Receiver Sensitivity Analysis and Results

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BIOGRAPHY

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ABSTRACT

GPS technology has found widespread applications in varied walks of life. GPS receivers serving these applications require among other performance factors, maximum possible sensitivity under non-conducive environments.

Both acquisition and tracking sensitivities play an important role in determining the overall performance of a GPS Receiver. As sensitivity is a function of various elements, it is important to analyze these parameters to study their impact on receiver sensitivity performance.

This paper describes the theoretical basis for acquisition algorithms and tracking loops to improve the overall sensitivity of the receiver. Extensive simulations and experiments were carried out to ascertain the level of improvement obtained.

The programmable architecture on the NAV2K™ family of GPS receivers facilitated easy implementation of the improved algorithms onto the GPS core. Extensive bench tests were then conducted to verify and validate the results.

INTRODUCTION

GPS receivers are gradually overcoming cost boundaries and are assuming a utilitarian form. Together with improvements in the related technologies, GPS is rapidly on its way towards donning the mantle of the de-facto navigational means of the 21st century.

One of the most important capabilities required for a GPS receiver is Sensitivity, which is defined as the minimum received signal strength that a receiver can work with. This dimension is being continuously redefined such that the current generation receivers are now able to work even under weak signal coverage.

The objective of this paper is to present the work conducted at Accord Software and Systems Pvt Ltd on improving the sensitivity of a stand-alone commercial GPS receiver and the results obtained thereof.

MOTIVATION

Human life is the most valued asset today and there is an all out effort to develop means and know-how of preventing human casualty. An example is the E-911 services, which has gained foremost importance in this direction. Together with support networks like GSM or CDMA, GPS forms a potent combination that provides reliable and fast information about the distress location.

Some other uses of GPS today are in the Tracking applications – be it human or vehicle. These applications are pushing the sensitivity limits for commercial GPS receiver operability.

In addition to the above applications, Automotive and Consumer electronics segments have taken to GPS receivers in a big way. The volumes generated in these segments are phenomenal and the GPS developers are striving to include more and more innovations and improvements in their products.

Such rapid advances in the GPS domain is very heartening, but at the same time it calls for focused research and development for GPS companies. Intense competition is another motivation for GPS companies to create killer features.

The endeavor to develop new algorithms to improve the sensitivity for stand-alone receivers was initiated with the intent of exceeding the existing market benchmark in acquisition and tracking sensitivity. The market requirement for improvement in sensitivity has justified the effort.

THEORETICAL FRAMEWORK

The GPS signal is typically buried in thermal noise and the minimum signal level that reaches the Earth is –130dBm. While the signal structure itself provides means to recover the GPS navigation data from under noise levels, these inherent properties fail under dense foliage or in urban canyons. In order to look at means of improving the signal detection and tracking beyond the limits of the GPS signal structure itself, a detailed study of the GPS receiver architecture is imperative.

The two core signal-processing blocks of a typical GPS receiver (Figure 1) are –

- RF Front End
- Digital Signal Processor (DSP)

The RF front end down converts the signal to a sufficiently low Intermediate Frequency (IF) and digitizes it. The digitized IF is processed in the DSP to perform correlation, acquisition and tracking.

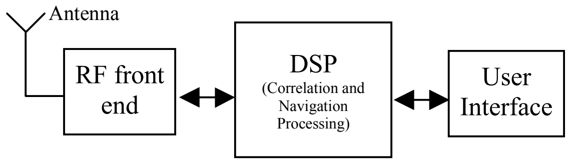

Figure 1: A typical software based GPS receiver architecture.

Both the RF front end and the signal processing in DSP determine the bounds for achieving a desired sensitivity level. Each block presents a set of tunable factors that need to be adjusted to obtain the desired performance level. These factors are addressed below.

RF Front End

The RF Front End is the first block that the GPS signal encounters in a receiver. The following factors are crucial in determining the signal flow through the RF front end –

- Low Noise Amplifier
- Filters
- RF Down Converter
- Clock
- Circuit layout

Low Noise Amplifier

A Low Noise Amplifier (LNA) is used at the input of the RF Front End. This may be built into the RF Down Converter or it may be a separate chip.

The LNA determines the Noise Figure of the entire receiver, which means that it defines the additional noise introduced in the RF chain. An integrated LNA inside the RF down converter is typically noisier than a stand-alone chip.

Hence, the first step towards obtaining higher sensitivity is to choose the LNA on its Noise Figure and gain characteristics.

Filters

The GPS signal has to invariably pass through filters to weed out unwanted noise. The filters used are typically Band Pass filters centered around the GPS L1 frequency and the Intermediate Frequencies generated from the RF Down Converter.

The first filter used is at the GPS L1 frequency with a pass band of 2MHz – 20MHz. This filter eliminates the image noise for the L1 frequency. Further filtering is needed at each stage of the down conversion process. If the frequency plan involves higher intermediate frequencies, simpler LC filters are sufficient. For lower intermediate frequencies, sharper filters such as a SAW filter should be used.

Hence, proper choice of filters with respect to the image frequencies, roll off characteristics and components used has to be judiciously done to ensure that it does not result in any loss of sensitivity.

RF Down Converter

The RF Down Converter down converts the L1 frequency to lower intermediate frequencies in one, two or three stages.

There are numerous commercially available RF Down Converters with defined frequency plans, which are currently used by many GPS designers. Some designers prefer to custom build their own RF Down Converters.

The frequency plan of a particular down converter determines the filters that have to be used. The choice of the down converter also determines the signal-processing component implemented on the GPS receiver. A down converter with high IF will impose more computational burden on the DSP if the signal processing is performed in software rather than hardware ASIC.

In addition, the output from the down converter also plays an important role in determining the sensitivity that can be achieved. A 2-bit output provides 1.5 dB more sensitivity than just 1-bit Quantization.

Clock

The clock used for down conversion is also an important determinant of sensitivity in a GPS receiver. A high stability clock provides less jitter and variations in the Doppler and Code, thus enabling edge-to-edge correlation. Stable clock also enables longer pre and post detect integration to be performed on the signal without loss of signal due to drift.

The clock jitter also plays an important role in determining the tracking threshold. At lower carrier to noise ratios, the clock jitter also becomes a considerable error source that cannot be discounted.

Circuit Layout

As the GPS RF design involves frequencies in the range of GHz, the choice of Printed Circuit Board (PCB), the track width and length, component placement and the number of physical layers on the PCB are critical issues to be addressed during the design.

The track width and length have to be correctly matched. Any mismatch affects the Voltage Standing Wave Ratio (VSWR) or can introduce parasitic capacitances. In addition, the isolation between the tracks and the critical components such as RF filters is essential to prevent leakage of signals.

As the signal processing is done digitally, the isolation between the analog and digital sections on the PCB have to be properly addressed. Incorporating separate ground planes for analog and digital components is one way to tackle the issue. A common and effective way of linking the analog and digital power supply lines is through a ferrite bead inductor.

Digital Signal Processor (DSP)

The next block in the GPS signal chain is the DSP. The DSP is a powerful platform for incorporating innovative algorithms that lead to improvement in sensitivity.

The DSP incorporates the following blocks –

- Base band signal processing
- Tracking Loops
- Aiding

Base band signal processing

This section consists of Integrate and Dump accumulators and Filters, which determine the extent to which the noise can be eliminated.

Integration periods are different for acquisition and tracking. The integration prior to data bit synchronization, also called as Pre detect integration, is typically less than the data bit period. This is done to avoid signal loss due to navigation data bit transitions. The integration after data bit synchronization, also called Post detect integration, is done typically over a single data bit period. If prior knowledge of the data bits is known, the integration can be extended beyond the data bit interval.

While it is known that longer integration yields better sensitivity, the limitations in normal receivers are –

- The data bit boundaries are not known during acquisition and tracking prior to data bit synchronization
- After data bit synchronization, information about successive bits is unknown which prevents integration times beyond the data bit intervals

Tracking Loops

The Tracking loops consist of Carrier and Code loops. Both loops have a set of design parameters based on the kind of application the receiver is intended for use. The sensitivity of the receiver is determined by the noise in the tracking loops.

Carrier Tracking Loop

Carrier loops can be either Phase Lock Loop (PLL) or Frequency Lock Loop (FLL). There are distinct trade-offs between using a PLL and a FLL. While PLL provides excellent carrier tracking as compared to a FLL, it is susceptible to higher dynamic stress.

The carrier loop considered for the analysis is a FLL. The dominant sources of frequency error in a FLL are the thermal noise frequency jitter and dynamic stress error. As a rule of thumb, the tracking threshold for the FLL, which is the 3-sigma value of jitter due to all sources of loop stress, is given by (Ref 1):

$$3\sigma_{FLL} = 3\sigma_{tFLL} + f_e \leq 0.25 / T(Hz) \qquad (1)$$

σ_t is the 1-sigma thermal noise frequency jitter

f_e is the dynamic stress error in the FLL tracking loop

The FLL tracking loop jitter due to thermal noise is,

$$\sigma_{tFLL} = \frac{1}{2\pi T}\sqrt{\frac{4FB_n}{c/n_0}\left[1+\frac{1}{T\ c/n_0}\right]}(Hz) \quad (2)$$

Dynamic Stress error does not come under the scope of the analysis. Only those parameters that affect the sensitivity are addressed.

From equation (2), it can be seen that the carrier loop is characterized by the Loop bandwidth (B_n), Integration period (T) and the Signal strength (c/n_0).

Code Tracking Loop

The dominant sources of range error in a GPS receiver code-tracking loop (Delay Lock Loop) are thermal noise range error jitter and dynamic stress error. As a rule of thumb, the tracking threshold for the DLL, which is the 3-sigma value of jitter due to all sources of loop stress, is given by (Ref 1):

$$3\sigma_{DLL} = 3\sigma_{tDLL} + R_e \leq d \quad (chips) \quad (3)$$

σ_{tDLL} is the 1-sigma thermal noise code tracking jitter

R_e is the dynamic stress error in the DLL tracking loop

The DLL thermal noise code tracking jitter is,

$$\sigma_{tDLL} = \sqrt{\frac{4F_1 d^2 B_n}{c/n_0}\left[2(1-d)+\frac{4F_2 d}{T\ c/n_0}\right]} \quad (chips) \quad (4)$$

Dynamic Stress error does not come under the scope of the analysis. Only those parameters that affect the sensitivity are addressed

From equation (4), it is seen that the code loop is characterized by the Loop bandwidth (B_n), Integration period (T), Signal strength (c/n_0) and the Correlator chip spacing (d).

Aiding

Inertial aiding is a popular means of assisting the GPS receiver either to provide reliable position during satellite outages or to improve position accuracy. The first application works on the measurements and on the position output of the receiver and is called “Loose coupling” while the second is more closely integrated into the carrier tracking loop enabling further reduction in the bandwidth. This is called “Tight coupling.”

Another means of aiding commonly known as Server aiding is employed to assist the GPS receiver to perform signal integration beyond the conventional data bit period. This method provides the data bit information apriori so that the receiver can integrate beyond the data bit period to achieve further sensitivity.

Both the above methods of aiding provide improved sensitivity to the receiver at the cost of additional components and complexity.

SIMULATION

Acquisition

To demonstrate the improvement in acquisition sensitivity, the integration boundary was increased beyond the data bit period. To overcome the effects of data bit transitions during the integration period, a data bit prediction algorithm was employed and a coherent integration was performed.

Simulations were performed on a data set collected over duration less than the data bit period. The data in Figure 2 shows the signal content in the presence of random noise.

The integrations were extended beyond the data bit period by collecting data for durations more than the data bit period. Multiple data bit transitions were introduced during this period. Figure 3 shows the signal content in the presence of random noise.

From figures 2 and 3, it can be seen that coherent integration beyond the data bit period yields significant improvement. The data bit prediction algorithm ensures significant improvement of about 6dB even in the presence of data bit transitions.

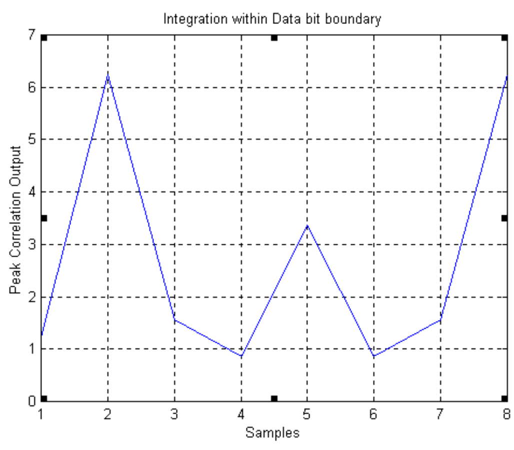

Figure 2: Acquisition sensitivity with integration over less than data bit period

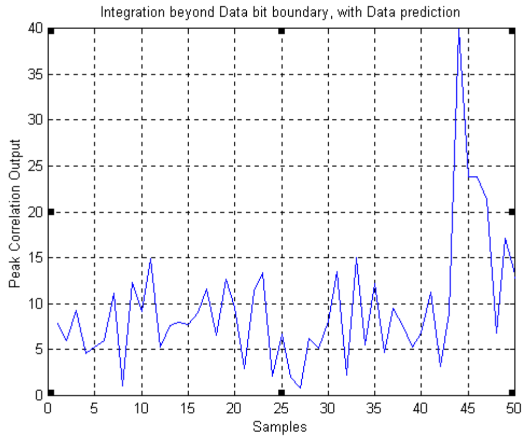

Figure 3: Acquisition sensitivity with integration over more than data bit period

Tracking

Carrier Tracking Loop

To test the effect of the carrier loop parameters on the sensitivity of the receiver, the following simulations were done –

- Thermal noise jitter v/s Signal strength for different Bandwidths (figure 4)
- Thermal noise jitter v/s Signal strength for different Integration periods (figure 5)

From figure 4, it can be seen that reduction of loop bandwidth results in a considerable improvement of about 6dB in sensitivity.

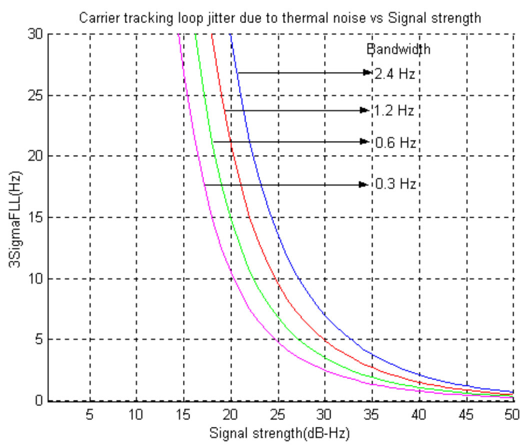

Figure 4: Carrier Tracking loop jitter v/s Signal strength

From figure 5, it can be seen that increasing the integration period from 10ms to 80ms will not yield any proportionate increase in sensitivity. This has been depicted in the table below.

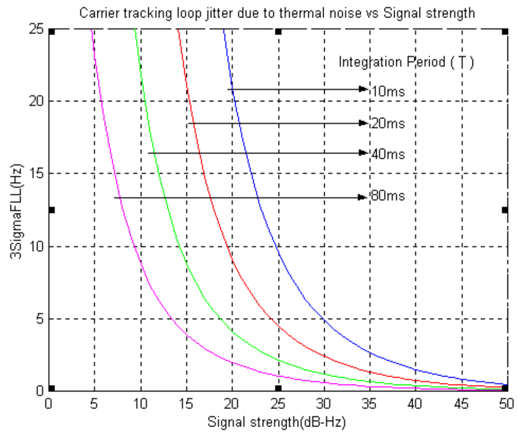

Figure 5: Carrier tracking loop jitter v/s Signal strength for different Predetection Integration period

Integration period (Tin ms)	Permissible carrier tracking loop jitter due to thermal noise (Hz)	Signal strength (dB-Hz)
10	25	19
20	12.5	18
40	6.25	17
80	3.125	16

Code tracking

To test the effect of code loop parameters, the following simulation was done –

- Code loop thermal noise jitter v/s Signal strength for a given Integration period and different Bandwidths

Figure 6 shows the variation of the thermal noise jitter for varying loop bandwidths with the given integration period.

As seen from the Figure 6, reducing the code bandwidth from 4Hz to 1Hz will yield an improvement of about 4dB

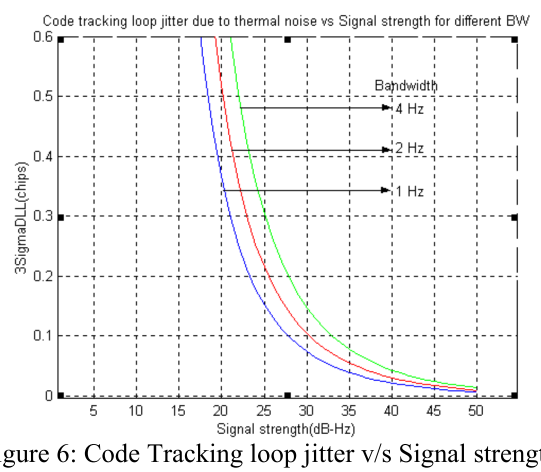

Figure 6: Code Tracking loop jitter v/s Signal strength

TEST PLATFORM

The ADI-Accord family of GPS receivers presents an ideal test platform to migrate the results from the simulations into real GPS performance. The NAV2300R core was chosen for the experiments.

The NAV2300R is the latest in the NAV2K™ family of GPS receivers. The NAV2300R is designed around a programmable fixed-point DSP from Analog Devices and incorporates a standard RF front end.

One of the key features of the NAV2K™ is the Soft-Correlator™. A software based correlator offers many advantages as compared to a hardware correlator. In addition to flexibility, a software correlator provides a convenient and inexpensive base to implement changes.

The DSP provides a seamless interface with the RF section to collect the digitized GPS signal. The DSP contains extensive peripheral interfaces such as Serial ports, Programmable Input/Outputs, software and hardware interrupts to support the signal processing and navigation algorithms. The DSP also provides sufficient memory and processing power while supporting high level of coding optimization to ensure continuous enhancements to the receiver software.

The receiver architecture is designed around a real-time Scheduler that controls the flow and execution of all modules. The modules are categorized into interrupt and periodic tasks. The interrupt tasks are given priority over the background tasks. All signal processing tasks that run on interrupts are given a major share of the resources while the lower priority navigation tasks are called at a relatively slower rate.

The interface between various modules is flexible, so much so that any module can be plugged in and out as desired. This feature enabled the addition of the improvements onto the GPS core with little effort.

TEST SETUP

The setup used to perform the bench tests consisted of a multi channel simulator, a NAV2300R GPS receiver, LNA with known noise figure and other accessories such as cables, power supplies and PC with Graphical User Interface software to monitor the GPS outputs.

The test setup used is as shown in figure 7–

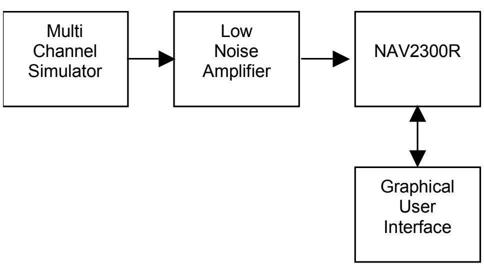

Figure 7: Test Setup for Sensitivity Analysis

Multi Channel Simulator

The Multi Channel Simulator used was the STR4760 from GSS. The simulator has the capability to simulate 24-satellite constellation and signals from individual satellite can have configurable signal strength in the range of –110 dBm to –150 dBm.

LNA

The LNA was used to simulate an active antenna of noise figure 1.5 and gain of 24dB. The cable length between the simulator and the LNA was kept to a minimum of 6 inches. The output of the LNA was given to the NAV2300R GPS receiver through a coaxial cable of 3 meter length.

TEST PROCEDURE

The tests procedure is elaborated below for Acquisition, Reacquisition and Tracking.

For all the tests, a particular satellite was identified on the Simulator and the signal strength on the Simulator was set to –120dBm. The signal strength was altered in steps and at each step the satellite status was monitored. The procedure was repeated over 50 trials and the value of signal strength corresponding to the test parameter with a statistical success of 90% was identified to be the threshold

TEST RESULTS

The simulations conducted were validated on the NAV2300R receiver. Extensive bench tests were conducted on the Multi-channel GPS simulator to determine the improvements in acquisition and tracking sensitivities.

Acquisition

The implementation of the algorithm on the NAV2300R receiver yielded 6dB as obtained from the simulations.

Tracking

The results of the tests are presented below –

- Carrier loop bandwidth cannot be reduced beyond a certain value to improve tracking sensitivity. This is due to the jitter of the low cost – low stability crystal used on the GPS receiver. To obtain the sensitivity demonstrated by the simulations, a highly stable clock should be used on the receiver.
- Overall, improvement of 6 dB was obtained in the tracking performance due to enhancements in the code and carrier loop parameters.

The consolidated figures for sensitivity of the NAV2300R GPS receiver after the bench tests are as tabulated –

Threshold	Signal Strength
Acquisition	-136dBm
Reacquisition	-139dBm
Tracking	-147dBm

Field Tests

The most important benefit of the improved sensitivity is felt on the GPS availability. The receiver with better sensitivity is capable of acquiring / reacquiring / tracking satellites even under dense foliage or in urban canyons.

Extensive field tests were conducted with the improved changes in dense foliage and in urban canyons. The improvement in the availability is depicted in the Figure 8.

Three trials were conducted under urban canyon conditions at different times of the day. Two near identical receivers were used with one receiver programmed with the improved software and the other receiver without the improvements.

The improvement in position availability is evident from the bar charts. As can be seen, the availability has risen by about 20%.

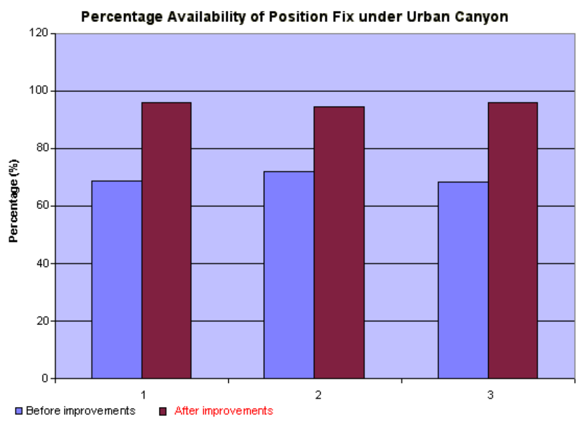

Figure 8: Urban Canyon tests

CONCLUSION

The simulations and tests conducted demonstrate that it is possible to improve the sensitivity of a commercial receiver to greater levels so much so that a stand-alone receiver without aiding can work reliably in applications demanding location information in harsh environments.

With sensitivity levels demonstrated above, a GPS receiver can provide continuous GPS coverage even in down town areas or under dense foliage conditions. This performance will benefit both Car Navigation and the hand held segments of GPS receivers.

In addition, the performance demonstrated above opens new vistas in emergency and safety systems where GPS performance is expected indoors. With aiding information, the overall sensitivity of the receiver can be taken to a newer plane ensuring continuous or near continuous GPS location information under the most inhospitable conditions.

ACKNOWLEDGEMENTS

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