Selection of Antenna and Cable for Optimum Automotive GPS Performance

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As the Global Positioning Satellite system (GPS) becomes more of a "household" word, and as the GPS industry matures from a few specialist systems into a ubiquitous utility, new applications are being tested and accepted by the consumer market as well as by commercial and industrial areas. The automotive industry in particular is examining a variety of ways that GPS can effectively be used to help the driver in terms of safety, emergency assistance, and efficient navigation in unknown areas. This is a case where an industry is struggling to understand concepts of a new system, while doing all possible to implement that system quickly. The goal of this paper is to help the user better understand the performance requirements that drive the choice of antenna and cable in an automotive GPS system.

In order to accomplish this goal, a brief description of the GPS system will be given. Second, issues affecting GPS performance in the automotive environment will be discussed. One specific issue, system sensitivity, will be described in detail. The effect of the antenna and cable on the GPS receiver sensitivity will be shown, in theory, and example. Methods to determine the best antenna will be given. Last, data taken in automobile driving tests will be shown to demonstrate the effect of antenna choice.

The GPS System

The GPS system consists of 3 segments. The space segment has 24 satellites orbiting in 6 orbital planes. The ground control segment, which monitors satellite health, consists of several monitor stations, a Master Control Station, and upload stations. The upload stations communicate with each satellite to update information on orbits and satellite health, that will be transmitted to users. The user segment is made up of receivers used in various applications.

The operational principles of GPS depend on a combination of high school trigonometry and sophisticated signal processing. Satellite signals are received by the GPS unit, and from the knowledge of the satellite position and the travel time of the signal, the distance from each satellite is calculated. With distance from four satellites, the intercept point of the four distances can be calculated, giving a position in latitude, longitude, and elevation. Four satellites are required for three dimensional positioning, as precise time is actually a variable to be solved as well as (x,y,z).

The actual operation of GPS is impressive in it's ability to give position to a precision of better than 100 meters anywhere on the globe, with the use of fairly inexpensive receivers that can be as small as a credit card. Much of the sophistication is in the satellites themselves. The satellites transmit current information to their precise location, as well as orbit information that will help predict future position. The satellites also transmit extremely precise timing information, derived from on board atomic clocks. This feature allows the ground based receivers to use inexpensive oscillators as their internal clock source. For automotive applications, this means that GPS receivers are able to be purchased in a cost range acceptable to consumers. As will be discussed in the next section, purchasing the receiver is not the only consideration.

Challenges in Integrating GPS into Automotive Applications

One of the challenges in implementing the GPS function comes from a consideration of the satellite signal itself. The GPS system designers chose a scheme similar to CDMA, in that each satellite transmits a different coded signal at the same frequency and power level. The power level seen on the ground is approximately -130dBm, at 1.575 GHz, in a bandwidth of approximately 2 MHz. If the general noise level were to be calculated for this bandwidth, from the thermal noise equation:

(Equation 1):

Noise power = Boltzmann's constant x Temperature x bandwidth = $(1.38\text{x}10^{-23}$ J/degrees K) (300 K) $(2\text{x}10^{6}$ Hz)

= $8.28\text{x}10^{-15}$ Watts

= -141 dBW

= -111 dBm

It is seen that the noise floor is actually above GPS signal. This means that the GPS receiver must act on statistically sampled noise. As the GPS signal is a spread spectrum signal, it can be extracted from the noise by correlating the received signal with a replica of the spreading code that is generated inside the receiver. Since the data rate is 50 bps, and the spreading code rate is 1.023x10^6 bps (the C/A, or coarse acquisition code) the processing gain is calculated by:

(Equation 2):
Processing Gain = chip rate/data rate
= 1.023x10^6 bps/50 bps
= 20.5x10^3
= 43 dB

Adding this processing gain to the actual signal power received, the total power becomes:

(Equation 3):
-130 dBm + 43 dB = -87 dBm

We'll use this result in the next section. For now, the fact that the signal is extracted from the noise by processing dictates a few things. First, the receiver must be able to sample noise without degradation from its own internal noise sources. Second, potential jamming signals must be attenuated as much as possible in order to not de-sensitize the receiver. In order to achieve both of these goals, the antenna, connecting RF cable, and receiver must be carefully chosen and positioned for the best overall system performance as shown in **figure 1**. Next, sensitivity, the receiver's ability to detect low level signals, will be discussed in detail. The issue of jamming from other systems will be discussed in a later application note.

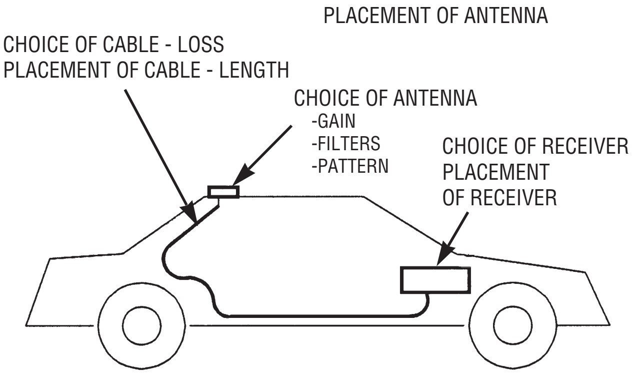

Figure 1: Factors affecting GPS performance

System Sensitivity

The issue of accurate noise sampling can be addressed by ensuring that the system design has adequate sensitivity. Sensitivity is calculated as follows:

(Equation 4):
Sensitivity = noise floor (dB) + C/N (dB) + 10 log BW(Hz)
+ noise figure (dB)

where

- noise floor = Boltzmann's constant x Temperature x bandwidth (1 Hz)
- C/N is the required signal to noise ratio (usually at least 10dB)
- BW is the receiver bandwidth, typically defined by the IF filter
- noise figure is the system noise figure, including LNA, cables, etc.

As an example:

- room temperature noise floor is -174dBm
- C/N is 10dB
- filter bandwidth is 10 MHz
- system noise figure is 2dB

(Equation 5):
Sensitivity = -174 dBm + 10 dB + 70 dB + 2 dB = -92 dBm

Recalling from **equation 3**, the incoming GPS signal, accounting for processing gain, is at a power level of -87 dBm. The sensitivity calculated for this example is below this level. This means that the receiver will be able to detect this signal. If the calculated receiver sensitivity was above -87 dBm, then the receiver may not be able to detect the signal, for its own noise would be above that level.

For the best sensitivity, we want to reduce noise contributions wherever we can. The filter bandwidth is typically fixed by the data bandwidth (for GPS the C/A code). The noise floor is fixed by temperature, which can be reduced for exotic systems, but only with great cost. We are left with reducing the system noise figure to increase the sensitivity. In the next section, it will be shown that the system noise figure is driven by the active antenna element.

System Noise Figure

The noise figure of the system can be calculated from the individual component noise figures. The cascade noise figure (NF_t) equation is:

(Equation 6):

$$NF_t(\text{dB}) = 10^{*}\ Log\,(F1 + \frac{F2 - 1}{(G_1)})$$

where NF_t = Total system noise figure.
NF_1 = Antenna LNA noise figure.
$F_1 = 10^{NF_1/10}$ = noise factor.
NF_2 = GPS receiver noise figure.
$F_2 = 10^{NF_1/10}$
G_1 = Front end gain, where
$G_1(\text{dB}) = G_{LNA}(\text{dB})$ - cable loss(dB)
$G_1 = 10^{G_1\text{dB}/10}$

The resulting total noise figure can be plotted using this equation. For sake of simplicity the receiver noise figure (NF_2) will be held constant, and the total noise figure(NF_t) in dB plotted vs. G_1in dB [G_1= LNA gain -cable loss] for two cases of antenna LNA noise figure (NF_1).

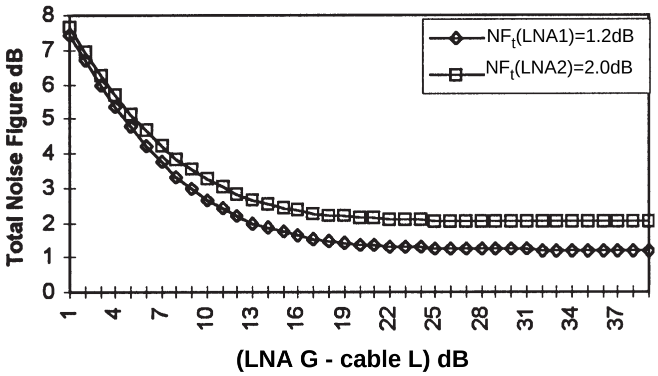

Figure 2: Comparison of Noise Figure to Front End Gain for 2 LNA NF cases

This equation and graph show that first, the noise figure minimum is fixed by the LNA. Second, the higher the front end gain, the less dependent the overall noise figure is on the GPS receiver noise figure. We will show in the following section how cable loss and active antenna characteristics can be chosen for best overall noise figure, resulting in the best GPS receiver sensitivity.

Choosing Antenna and Cable from Vendor Specifications:

It has been seen in **equation 6** that the antenna's gain and noise figure affect total receiver performance. In choosing an antenna and cable, one can sometimes use the vendor's suggestions for antenna gain as a rule of thumb. Usually GPS vendors have a specification for antenna performance. This makes the antenna and cable selection a simple process, and can be shown in an example.

One GPS receiver vendor suggests 26dB gain before the receiver (front end gain). Choosing the M/A-COM ANPC-135, we have 33 dB LNA gain. Using 20 ft of MACOM FE10ST cable, with a maximum cable loss of 0.3dB/ft., the overall cable loss is 0.3 dB x 20 = 6 dB (20 feet of cable is standard for some commercial vehicle applications). The overall front end gain is 33dB - 6dB = 27dB. This equates to 1dB over the minimum gain specification. *Note: Using a combination of antenna & cable that exceeds the vendor recommendation is usually not harmful to the system performance, but the GPS vendor should be consulted.*

Choosing Antenna and Cable by Calculation of the System Performance

In the case where the receiver noise figure is known, the effect of the antenna LNA gain, cable loss, and noise figure is more obvious. As an example we'll use a GPS receiver noise figure of 8dB. This is fairly typical for the active downconverters that make up the first stage of some GPS receivers. **Table 1** shows data for one possible choice of antenna and cable:

Specification	Value (dB)	Numerical value
Antenna LNA Gain(G_{LNA}) (M/A-COM ANPC-131)	G_{LNA} (dB) = 26	$G_{LNA} = 398$
cable loss (Lc)(15 ft at 0.5dB/ft) (generic RG-174 cable)	L_C (dB) = 8	$L_C = 6.3$
G_1 [in dB = G_{LNA} dB - loss_{cable}dB]	G_1 (dB) = 18	$G_1 = 63$
F_1 Antenna LNA noise figure (M/A-COM ANPC-131)	$NF_1 = 1.2$	$F_1 = 1.3$
F_2 Receiver Noise	$NF_2 = 8$	$F_2 = 6.3$

Table 1: Data for first antenna/cable choice

Using **equation 6**, (or using the graph on **figure 2)** the resulting system noise figure is:

(Equation 7):

$$NF_t(\text{dB}) = 10^{*}\ Log\left[(1.3) + \frac{6.3-1}{(63)}\right] = 1.5dB$$

First, it is seen that the system noise figure (1.5dB) is higher than the LNA noise figure (1.2dB). There is a contribution to the overall noise figure from the components after the LNA. If the front end gain G1 can be increased, by a lower cable loss or higher antenna gain, then the overall noise figure will rely more on the antenna LNA noise figure. **Table 2** shows the data with the higher gain M/A-COM ANPC-135 antenna:

Specification	Value (dB)	Numerical value
Antenna LNA Gain(G_{LNA}) (M/A-COM ANPC-135)	GLNA(dB) = 33	GLNA = 1995
cable loss (Lc)(16 ft at 0.5 dB/ft) (generic RG-174 cable)	L_c(dB) = 8	$L_c = 6.3$
G_1 [in dB = G_{LNA} dB - loss_{cable}dB]	G_1(dB) = 25	$G_1 = 316$
Antenna LNA noise figure (M/A-COM ANPC-131)	$NF_1 = 1.2$	$F_1 = 1.3$
Receiver Noise	$NF_2 = 8$	$F_2 = 6.3$

Table 2: Data for second antenna/cable choice

Given the data with a higher gain LNA, the system noise figure is again calculated.

(Equation 8):

$$NF_t(\text{dB}) = 10^{*}\ Log\left[(1.3) + \frac{6.3-1}{316}\right] = 1.25dB$$

It is seen that the system noise figure is dominated by the LNA noise figure. The system sensitivity will not be degraded by receiver noise.

A last word needs to be added here. A case has been shown where the higher LNA gain antenna resulted in better receiver performance. This does not mean the higher gain antenna should always be chosen! A sufficient G_1 (antenna gain and cable loss) should be chosen such that the noise figure (NFt) is determined by the LNA noise figure (NF_1). A higher G_1 does *not* further increase receiver sensitivity. It can actually *adversely* affect performance in a jamming environment, as the higher gain will boost jamming signal power into the receiver. The designer may also pay more for higher, but not required, gain

System Tests

It is possible to test the antenna performance needed by any GPS receiver instead of relying on vendor suggestions. One test setup is shown in **figure 3**.

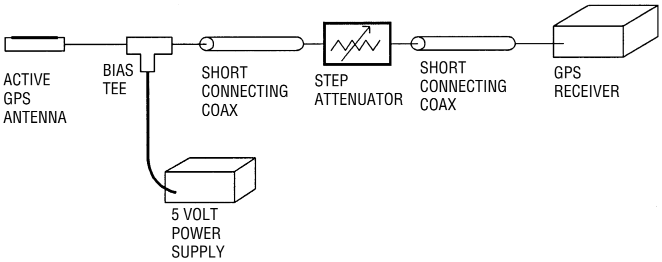

Figure 3: Test Setup for required antenna gain

The goal of this test is to determine the point at which the antenna gain is low enough to degrade the system performance. For best results in this test, a high gain antenna should be used with short coax cables. This allows the greatest range of measurement.

This test must be performed in an area where satellite reception is possible, such as a parking lot. In the setup, the antenna is connected, through a bias tee, to the step attenuator (1dB steps preferred). The bias tee is used to provide power to the GPS antenna, as the attenuator blocks the DC path from the GPS receiver to the antenna. The step attenuator is connected to the receiver to be tested. The coax cable loss should be known so that the gain of the entire setup into the receiver can be determined.

The receiver is turned on and the SNR (signal to noise ratio) on the receiver display (or laptop monitor) is examined for a high elevation satellite. The SNR is recorded for a step attenuator setting of 0 dB. As the step attenuator is stepped up, the resulting SNR is recorded. What should be seen is that the SNR is constant for a certain level of attenuation, but at higher than that level, the SNR degrades for each step up until loss of satellite lock occurs. A graph for one test performed is shown in **Figure 4**.

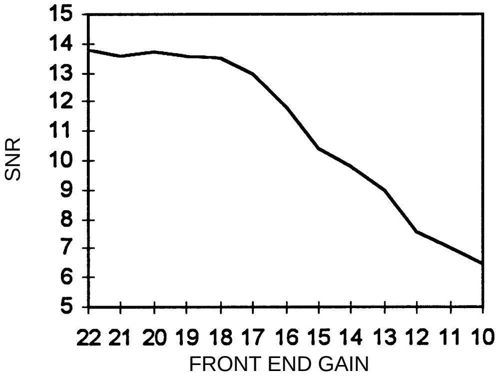

Figure 4: Antenna performance with step attenuator

Figure 4 shows the SNR performance compared to overall front end gain, where front end gain is:

(Equation 9):

front end gain = GPS antenna LNA gain - cable losses - step attenuator loss

It can be seen that at 17 dB the SNR begins to degrade in fairly linear fashion with decreasing gain (the "knee" of the curve). (Warning: The "SNR" read on the receiver display may be calculated in different ways by different GPS software routines. What is being looked for is the change of slope that shows a *change* in receiver performance. What is considered a "good SNR" number may be different for various receivers.) A "rule of thumb" is to add 10 dB to the front end gain indicated at this "knee" to calculate the gain necessary for robust performance. In this case the necessary gain would be 26 dB, and the antenna and cable choice would be made to equal 26 dB gain into the receiver.

Two notes should be made here. First, the antenna pattern varies from one antenna to another. This variance may result in slightly different results from one antenna to another. Since all GPS antennas need to have hemispherical reception, different antenna patterns are similar, though not equal. Nonetheless, this test gives a good indication of the LNA gain needed for a particular receiver.

Second, if only a sloping performance with no "knee" is seen, then the antenna does not have sufficient gain to overcome the receiver's noise. If no higher gain antenna is available, a second amplifier can be added to the chain after the antenna to further boost the gain. This complicates the test somewhat as the gain and noise figure for the entire amplifier/cable/attenuator chain must be known.

Performance Results

To demonstrate the GPS system performance using an antenna with sufficient gain and one without, field tests were run using two configurations. The first, shown in **figure 5a**, uses a 23 dB gain antenna with 8 dB cable loss; total front end gain is 15 dB. The second, shown in **figure 5b**, uses a 33 dB gain antenna with 8 dB cable loss; front end gain is 25 dB. Both tests were run using the same receiver on the same ground track, at times with similar satellite visibility. Data was taken at 10 second intervals and plotted as number of satellites tracked during the time period (about 15 minutes).

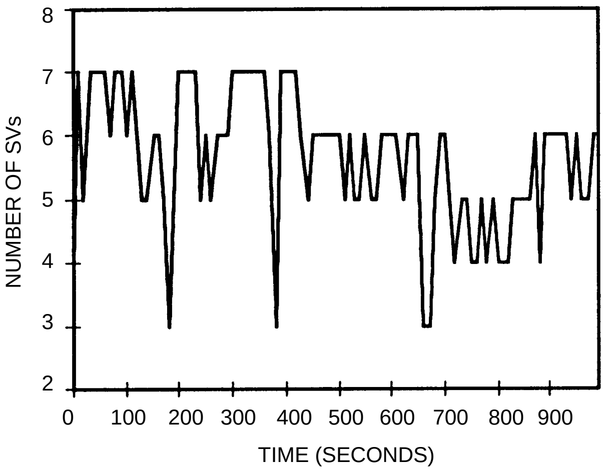

Figure 5a: Number of SVs tracked for G1 = 15dB

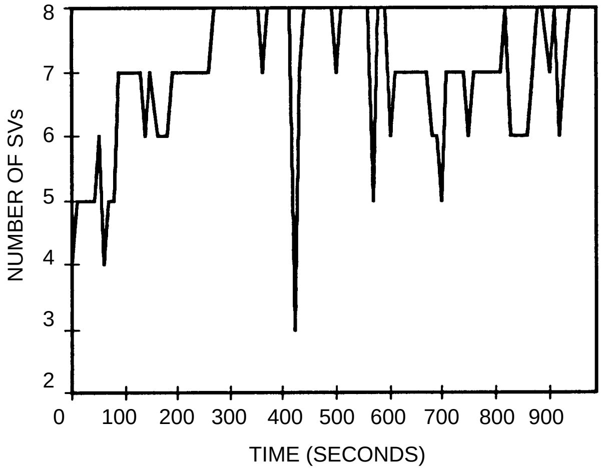

Figure 5b: Number of SV’s tracked for G1 = 25 dB

As can be seen in **figure 5a**, the highest number of satellites tracked is seven, and the lowest three. There are four points where only three satellites are tracked. This means that only two dimensional position can be acquired at that time. A minimum of four satellites are required for three dimensional tracking. The average number of SVs tracked was five.

In **figure 5b**, the data shows one point were three satellites were tracked, and an average number of satellites tracked was over six. For many points, eight satellites were seen. These two graphs show that GPS performance, based on number of satellites received, is affected by the choice of antenna and cable.

As a matter of separate interest, the accuracy with which the GPS system can track a route is demonstrated in **figure 6**. The data taken in the second part of this field test was plotted in latitude vs. longitude coordinates, and overlaid on a map of the local area (Salem, MA). The track, including a cloverleaf turn from Rte 114 through the underpass for Rte 107 can be clearly seen.

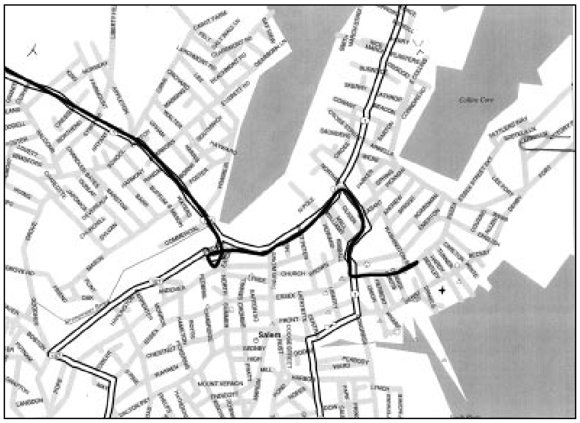

Figure 6: GPS resolution demonstration in Salem, MA.

Conclusion

It has been shown that the choice of antenna and cable can affect GPS system performance by increasing or reducing the system sensitivity. Methods of choosing the best antenna and cable have been discussed, both using vendor suggestions and by direct calculation of the sensitivity for any configuration. A method of testing the receiver’s front end gain requirements has been outlined, and experimental performance data for two possible configurations shown.