LOW POWER GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS) SIGNAL DETECTION AND PROCESSING

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ABSTRACT

The ability to detect and process weak Global Navigation Satellite System (GNSS) signals is extremely valuable as the specified received power levels of such signals are already quite low. For example, the GPS-SPS signal specification indicates the signal power at the antenna will be -130 dBm. Such weak detection techniques would be of importance for a number of applications.

This paper presents the results of postprocessing acquisition attempts on actual GPS signals of power levels significantly below nominal received power levels. Software based signal processing techniques and extended integration times are utilized to improve signal detection with GPS but are also applicable to GLONASS and other GNSS. Two different approaches, aided and unaided, are explained and exploited in the paper.

INTRODUCTION

The ability to detect and process weak GNSS signals is extremely valuable. Typically GNSS signals are already extremely low power, such as the specified power level of GPS-SPS at the antenna of -130 dBm. Desirable operating environments such as under a forest canopy, passive ranging, wide-band interference or even indoors make traditional GNSS signal processing ineffective - particularly for initial detection, or acquisition, of the GNSS signal.

The traditional approach for acquiring a weak GNSS signals is to use coherent processing over a multiple samples. Coherent processing can significantly improve the signal-to-noise ratio over noncoherent methods, however such techniques can be very time consuming or computationally expensive.

The idea behind this paper is to focus on the acquisition rather than tracking since it is possible to derive coarse (1-100m) position estimates from the acquisition result alone. The goal of acquisition is to find the code phase and a carrier frequency estimate for a particular satellite. In order to average out the noise in the GNSS data set, a longer integration time over multiple samples is utilized.

When the integration time of the correlation function is increased other aspects needs to be considered. GNSS signals contain unknown data bits that are bi-phase coded in contrast with the known bi-phase coded periodic PRN sequences. In addition, over very long integration times the carrier and code frequency can change as a result of Doppler variations. Therefore, without considering the data bits and Doppler carrier frequency information, integration times cannot be extended over 10 ms. In this paper integration times shorter then 10 ms are referred to as "unaided acquisition" and described in the first part of this paper. The second part details results from what is referred to as "aided acquisition", when a second receiver that has a clear view of the sky, and thus a stronger received signal, is utilized to provide critical information regarding the state of the various satellites. This allows for very long integration times and the ability to detect very weak signals.

The two approaches of acquisition are compared and collected data provides an experimental results for the relation of the signal attenuation level and the integration time.

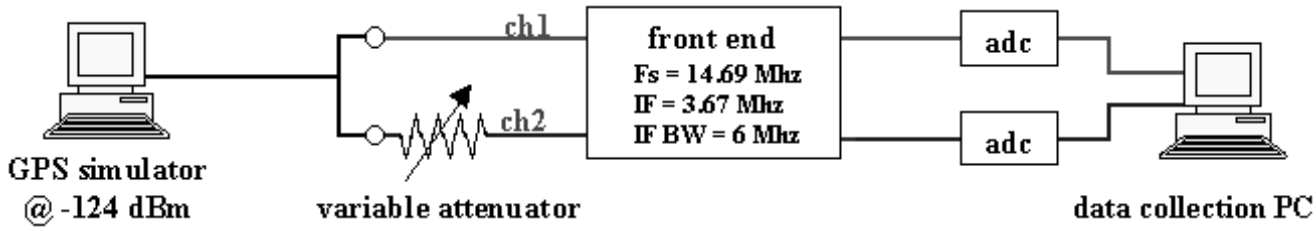

figure 1. Data collection setup

BACKGROUND

Acquisition is the first step in processing the GNSS signal. The goal is to find specific PRN codes, their initial code phase estimate, and carrier frequency information. The process can be described as a sequential search in a 3-dimensional search space.

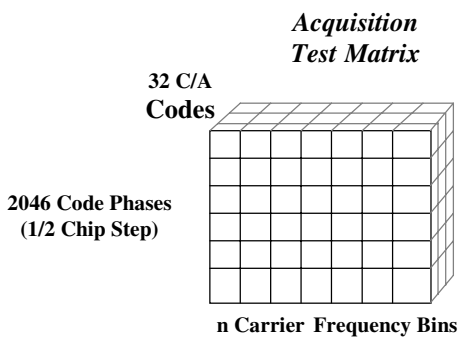

figure 2. Acquisition test matrix

The typical procedure involves starting with the GNSS signal which has been downconverted to some intermediate frequency and sampled. The signal is then mixed with digital oscillator samples as an attempt to remove the intermediate frequency completely from the signal. The difficulty is that the exact intermediate frequency is not known as a result of the possible Doppler impact on the signal as well as clock variations in the receiver and multiple frequency bins must be tested. Once at baseband the resulting signal is correlated with an internally generated version of the specific PRN code at various code phases.

At the correct code phase and carrier frequency estimate the traditional correlation peak will occur as is illustrated in figure 3. This figure represents the optimal result as in this example the carrier frequency is completely removed and there is no thermal noise present. Finding this correlation peak and detecting the satellite is the goal of the acquisition. This goal is significantly more difficult when thermal noise is present. A confidence measure, referred to as *ratio* in this paper, can be used to decide whether to declare satellite detected or not. The *ratio* is the value of the highest peak divided with the next highest peak. For the ideal case depicted in figure 3, the

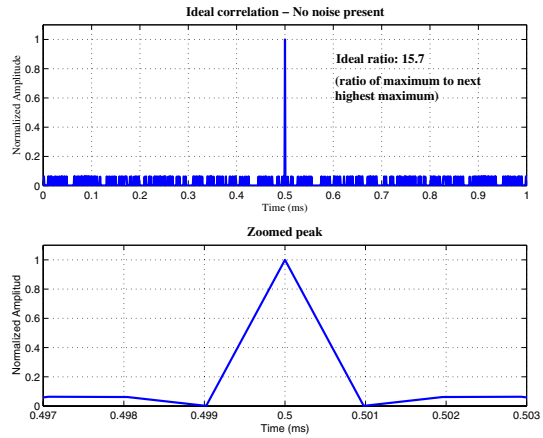

figure 3. Ideal correlation peak

ratio is 15.7 that is the maximum that can be expected. The *ratio* will, under nominal conditions, be reduced as a result of: residual carrier phase from the downconversion process, decorrelation from a difference in received and locally generated code rate and variations in received signal-to-noise ratios (SNR). It is important to recognize that this *ratio* is a statistical measure of the confidence of the acquisition result. The *ratio*, by definition, will always be a value greater than 1.0. However, a low *ratio* value, perhaps 1.1 as an example, may indicate a correct code phase or is more likely an indication of a false code phase estimate. Also, a high *ratio* could provide a false sense of security the correct value had been obtained when it simply was a statistical extreme and a false noise-based maximum. For this work, it will be important to have a truth reference to verify the acquisition result.

In order to experimentally determine what level of signals can be found, it is necessary to collect GPS data using traditional hardware which will then be postprocessed. A controlled environment is obtained using a GPS simulator as a signal source. This signal is split into two paths as shown in figure 1. One path goes directly into a traditional GPS front end. The other path goes through a variable attenuator, in order to reduce the signal power, and then into an identical GPS front end. This allows one signal to be attenuated while the other can remain as a truth reference with nominal signal values. The front end designs utilize a common clock configuration for mixing and sampling in order to characterize the attenuated channel's oscillator. This is

used in addition to the data bit information provided by the unattenuated signal processing for the "aided" acquisition trials in conducted in the second part of this paper.

It is important to provide some basis as to why longer integration times improve signal acquisition. The GPS signal can be used as an example. The GPS-SPS signal power is guaranteed to be -130 dBm into a properly designed antenna. The bulk of this power, 90%, is contained within the 2 MHz null-to-null bandwidth of signal. It is possible to estimate the thermal noise power in the same observation span. This is accomplished using the following well known equation:

$$N_{power} = k \ T \ B \qquad (1)$$

Where k is Boltzman's constant, T is the equivalent noise temperature (typically 273 K), and B is the bandwidth considered. Thus in a 2 MHz BW, the noise power is -111 dBm which is higher than the power of the GPS signal. Such a relationship is typical for most GNSS spread spectrum signals. After correlation with the PRN code what remains is the carrier modulated with the 50 Hz navigation data, which has a null-to-null bandwidth of 100 Hz. Typically integration times are on the order of 1 ms which provides reduction in bandwidth to 1 kHz. Computing the noise power in this reduced 1kHz bandwidth gives a power measure of -144 dBm. Thus the GPS signal power, nominally at -130 dBm, will now be above the noise floor and should be detectable. As the bandwidth is decreased further, there will be the corresponding reduction in thermal noise power.

Thus of interest here is what specific power levels can be detected using what integration times. Again, this question does not have a distinct answer as noise is a random process with statistical properties. For the purpose of this work, it is possible to declare success if the true code phase estimate, known from the unattenuated result, provides a maximum in the attenuated case as well. Issues associated with false and missed detection can be interpreted quantitatively in the *ratio* metric computed for the result.

Lastly, it is important to note that Equation 1 provides the basis for determining the necessary integration time. However, as is often the case when dealing with real implementation and hardware, additional losses can hinder performance. This is particularly true when dealing with decorrelation over extended integration windows.

SIGNAL POWER LEVEL COMPARISON

GPS signals from satellites with high elevation angles typically give clear and strong correlation results and they provide maximum power. However, GPS signals from low elevation angle locations can be more difficult to detect. The nominal power level from the signal channel simulator depicted in figure 1 was set to –124 dBm, thus after the splitter the power level should have been on the order of –127 dBm. This is stronger than the minimum specified but is in line with the current received power levels. In order to verify this an antenna was connected to the front end/data collection system in figure 1. Data was collected using both the simulator configuration and the antenna implementation. The acquisition operation is performed and the results are shown in figure 1. What is illustrated in this figure is a number of different aspects important to the concepts in this paper.

First, plotted in this figure are the results of six different acquisition trials. The plots in the top row are all using an integration period of 1 ms. The plot in the top row on far left is for data collected from the antenna for PRN 4, a satellite that was visible at the time of data collection. The middle plot in the top row is the result when using the unattenuated simulator signal. The right top row plot is for PRN2, another satellite also visible when using the antenna for data collection. Note that the ratios for these three plots are significantly less then for what is observed for the ideal correlation function in figure 3. Also note that the ratio for the simulated signal falls between the result computed for the two live satellites signals collected with the antenna. Thus it is possible to state that the simulated signal base power level used for testing are neither overly strong nor weak and correspond to current satellite power levels.

Second, this plot also show the results for these same signals or data sets when the integration time is increased to 5 ms. These results are shown in the bottom row of plots. As expected, the ratio value computed for each of the cases improves over the 1 ms integration as the noise bandwidth is reduced. Thus this observation is the basis for this investigation. Longer integration times should provide improved detection capabilities.

In figure 4, the correlation results are shown over an entire code period. As a result, the traditional correlation triangle appears as a "spike" in the resulting plot. It is both necessary and important to perform the correlation operation over an entire code period, testing all possible code phases, to determine the maximum as well as the second maximum in this range to compute a valid ratio. As such, these plots will be the basis for the

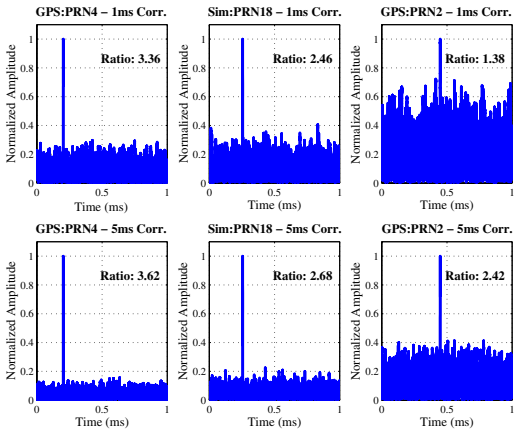

figure 4. Signal comparison

results presented in the paper. However, it is possible to zoom in around the spike from the above plots in figure 4. This is done in figure 5 and the more traditional correlation triangle is clearly illustrated.

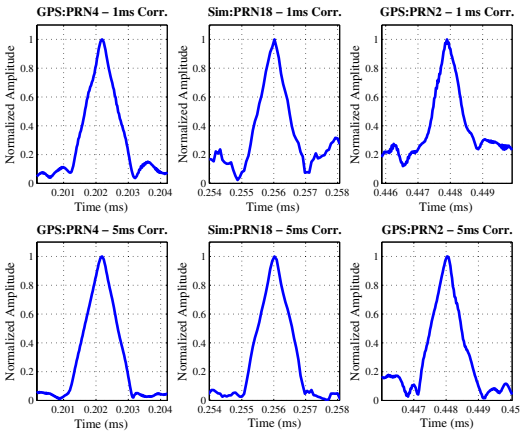

figure 5. Zoomed view of correlation peaks

UNAIDED ACQUISITION

Without knowing the data bits and using a constant carrier frequency assumption, unaided acquisition is performed.

The data bits puts a 10 ms upper limit of acquisition time with the GPS-SPS signal since they are bi-phase coded with the CA-code at a rate of 50 Hz. Each data bit is 20 ms long and acquisition of two consecutive 10 ms blocks assures that at least one block do not contain a data bit transition.

A data bit transition causes the correlation peak to lose power and the block that provides the largest peak is selected. If there is a data bit transition within the block, the correlation peak will be smaller as shown in figure 6.

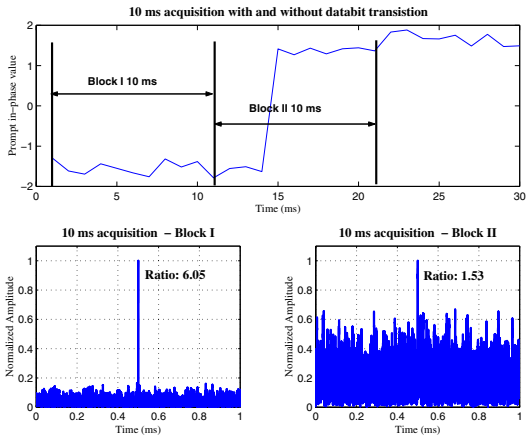

figure 6. Acquisition with & without data bit transition

The hardware configuration from figure 1 is utilized collecting multiple data sets. Each data set is taken using a different attenuation level. For the unaided acquisition case, attenuation levels of 0, 5, 10, 15, and 20 dB are tested and the results are discussed in the next section.

UNAIDED ACQUISITION RESULTS

For the no attenuation case the results are plotted in figure 7. With 1 ms of data, the signal is easily identified. Although there is no attenuation in either channel, the resulting ratio computation differs between the two cases. This is a result of the statistical nature of the noise present in the system. Also the ratio should be indicative of what could be expected for a true acquisition result.

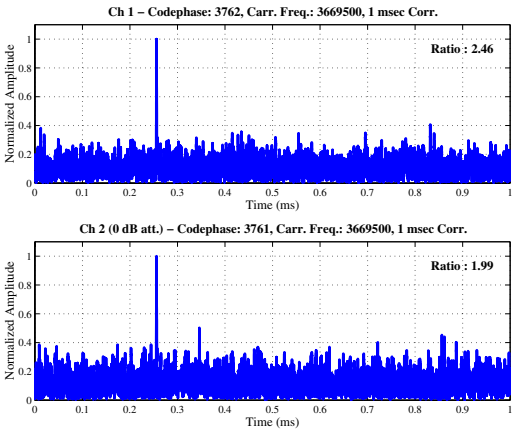

figure 7. 0 dB attenuation, 1 ms

With 5 dB attenuation, it is still possible to acquire the signal using only 1 ms integration times as illustrated in figure 8. Note that the corresponding ratio is reduced for the attenuated signal, yet the maximum peak occurs at the same location as that indicated for the "truth" reference which is the unattenuated signal in channel 1.

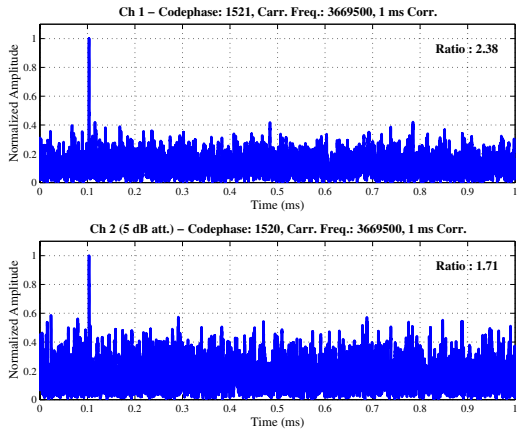

figure 8. 5 dB attenuation, 1 ms

For a 10 dB attenuation level, a 1 ms integration time is not sufficient to detect the signal as shown in figure 9. The maximum correlation spike is associated with the incorrect code phase and carrier frequency. Also, the ratio is close to 1, indicating a lack of confidence in this estimate.

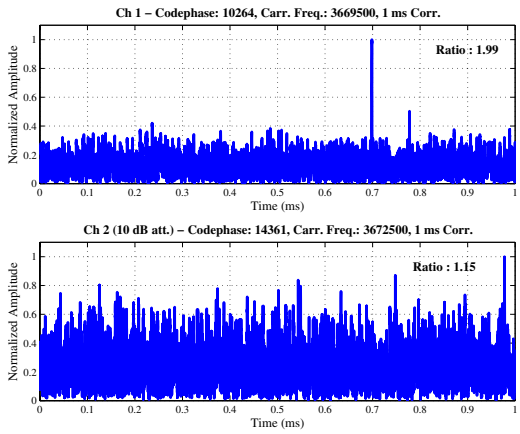

figure 9. 10 dB attenuation, 1 ms

If the integration time is increased to 2 ms, as is shown in figure 10, the true code phase estimate is determined.

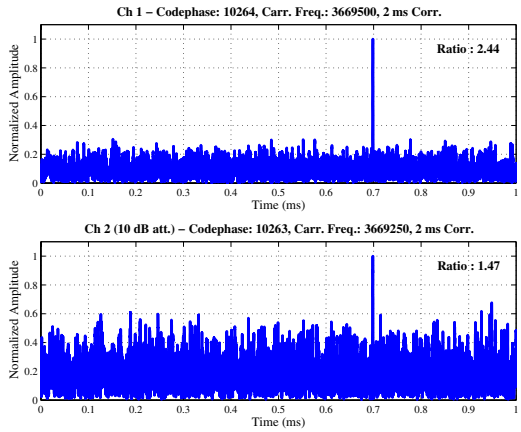

figure 10. 10 dB attenuation, 2 ms

With 15 dB attenuation, the signal could not be found using a 2 ms integration time. This is illustrated in figure 11. After testing integration periods successively, it is found that a 7 ms integration time is required to detect the signal with the correct code phase. This is shown in figure 12. Also note the impact on the unattenuated channel 1 results in this figure. As the integration time is increased, the ratio improves and the noise floor is visibly lowered.

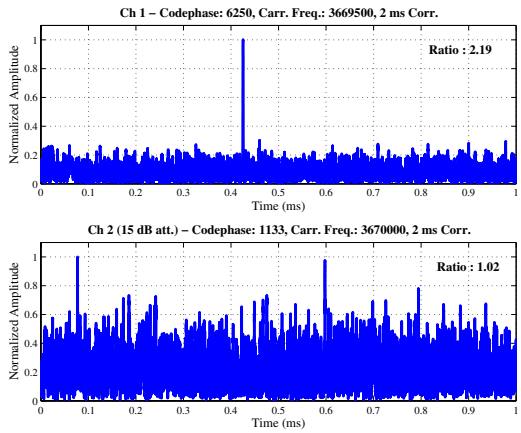

figure 11. 15 dB attenuation, 2 ms

Also note that using 7 ms of data enables the correct code phase to be determined. However, this is only clear as there is a truth reference for comparison. If it were necessary to make a judgment based solely on the ratio metric – results would be inconclusive.

As a result, increasing the integration time to 8 ms was tested and the results are shown in figure 13. As expected the true correlation result remains a maximum and the ratio improves. In this work, it is possible to declare a successful acquisition when the attenuated channel

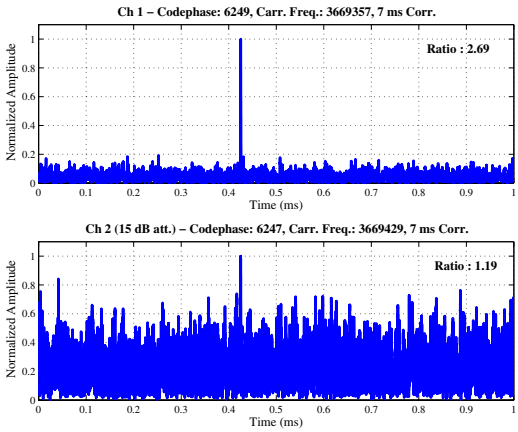

figure 12. 15 dB attenuation, 7 ms

2 result matches that obtained using the unattenuated channel 1 result. Should a truth reference not be available, estimation confidence can be derived from the ratio metric.

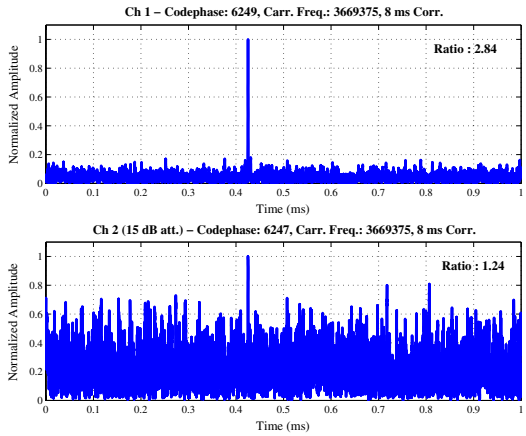

figure 13. 15 dB attenuation, 8 ms

For 20 dB attenuation case, it was not possible to detect the signal. This is true even if the maximum of 10 ms integration time is utilized. Therefore, in order to detect signals weaker than -142 dBm, it can be concluded that more than 10 ms integration times are required which implies that aided acquisition techniques should be applied.

A summary of the cases tested for unaided acquisition is displayed in table 1.

AIDED ACQUISITION

Aided acquisition implies an antenna with a clear view of the sky, and thus receives a strong satellite signal, can provide information to an antenna that is hidden and

Attenuation Level	Integration time of Channel 2
0 dB	1 ms
5 dB	1 ms
10 dB	2 ms
15 dB dB (≈ -142 dBm signal)	7, 8 ms
> 15 dB	> 10 ms

table 1. Unaided acquisition integration times

receives a much weaker GPS signal (under a forest canopy, passive ranging, inside etc). Acquisition aiding can be of various levels: navigation data bits, frequency information and local oscillator characteristics. All this information makes very long integration times possible for averaging the noise and improving the relative SNR.

Before the signal is correlated with the local CA code, it is necessary to downconvert it to baseband. This is a very important step particularly when considered with long integration times as the Doppler offset of the carrier estimate needs to be very accurate. For 10 ms integration time the carrier frequency should be within 25 Hz and for 100 ms integration time the carrier estimate should be within 2.5 Hz. The range of the carrier frequency is proportional to the integration time.

If the carrier estimate drifts away from that limit, the correlation function loses power. Since it is the local oscillator that controls the carrier frequency, its characteristics also need to be known. It does not matter how good the frequency estimate is if the oscillator cannot produce that exact frequency or has a large phase noise variance.

AIDED ACQUISITION RESULTS

For the aided acquisition trials, the attenuation levels were increased as was the case in the previous section. Since it has been shown that it is possible to detect signals with up to a 15 dB attenuation level, the starting point for the aided acquisition trials will begin with the 20 dB case. In addition, attenuation levels at 25, 30, and 35 will be tested over integration periods extending up to 800 ms.

The first aided acquisition trial was done working with the undetectable signal from the unaided case which was the 20 dB attenuation case. The initial integration time considered is 100 ms and the results are shown in figure 14. Note the significant improvement in the ratio for the unattenuated result. Even though this is still a signal in noise, the correlation function and corresponding ratio begin to approach the ideal case that was depicted in figure 3. Also note that the signal with 20 dB attenuation, or an approximate signal power of -147 dBm, is easily detected using the extended integration time.

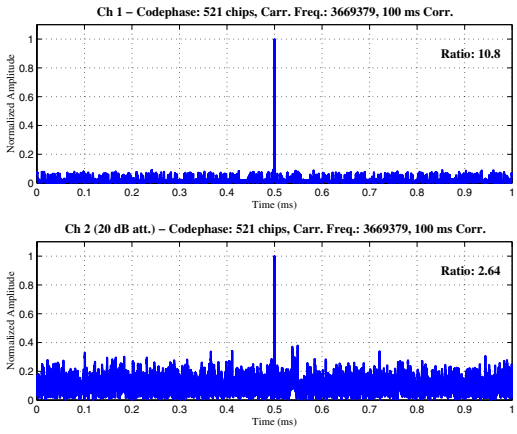

figure 14. 20 dB attenuation, 100 ms

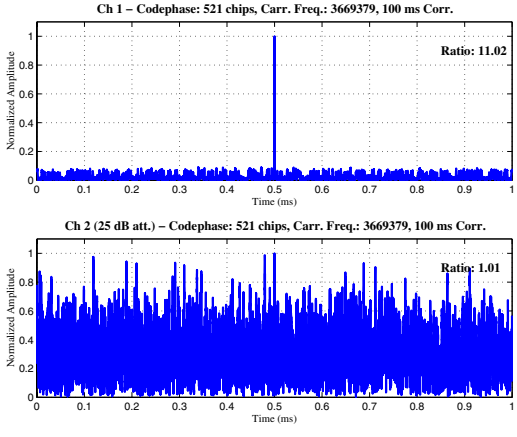

figure 15. 25 dB attenuation, 100 ms

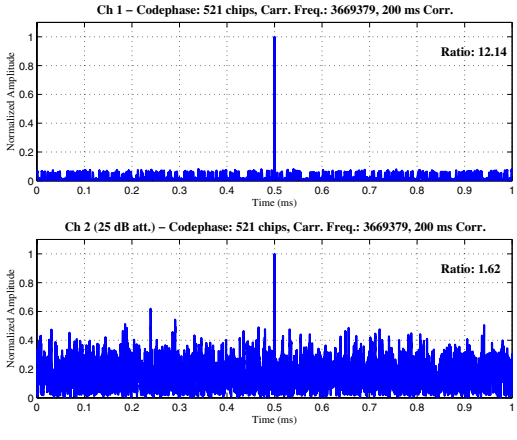

figure 16. 25 dB attenuation, 200 ms

When the attenuation level is increased by an additional 5 dB, 100 ms no longer provides enough noise averaging to determine the correct signal parameters. This is illustrated in figure 15. As such it is necessary to turn to longer integration times.

Increasing the integration time to 200 ms allows this signal to be detected as is shown in figure 16.

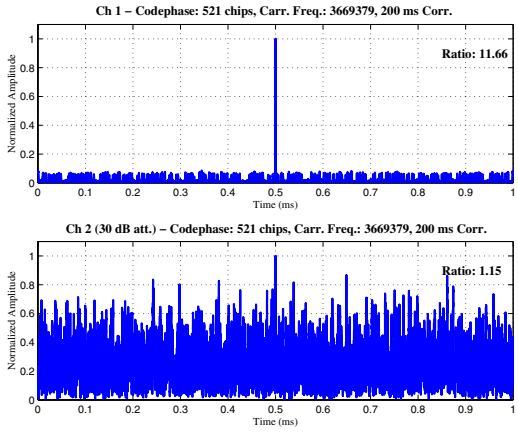

figure 17. 30 dB attenuation, 200 ms

Testing the 30 dB attenuated signal with a 200 ms integration time provides the correct code phase estimate as is shown in figure 17. However, the ratio is extremely low and does not provide confidence in the estimate. As such, the integration window can be extended. Since the truth reference is known, it is possible to plot the results only for the attenuated signal for the remainder of results rather than plotting both plots as has been done up until this point. The data will be plotted such that the true correlation peak should appear in the center of the plot as has been the case for all the aided acquisition results thus far.

Figure 18 shows the result of a 400 ms integration time. There is a distinct peak in the middle, but also a significant peaks to the right. These peaks are due to random nature of the noise, and reduces the ratio to 1.18 which is a low confidence value. Performing a 400 ms

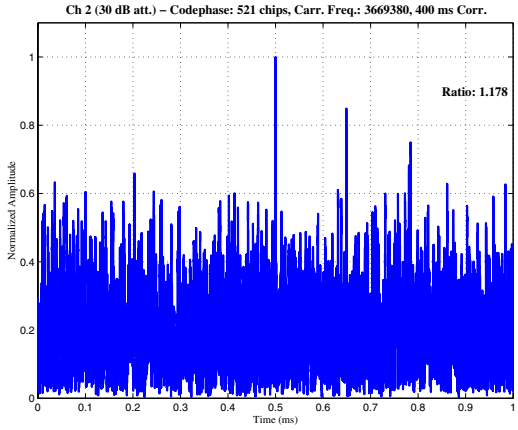

figure 18. 30 dB attenuation, 400 ms

integration time with a second dataset with the same attenuation would most likely show a greater ratio since these statistical extreme peaks would likely not be included.

Finally, a 800 ms integration time has been utilized to find a signal that is attenuated 35 dB (-162 dBm). There is a distinct peak and the ratio is 1.36 which in this case is enough to declare signal detected. This result is depicted in figure 19.

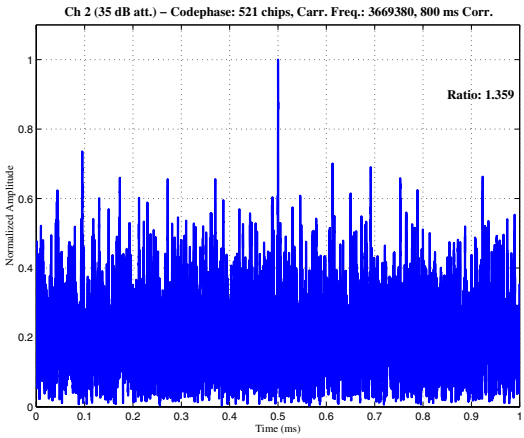

figure 19. 35 dB attenuation, 800 ms

Table 2 summarizes the attenuation levels and integration times used for find the signals with aided acquisition.

Attenuation Level	Integration time of Channel 2
20 dB	100 ms
25 dB	200 ms
30 dB	400 ms
35 dB (≈ -162 dBm signal)	800 ms

table 2. Aided acquisition integration times

SUMMARY

This paper has presented the experimental results of acquisition attempts for signals of nominal GPS power levels and below. Expected performance can be predicted by computing the noise power in a given bandwidth. Longer integration times provide improved noise averaging and that serves as the basis for weak signal detection. The difficulty with long integration times is the decorrelation that can occur as a result of potential offsets in oscillator frequency and phase. As a result the acquisition methods are divided into unaided and aided techniques. This paper presents power levels and the required integration times necessary to detect such signals. A ratio metric is utilized to indicate the confidence of those measurements.

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