrypted P-code or the encrypted Y-code, but not both. The Y-code is normally broadcast, and thus the P-code is usually not available. The P-code has a repetition period of one week. The Y-code, which is the encrypted version of the P code, does not repeat.

In a way similar to C/A signal generation, the NAV message is added to the P(Y)-code prior to phase shifting the carrier. In this case, however, the signal is applied to two transmitted carriers, the L1 carrier, in quadrature with C/A, and the L2 carrier at 1.22760 GHz. The P-code signal component power specification is -163 dBW on L1 and -166 dBW on L2. The spread spectrum of the signal is about twice the chipping rate, or 20 MHz. This offers better resistance to wideband interference than the C/A code, which is only spread over 2 MHz.

SIGNAL ACQUISITION, TRACKING, AND PVT COMPUTATION

To acquire a SV, the received RF signal is first down-converted and then correlated with the PRN code of a particular SV generated within the UE. If a current constellation almanac is available in UE memory and if the UE roughly knows its location, then the acquisition mode logic can select a SV which is within view. For example, a satellite most nearly overhead would have the highest power level and slowest change in geometry, thus being better suited for the first SV to acquire.

Current UE, including some military UE, first acquire C/A code. Following acquisition, SPS or civilian UE track C/A code while PPS, or military UE, hand over to Y-code.

The C/A code repeats every 1 ms. UE performs acquisition by a search over time (in intervals of half chips or smaller fractions of a chip) until a peak shows up in the correlation function. The time offset giving the peak is the amount of time that the code has to be slewed, relative to the UE clock, to track the SV signal. Figure 1 illustrates how the receiver correlates the received signal to a known algorithm that is stored in memory. In some cases, an additional search over frequency may be needed to limit signal processing losses due to loss of coherency. During integration, loss of signal coherency is caused by phase-shifting (Doppler) of the signal relative to the generated PRN code. Doppler is due to to such effects as user velocity along the line of sight (LOS) and oscillator frequency offset.

SPS USER EQUIPMENT

To solve for user position and time, unaided GPS sets use PR measurements from four satellites. First, the set generates a duplicate of the C/A code for the satellite it wants to track. It then slews the code forward or backward in time to maintain correlation with the incoming signal. The amount of time shift between the user clock and the incoming signal is the PR measurement. This can be seen from Figure 1, as discussed above. PR is simply the time shift multiplied by the speed of light.

PR measurements are corrected for ionospheric and tropospheric delays (which affect the speed of transmission through the atmosphere), the SV clock error (which is included in the navigation message), relativity effects, and interchannel bias. The corrected PR measurements and satellite location (via ephemeris data) are used to estimate user Position, Velocity, and Time (PVT).

A batch least-squares algorithm can be applied to four or more PR measurements to estimate user location and UE clock time offset. The precise instantaneous GPS time can then be obtained by adding the estimated time offset to the UE clock time. Rather than a batch filter, the navigation solution is usually obtained through the use of an iterative Kalman-Bucy navigation filter, which optimally weighs the PR measurements (and DR measurements if available) based on measurement and user motion statistical models.

PPS USER EQUIPMENT

The military UE that first acquire C/A code then begin tracking and demodulation of the NAV message, and read the HOW in the NAV message. The HOW of a particular epoch corresponds to an epoch in the P(Y)-code sequence. The UE uses this information to determine where in the internally generated P(Y)-code sequence to initiate correlation for tracking. If the user has a rough knowledge of location, a current almanac, and SV clock corrections, the Y-code acquisition of subsequent channels should proceed fairly quickly. To initiate tracking, subsequent channels need only slew their code phase, relative to the first channel, by an amount corresponding to the difference in user to satellite path length between the first SV and the subsequent SV.

C/A CODE ACQUISITION VS. DIRECT-Y ACQUISITION

Since the C/A code repeats every 1 ms and chips at 1.023 MHz, then at most, 1023 chips (or 1 ms) of time uncertainty would have to be searched in order to acquire. The military UE that acquire C/A code demodulate the NAV message and use the HOW to transition to Y-code. Now consider direct P(Y) acquisition without the HOW. P-code repeats once per week and chips at 10.23 MHz. The starting phase for the P(Y)-code correlation search would be based on the time as given by the UE clock (or an externally provided GPS time fix). If the UE clock were just one second in error, 10.23 million chips would have to be searched to acquire Y-code directly. Assuming 20 ms of integration dwell on each half-chip searched, a single dwell sequential searching scheme would take about 5 days to complete.

WHY DIRECT-Y?

As the role of GPS as a force-enhancer matures, an increasing number of military users are finding applications for it. Among them are Precision Guided Munitions (PGMs), Combat Search and Rescue (CSAR) forces, tanks, transporter vehicles, and many others. The increasing reliance on GPS may make it a target for enemy jamming and spoofing in the field. Since C/A code can be rendered unreliable by such tactics, military users should reduce their reliance on it to the extent possible.

HOW TO ACHIEVE DIRECT-Y — TECHNOLOGIES AND CONOPS

So what is needed to support direct-Y acquisition? Obviously, as the above example illustrates, accurate time is very helpful. Thus, clock and oscillator technology and stability are very important. However, another approach is to apply fast acquisition Application Specific Integrated Circuits (ASICs) that perform many correlation searches in parallel. ASICs having the ability to perform 1023 parallel correlations have already been developed, and a 2046 direct-Y chip development is currently being sponsored by the GPS Joint Program Office (JPO) and the Avionics Lab at Wright-Patterson AFB. Other approaches are related to constraints or modifications made to the Concept of Operations (CONOPS). For example, an external time fix may be provided prior to a direct-Y acquisition attempt.

So the three ways to attack the problem are: (1) use of enhanced oscillator technology, (2) use of parallel correlation ASICs, (3) CONOPS to initialize time and GPS parameters. However, each platform and user set, along with its standard operational concept, will impose certain constraints on power, battery life, size, weight, cost, and ability to initialize. For example, an atomic clock may be entirely appropriate for an avionics unit, but not so for a handheld unit due to size, battery life, and cost constraints.

These issues are described below in more detail along with other supporting technologies.

CONOPS

The Concept of Operations refers to how the GPS UE is initialized, used, and maintained. Initialization for direct-Y consists of accurate time, current almanac or ephemerides, and other SV parameters. For very fast Time to First Fix (TTFF), the satellite ephemeris needs to be provided via data initialization. The reason for this is that 30 seconds or more is required to read the ephemeris subframe data after track and data demodulation begins. Ephemeris data for four or more SVs in track are needed before an accurate PVT solution can be computed. Also, for the case of direct-Y acquisition, the cryptokey needs to be provided so that Y-code may be generated in the UE correlation block.

Some UE, like handheld units, are able to get initialization parameters via data transfer from another handheld which is currently tracking or has recently tracked GPS. Other UE, like avionics units, may be initialized via other means prior to launch. For example, an atomic clock, which is free-running between missions and GPS fixes, may allow accurate enough time to support fast direct-Y. The various initialization alternatives are being investigated in a CONOPS trade study by the GPS JPO.

PARALLEL CORRELATORS

Consider the previous example of direct-Y acquisition in the presence of a one-second time uncertainty. The single-dwell sequential search requires about 5 days. If a 1000 parallel correlator ASIC is used, then the acquisition time reduces from 5 days to 5 days/1000, or about 7 minutes.

CLOCK ACCURACY AND STABILITY

For large time uncertainties (uncertainties larger than the number of chips that can be searched in parallel), the acquisition time is approximately proportional to the uncertainty. A free-running clock has error that depends on the initialization accuracy plus the error that develops over time due to oscillator frequency error. The frequency-dependent error generally depends on the elapsed time since the last fix. These errors are also sensitive to temperature variations for uncompensated oscillators. A GPS UE clock may be synched by reacquiring GPS and resetting the receiver clock to match GPS time. This is one way of limiting time error growth.

BATTERY AND SOLAR CELL TECHNOLOGY

A handheld UE will most probably operate on battery power. In the battlefield, an external time fix prior to direct-Y acquisition may not be practical. Thus, the UE clock will need to be left free-running between GPS fixes. Depending on oscillator power requirements (more accurate oscillators generally require more power), this may cause significant power consumption which will reduce battery life. Also, periodic GPS fixes may be performed for the sole purpose of limiting build-up in clock error, but each fix would further drain the battery. GPS tracking cannot be left running continuously due to large power demands and battery life constraints. Thus improved battery technology or the use of solar cell technology are of value.

TECHNOLOGY/CONOPS TRADES

Direct-Y acquisition time is directly related to the number of chips which need to be searched, which depends on the time uncertainty. The acquisition time is approximately inversely proportional to the number of chips which can be searched in parallel, or the number of parallel correlators. Thus, there is an obvious trade-off of correlator technology and clock technology.

If time can be maintained accurately with a free-running UE clock, then an accurate time fix for direct-Y is not needed. If an accurate external time fix can be provided at commencement of a direct-Y acquisition attempt, then an accurate free-running clock is not needed.

Trade-off parameters include technology, such as the number of parallel correlators in an ASIC, clock stability, and battery capability. All these factors affect cost, weight, size, logistics, and technology development and integration risk. Additional operations to initialize prior to mission start may also be traded with ASIC and clock technology. However, there is always an advantage in making a system as autonomous as possible in order to minimize operational burden.

SEARCH OVER TIME AND DOPPLER

Several contractors have been funded to perform analysis to characterize direct-Y requirements and to develop technology directly applicable to direct-Y. These studies have determined that a two-dimensional search may be required in order to detect the SV signal in high jamming environments – a search both over time and frequency. The search in frequency is called Doppler search. Doppler causes the received signal to gradually move out of phase relative to the generated SV code. This out-of-phase effect causes losses in correlation. Losses are more pronounced in high J/S environments since longer integration intervals are required to increase the SNR to a sufficient level to allow detection. The Doppler search partially compensates for these losses. Doppler is due to several effects: (1) errors in the SV velocity (this is the reason for the requirement of current almanac or ephemeris), (2) errors in the user velocity (these may be compensated for by providing inertial aiding data from an INS), (3) oscillator frequency offset and frequency drifts during the correlation interval. Considering item 3 and previous discussion, both clock accuracy (absolute time accuracy) and short-term stability (constancy of oscillator frequency over the correlation interval) are important when performing direct-Y.

DIRECT-Y PERFORMANCE MEASURES

Some criteria to measure direct-Y acquisition performance are acquisition time, probability of detection, and probability of false detection. Acquisition time is defined as the time required to detect a satellite or to obtain a positive correlation after a search over time and frequency. Probability of detection is the probability, given some correlation search procedure, of detecting an SV signal, given that it is actually present in the received signal. Probability of false detection is the probability that a SV is declared present, and is actually not present in the received signal. Also, for this application, probability of false detection includes the case of a SV being detected at an incorrect time offset and/or frequency offset. Once detection occurs, the time and frequency offsets are used to initiate code and carrier phase tracking loops. If the initial time and frequency parameters are incorrect or are not accurate enough, the tracking loops will not be able to maintain track. Considering this, a parameter more important than the probability of false detection is the probability of correctly initiating a successful track. Other performance measures are the time to recover from a failed tracking attempt and achieve a successful acquisition, by either: trying other peaks in the time/frequency region, expanding the search over a larger region of time and/or frequency, extending the integration interval to provide a higher probability of detection and a lower probability of false detection, switching the acquisition attempt to other SVs, etc.

Other performance parameters include: (1) TTFM (Time to First Measurement) - time to positively acquire and begin track of an SV and obtain a PR measurement, (2) TTFF (Time to First Fix) - time to first obtain a valid PVT navigation solution at mission start, (3) TTSF (Time to Subsequent Fix) - following a GPS track interruption, the time to reacquire and obtain a valid PVT solution. Often a TTFF measure needs to include probability of success, e.g., TTFF=10, 95%.

In order to obtain an unaided PVT solution, the following steps are required, assuming a valid almanac. First, a SV signal has to be acquired, as described above, using either C/A code or P(Y) code. Then code and carrier track has to be established on the first SV and three or more subsequent SVs. The navigation message of each SV has to be demodulated to provide SV ephemeris and other parameters which are used in the solution of PVT. About 30 seconds are required to read the navigation subframe data to give the ephemeris data pertaining to a satellite (unless the ephemeris data are downloaded into UE prior to mission or direct-Y start). PR (and DR if available) measurements can be extracted for each channel while in track lock. The measurements are fed to a navigation filter to estimate PVT. In addition, to obtain PPS accuracy, a military UE needs the cryptokey to allow generation and track of Y-code and the removal of the SA errors.

Parameters which affect acquisition performance include:

- J/S - Jammer-to-signal power ratio, usually expressed in dB or dB per unit BW
- Time uncertainty - The error between GPS time and the UE clock time.
- Oscillator error - The frequency offset and drift in frequency. Since time is obtained by integrating frequency, these effects cause a buildup in time offset. Also, the variation of the oscillator frequency from a standard constant value. An oscillator frequency offset causes a Doppler offset. The oscillator stability over the correlation period is important, since drift causes loss of signal coherency and subsequent signal processing losses.
- User position and motion uncertainty - User position error contributes to the size of the time search window, but is usually small relative to the time uncertainty effect. User velocity and acceleration, unless compensated for, contributes to the Doppler offset. To compensate for user velocity and acceleration during correlation, an inertial aiding signal from an INS can be provided to appropriately slew the code and carrier signals. Even with inertial aiding, INS errors will contribute to a Doppler offset.
- SV motion uncertainty - Primarily due to SV velocity errors. For current almanac or ephemeris, they will probably be much smaller than the user position and velocity errors.

Figures 2 and 3 illustrate the effects of J/S and time uncertainty on acquisition time.

ENHANCED GPS FOR COMBAT SYSTEMS (EGCS)

Due to the importance of GPS in the battlefield, the GPS JPO at Los Angeles AFB and the Avionics Lab at Wright-Patterson AFB have been funding studies aimed at developing technologies to enable direct-Y acquisition. The Enhanced GPS for Combat Systems (EGCS) Program consists of four primary projects that, if completed, would result in significant advances towards achieving this capability. There are two main approaches to this problem. The first is to have very accurate time information input to the correlator that is searching the Y-code. The second approach uses multiple correlators (or similar signal processing techniques), which operate in parallel to simultaneously search over different correlation time offsets.

CLOCK ACCURACY

Many current GPS UE use relatively low-power, low-cost quartz oscillator technology that provides a free-running accuracy on the order of a millisecond for elapsed times approaching an hour. As discussed above, these oscillators are not well-suited for direct-Y acquisition. Two issues are important. First, in order to avoid searching over a large interval of time, the unit must know the GPS time extremely accurately. Microsecond level accuracy would make direct-Y acquisition attainable without the need for parallel correlation circuits. The second issue is the stability of the oscillator. User sets that are employed in the field, in most cases, are not able to calibrate their clocks frequently, at least not without a GPS fix. Initialization of the units can be performed periodically, but not regularly enough to keep the oscillator frequency from drifting significantly from the calibrated value. Most GPS UE will not observe a stability problem. Every time the unit acquires the GPS signal, it resets its clock and recalibrates the oscillator frequency using the time available in the PVT solution. If the unit is used a few times a day, its accuracy may stay within acceptable limits. However, some UE, like handheld units, can be left inoperable for longer periods to conserve battery power. Still others, like the Combat Survivor Evader Locator (CSEL) survival radio currently under development, may go months without use. The operator may not be able to plan on its use ahead of time to have it calibrated beforehand.

For these reasons, EGCS is monitoring an effort to miniaturize atomic (cesium) clocks. The miniature atomic clock under development is projected to provide time accurate to 10 microseconds after one day. If successful, this approach could enable direct-Y acquisition without the need for many parallel correlators. While the atomic clock may be suitable for avionics UE, it may not be applicable to handheld UE due to the power requirement of about 300 mW. Key issues for the miniature atomic clock are the power requirement, size, and cost. So far, great strides have been made in all three areas, but it may be a few more years before this technology will be available for operational use.

Another clock technology has been developed by the Army Research Lab[2]. This is the Microcomputer Compensated Crystal Oscillator (MCXO), which has the property of providing time accuracies on the order of 1 ms per day with very low power requirement (25-75 mW).

The JPO is actively seeking other methods of getting an accurate time signal into the hardware on demand without relying on reading the navigation message. Potential solutions include developing the necessary interfaces to transfer time and other parameters between two GPS user sets, or directly from an off-board atomic clock. Additionally, a time mark can be braodcast in the UE.

PARALLEL CORRELATION SIGNAL PROCESSING

The other three projects within EGCS are analyzing and/or developing various multiple correlator designs. Two approaches consist of correlation ASICs having between 1000 to 8000 taps, effectively allowing 1000 to 8000 parallel correlations. Preliminary analysis shows that the designs are promising. Using an 1023 tap ASIC developed by another project, the acquisition of the Y-code was demonstrated in a laboratory environment using GPS signal generators[3]. The significant challenges that remain are miniaturizing the technology enough to fit the size constraints of the smaller UE, and reducing the power consumption of the chips to be compatible with power budgets and battery life.

The third approach is also a parallel processing scheme. The design performs a Fast Fourier Transform (FFT) on the incoming signal and the known Y-code, and multiplies the two in the spectral domain. The correlation function is then given by the inverse FFT. This procedure takes less steps than the correlation approach, and is expected to yield better results. However, the implementation of this approach in a brassboard for demonstration has proven to be more challenging.

RELEVANCE TO THE PTTI COMMUNITY

Clearly, direct-Y causes the user to be much more dependent on having as accurate time as possible. As indicated by Figure 3, acquistion time is highly dependent on time uncertainty. Therefore, one of the key avenues for improving direct-Y performance is to provide more accurate time information to the UE so that parallel correlation can be done over a narrower search window. We have examined various notional schemes for providing periodic time updates to an airborne receiver to keep its clock accurate and calibrated within acceptable limits. Various data busses have been suggested, such as the 1553 digital data bus, as well as the RS422 data interface, and the PTTI port[4]. However, there is very little concurrence on what type of time accuracy is attainable from each of the above-mentioned approaches.

One interesting approach leverages technology that is already being incorporated into the GPS Receiver Applications Module (GRAM)[5]. The GRAM will eventually be an open architecture interface board that enables GPS receivers to interface with a variety of commercially available applications cards via a standard interface protocol. Included in the GRAM design is an interface to a PTTI time source that may be provided by the vehicle hosting the receiver. Today, this PTTI "hook" may have little use. Re-integrating existing receivers in aircraft platforms in order to provide the PTTI signal to the receiver would be cost-prohibitive. But the ramifications of this approach to future generations of receivers are unmistakable. The battlefield of the future is becoming more communications-intensive. Already, major programs are underway to link a multitude of weapons platforms into single battle management functions. It is envisioned that a single theater commander can have total control over all assets in the theater. The commander will be able to get status on each unit in the field, sea, or air and optimize an offensive or defensive strategy based on location and condition of all assets. Finally, the commander would be able to automatically task each unit, even in an electronically saturated environment. As this vision becomes reality, there may be a growing interest in accurate time sources for all military weapons platforms. Accurate time may be necessary to enable the use of Time Division Multiple Access (TDMA) communications concepts that allow a multitude of users to share the same bandwidth by assigning each user a precise time window in which to transmit.

Other applications, like weapons guidance systems and many others have been proposed that require highly accurate time. As these applications mature, the value of delivering precise time to the platforms increases. Ultimately, it is conceivable that the value of time would be high enough to justify major investments into methods of providing precise time.

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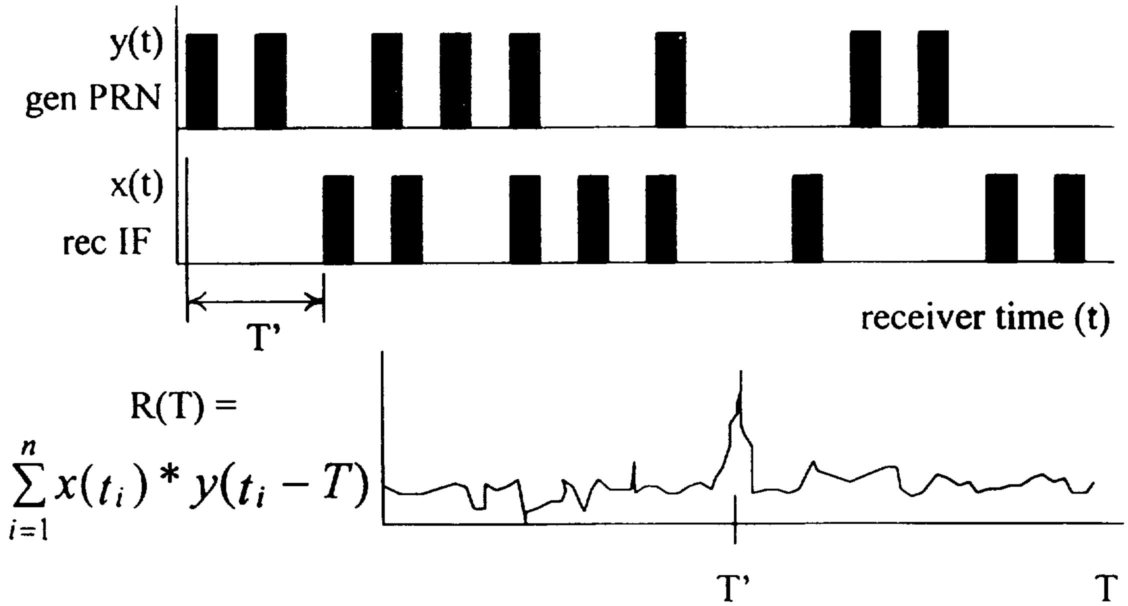

Figure 1   Acquisition by Correlation

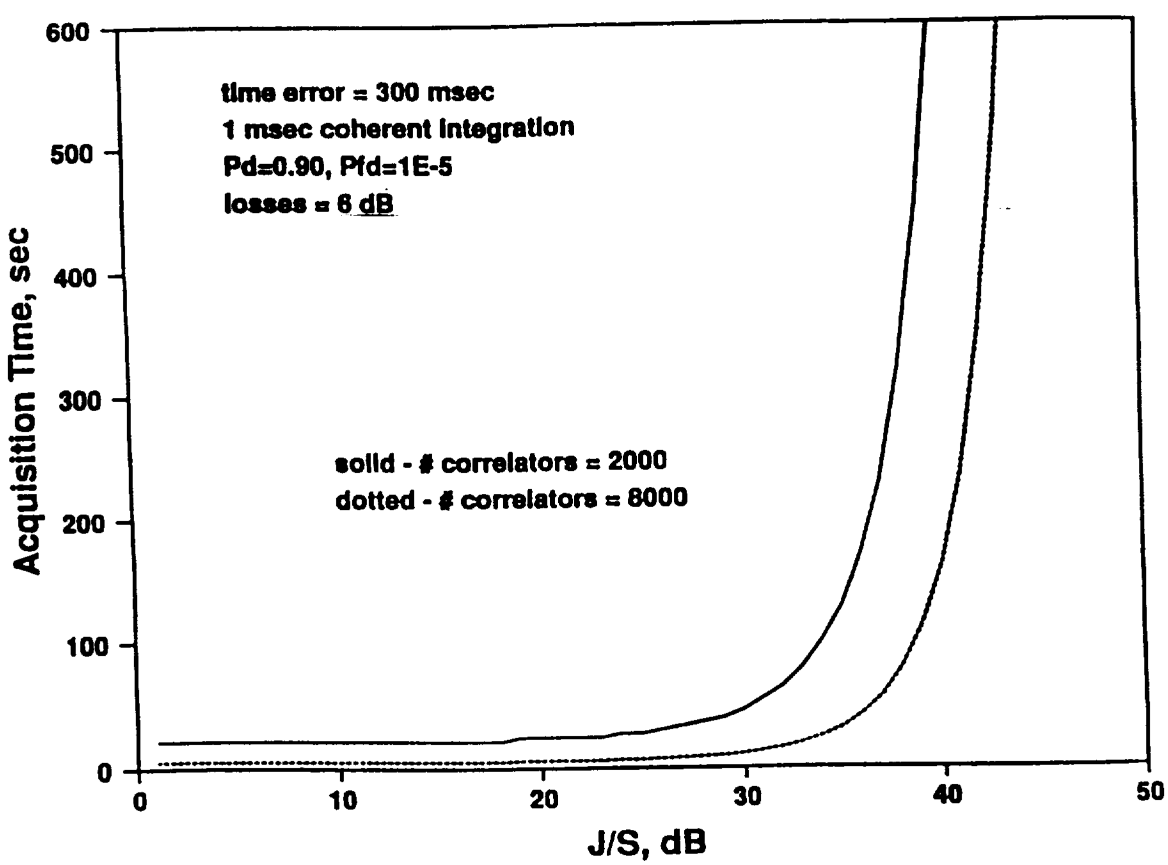

Figure 2 Acquisition Time Vs JS

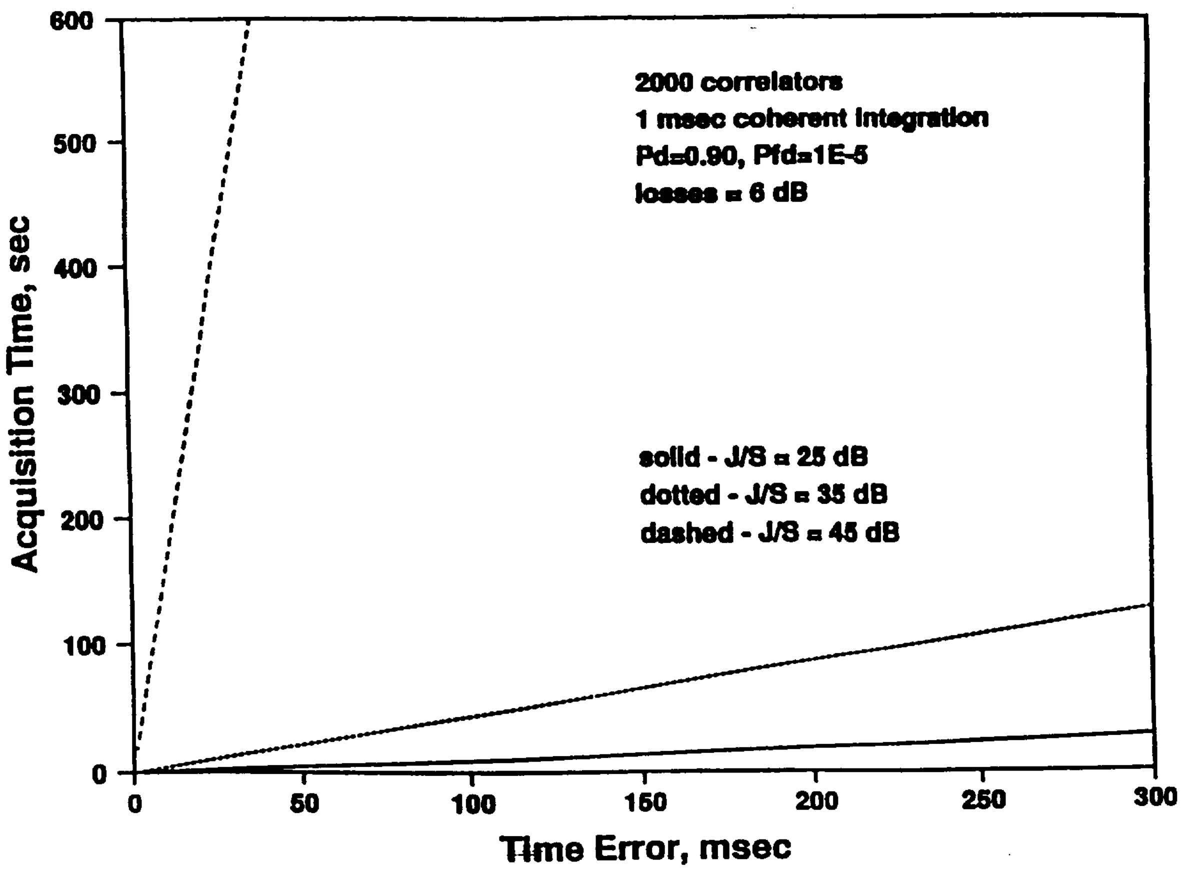

Figure 3 Acquisition Time Vs Time Error