Characterization of L5 Receiver Performance Using Digital Pulse Blanking

Joseph Grabowski, *Zeta Associates Incorporated*, Christopher Hegarty, *Mitre Corporation*

BIOGRAPHIES

Joe Grabowski received his B.S.EE from Carnegie-Mellon University and M.S.EE from Purdue University. Since 1990 he has worked at Zeta Associates Incorporated on various communications and digital signal processing projects as a systems engineer with the last three years concentrating on GPS applications. Previously he has worked at ESL Inc. from 1984 to 1990 and Harris Corporation from 1978 to 1982.

Dr. Christopher Hegarty received his B.S and M.S from Worcester Polytechnic Institute, and his D. Sc. from The George Washington University. He has been with The MITRE Corporation since 1992. He was a recipient of the 1998 ION Early Achievement Award, and currently serves as Editor of *Navigation: Journal of the Institute of Navigation*, co-chair of IGEB ad hoc Working Group 1 (Validation of L5 Coexistence) and co-chair of RTCA SC159 Working Group 1 (3rd Civil GPS Frequency).

ABSTRACT

In November 1999, the Interagency GPS Executive Board (IGEB) endorsed a set of recommendations for implementation of the third civil GPS frequency (L5) that included specific measures to be taken within the United States to ensure that L5 can coexist with government systems operating at the same or nearby frequencies. The L5 frequency (1176.45 MHz) is located in a band that includes many pulsed emitters. To minimize the impact of L5 on existing systems, the IGEB has recommended that GPS L5 receivers incorporate increased receiver sensitivity and pulse blanking. Further the IGEB sponsored the development of a prototype L5 receiver implementing digital pulse blanking in order to test and evaluate practical implementation issues for this approach. The goal of this effort was to establish design criteria for successful implementation of digital pulse blanking. This paper describes those design requirements along with results characterizing the prototype receiver performance. Testing included laboratory testing under controlled conditions and also tests in simulated environments expected to present the most difficult scenario for the pulse blanker. Furthermore, implementation of digital pulse blanking is independent of the Radio Frequency (RF) and thus can provide benefits to GPS receivers operating at frequencies other than L5, in particular L2 with its known dense pulsed environment.

INTRODUCTION

In November 1999, the Interagency GPS Executive Board (IGEB) endorsed a set of recommendations for implementation of the third civil GPS frequency (L5) [1] that included specific measures to be taken within the United States to ensure L5 coexists even with systems operating in the same 960 – 1215 MHz Aeronautical Radionavigation Services (ARNS) frequency band. These recommendations not only included system issues related to the L5 signal and reassignment of select Distance Measuring Equipment (DME)/Tactical Air Navigation (TACAN) near L5 [2] but also user equipment implementation. In particular, recommendations for these L5 receivers included the following:

1. Incorporate amplifiers capable of handling higher power levels and recovering from saturation more quickly.
2. Provide greater selective filtering at the front end of the receiver to minimize the effects of any nearby pulsed interferers.
3. Implement blanking, i.e., zero the received signal prior to subsequent processing when its amplitude exceeds a threshold indicating the presence of pulsed interference.

Previous efforts validated some of these recommendations through software simulation and also by building a prototype receiver operating at L1 that implemented pulse blanking using an analog technique [2]. Those test results indicated that analog pulse blanking implementation requires great care to achieve maximum blanking performance especially for short duration pulses. Digital pulse blanking was expected to be less expensive and easier to implement. Consequently, the IGEB agreed to sponsor the development of an L5 prototype receiver that included the above recommendations. Characterization of this receiver performance also required the development of an L5 simulator (single channel) to produce an L5 signal.

HARDWARE DESCRIPTION

A prototype L5 simulator and L5 receiver were developed to demonstrate the viability of digital pulse blanking and to identify any additional design requirements for L5 receivers. Development of an L5 simulator was required since L5 signal sources are not yet available. Simulator design requirements were limited to the minimum needed for the intended L5 tests. While the L5 simulator generates an L5 signal in full compliance with the proposed signal structure [3], it only generates a single channel of any one of 32 possible pseudorandom noise (PRN) code pairs and without Doppler. Data and navigation messages can be updated under host computer control but for test purposes (at this time) were left static.

Both the L5 simulator and L5 receiver were built by NovAtel Incorporated and are based on their OEM4 receiver technology. Additional circuits were added to an existing OEM4 to incorporate the IGEB recommendations and to operate at L5. New analog circuitry replaced the OEM4 RF front end and provided more selective filtering and amplifiers capable of higher power. The new digital functions (not found in GPS receivers) were implemented within an FPGA that was added to the OEM4.

Figure 1. L5 Receiver with Cover Off

An L1 GPS receiver was also included within the L5 chassis for two purposes, provide a time source for logging of data and also position information. One test scenario considered for the L5 receiver is a flight test on an airplane over areas predicted to have dense pulse interference environments. In such a test environment, establishing GPS time will be necessary for data collection operations.

Digital pulse blanking (DPB) was implemented by zeroing on a sample-by-sample basis. Rather than implement a pulse detector circuit to determine the edges of any potential pulse and then zero out a contiguous sequence of samples, a much simpler technique was used. Here individual samples are compared against a user specified threshold and are zeroed if the threshold is exceeded. This approach has several advantages; it is much simpler to implement, it does not require a pulse detector circuit to identify the beginning and end of an individual pulse, and it does not require memory to also track samples that are part of a pulse. There are some minor disadvantages with this technique. The loading of the analog-to-digital (A/D) converter is a Gaussian distribution and there is always the possibility that some samples will exceed the threshold even when no pulsed interference is present. When strong pulsed interference is present (pulses greatly exceeding the background noise) some of the samples during the pulse will be below threshold. The optimal approach to minimize pulsed interference is to zero out all samples during the pulse on-time. Neither of these limitations was expected to significantly reduce the benefits of blanking on a sample-by-sample basis. The percentage of samples exceeding expected thresholds was so small that signal loss was expected to be less than 0.2 dB. Simulations indicated that, when pulsed interference was present, zeroing on a sample-by-sample basis would also approach the predicted blanking performance with only minor loss.

An A/D converter sampling at 56 MHz with 8 bits of resolution was used to convert the receiver analog intermediate frequency (IF) to digital samples. The sample clock was chosen to process the wider L5 signal bandwidth and also determines the shortest pulse duration that can be identified and zeroed. Even though pulses shorter than the sample clock cannot be readily identified and zeroed, they also occupy bandwidths greater than the receiver processing bandwidth and therefore are reduced in amplitude and spread out over time. Sufficient spreading reduces their impact on processing and also reduces the need to blank them.

A functional block diagram of the digital data path for DPB is shown in Figure 2. There are two independent channels shown and each was assigned separate channel numbers 10 and 11 within the receiver. Each channel can use a different threshold or none at all. DPB was performed immediately after the A/D output where the DPB threshold was selectable with a resolution of 7 bits (ignoring the sign bit). The resolution available is considered significantly greater than necessary but was implemented since it was straightforward with this receiver. DPB statistics (such as number of samples blanked) are accumulated within the DEBUG function. After the

DEBUG function the 8 bit data samples are reduced to 3 bits for further processing by the AGC and correlators. A pulse detected data line is synchronized with each data sample and indicates whether or not that sample exceeds threshold. Subsequent processing can use the pulse detected signal and under software control either include or exclude samples that are tagged as including a pulsed interference component.

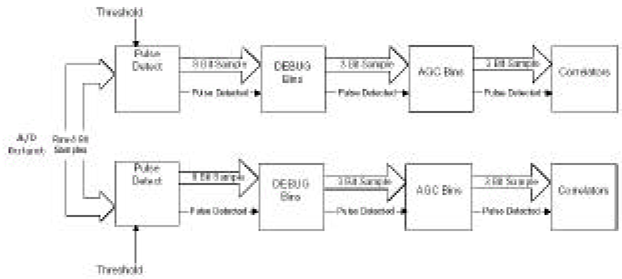

Figure 2. Digital Pulse Blanking Data Flow

The two independent channels are included in the prototype design to allow simultaneous testing of performance with and without pulse blanking. This feature makes it easier to compare receiver performance for a given test configuration without having to repeat tests. Most tests were conducted with one channel configured for pulse blanking and the second with pulse blanking disabled.

Automatic Gain Control (AGC) was a design concern since DPB inherently removes energy while the purpose of an AGC is to maintain constant power. If the AGC used all samples prior to DPB or just after DPB it can improperly load the A/D when pulsed interference is present. Using samples prior to DPB will include the pulse energy and reduce A/D loading while using samples after DPB will include zeroes and potentially set A/D levels too high. Samples that are zeroed should not be used in determining the correct AGC level. The desired AGC level is one that loads the A/D based on noise only. Consequently an additional receiver requirement was for AGC to only use those samples that were not blanked. Excluding samples that have been blanked prevents them from affecting the loading of the A/D. The L5 receiver AGC can be programmed to use either all of the samples or only those below the threshold.

Expected test scenarios require not only the L5 simulator and noise but also various pulsed interference sources. To simplify testing, multiple ports were provided on the L5 receiver input and essentially placed a summing device within the L5 receiver chassis. A total of three input ports were provided. One port was used for the L5 simulator, a second port to set the reference noise floor and a third port to sum in pulsed interference signals.

TEST DESCRIPTION

Numerous tests were carried out to characterize the L5 receiver performance. Some of these were intended to verify the basic functionality of the receiver while others determined the receiver performance when exposed to pulsed interference signals.

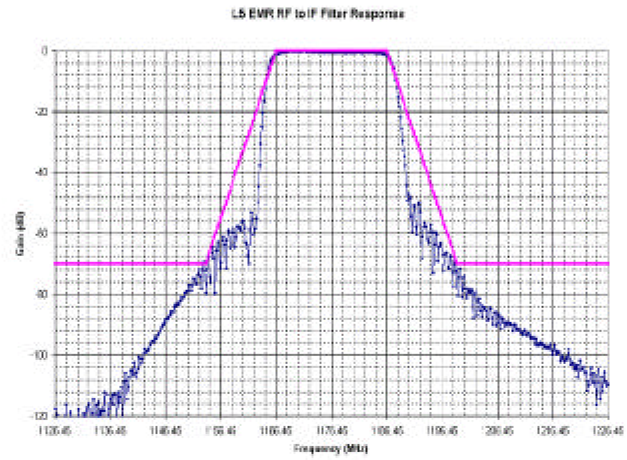

Figure 3. L5 Receiver Frequency response

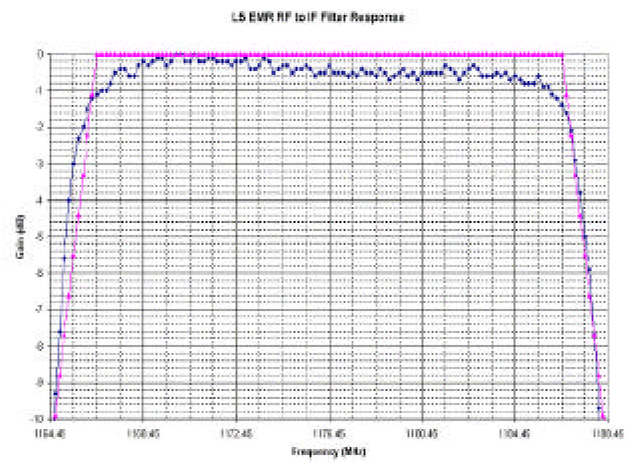

Figure 4. L5 Receiver Frequency Response (Zoom)

Figure 3 shows the measured frequency response of the receiver RF up to the A/D input while Figure 4 is an expanded representation of the passband. The frequency response includes the cascaded response of RF filters and a surface acoustic wave (SAW) IF filter. Also included in these figures is the recommended mask that L5 receivers should meet. The prototype receiver was slightly outside of the mask requirements for some frequencies. Tighter responses can be readily achieved by using a narrower IF filter. This receiver was allowed to approach and slightly exceed the recommended mask to assist in determining selectivity effects on receiver performance.

Tests were also carried out to determine the effects of varying the pulse blanking threshold. Figure 5 shows the A/D sample distribution along with the mapping of the 7 bit threshold. C/N_0 data was recorded from the receiver while adjusting the threshold over its full span. No pulsed interference was present for this test. Predicting the degradation in C/N_0 is accomplished by first determining the percentage of samples exceeding threshold and then computing the resulting signal loss using Equation 1. This equation assumes that for a pulse that exceeds threshold all contiguous samples during the pulse on-time are zeroed. Predicted losses versus DPB threshold are shown in Figure 6 using Equation 1 [4].

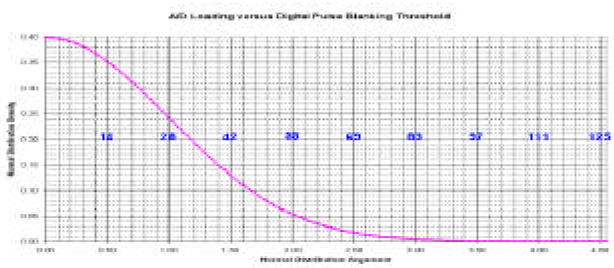

Figure 5. A/D Loading and DPB Threshold

$$C/N_0\,(loss) = 10 * LOG(1 - P_{DCB})$$

where P_{DCB} = Duty Cycle Fraction Blanked

Equation 1. Strong Pulse Predicted Loss

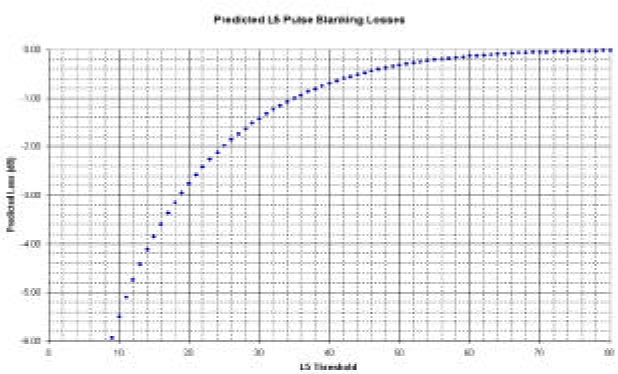

Figure 6. Predicted C/N_0 Loss vs. DPB Threshold

Figure 7 and Figure 8 are the results from varying the DPB threshold without pulsed interference present. The test shown in Figure 7 had the AGC held constant while results where the AGC was allowed to update are shown in Figure 8. Both receiver channels were used with one channel not blanked (curves labeled "Normal") and the second channel blanking (curve labeled "DPB"). When the AGC was enabled the degradation in C/N_0 was not as much as when the AGC was held constant. The results for AGC enabled are close to those predicted by Equation 1 and shown in Figure 6. When the AGC is held constant and a high percentage of samples are zeroed, the resulting A/D loading is significantly different from desired and is most likely the explanation for this result.

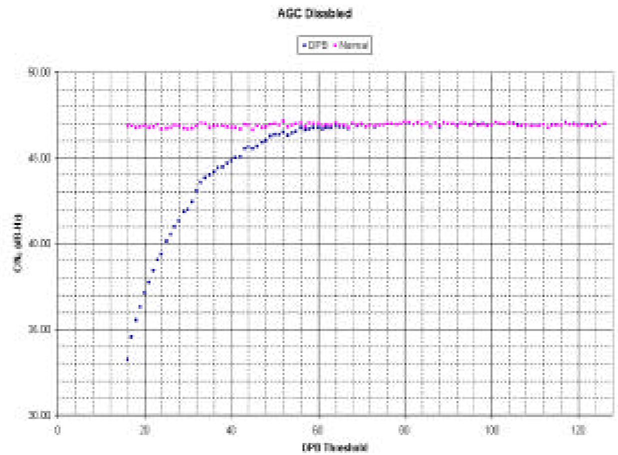

Figure 7. Measured C/N_0 Loss vs. DPB Threshold with AGC Disabled

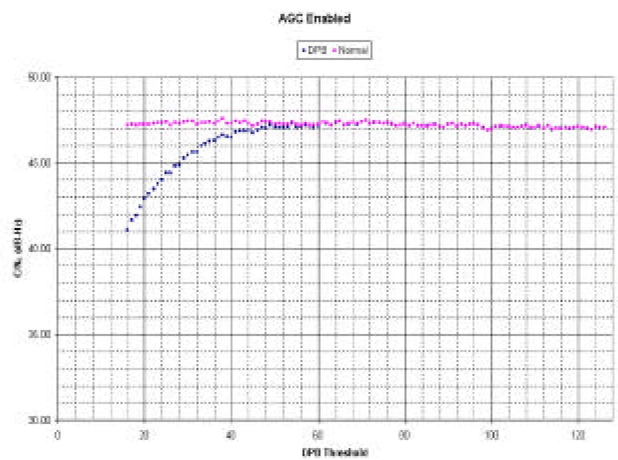

Figure 8. Measured C/N_0 Loss vs. DPB Threshold with AGC Enabled

Acquisition tests were conducted to determine the time to first acquisition. The L5 simulator was restarted repeatedly while monitoring L5 receiver logs for tracking of the L5 signal. For each trial, the time from L5 simulator restart until acquisition of the L5 signal by the L5 receiver was recorded. Results were accumulated within histogram bins of 5 second intervals and then plotted by the number of acquisition counts versus acquisition time and are shown in Figure 9. Even though the acquisition tests were conducted with a relatively strong L5 C/N_0 of 46 dB-Hz the time to first acquisition could be relatively long and in some cases greater than 300 seconds. Further investigation will be carried out to determine whether or not this is due to a receiver implementation issue.

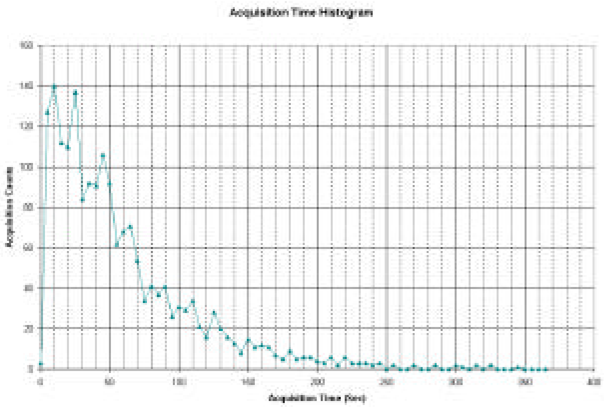

Figure 9. Acquisition Trial Histogram

Controlled pulsed interference tests were carried out in a laboratory environment to carefully characterize L5 receiver performance. These tests used square pulses with pulse widths from 100 microsecond to as little 1 microsecond and duty cycles from as little as 2.5% to as much as 80% in steps of 2.5%. The typical test scenario collected data without any pulsed interference for a fixed amount of time followed by the same time interval with pulsed interference at a fixed duty cycle. Subsequent intervals increased the duty cycle by 2.5% while maintaining the pulse width and interference level. Data collected included receiver C/N_0 for both blanked and non-blanked channels. An example plot of recorded C/N_0 versus time for a given test of this type is shown in Figure 10 and Figure 11.

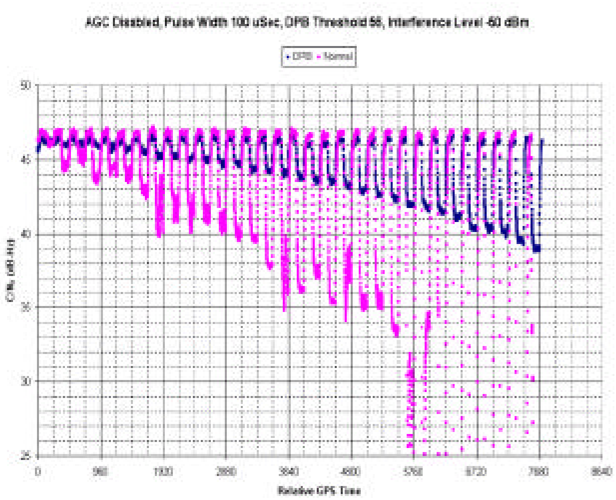

Figure 10. C/N_0 vs. Increasing Pulse Duty Cycle with AGC Disabled

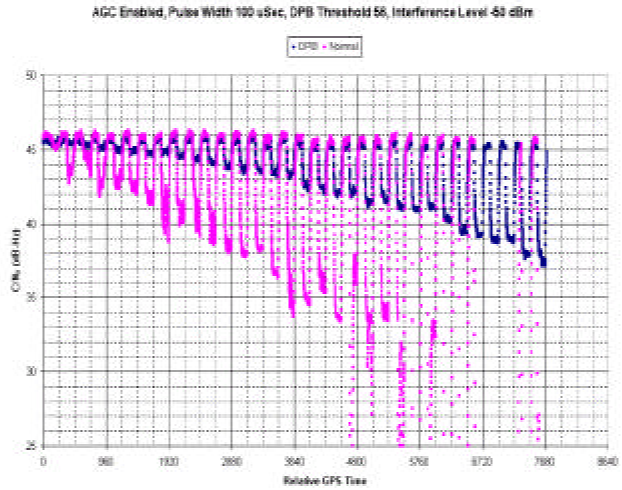

Figure 11. C/N_0 vs. Increasing Pulse Duty Cycle with AGC Enabled

Major grids along the horizontal axis in these figures coincide with intervals of 10% duty cycle while minor grids coincide with 2.5% duty cycles. For example, a relative GPS time of 1920 is the completion of a 20% duty cycle. The curves labeled "Normal" refer to the non-blanked channel while those labeled "DPB" the blanked channel. In this particular test case it is readily apparent that the channel without blanking had significant reduction in C/N_0 compared to the blanked data especially for higher duty cycles. Losses for the DPB channel on the other hand follow closely the predicted curve calculated using Equation 1.

Results from numerous test cases are shown in Figure 12 and Figure 13. Predicted losses versus duty cycle are based on analysis described in [4] and are shown in these figures as a solid line. Individual colored data points come from specific test cases and span puls e widths from 100 microseconds to 1 microsecond. Figure 12 shows results when the AGC was held constant while Figure 13 is for the case where the AGC was allowed to update. When the AGC was allowed to update it only used those samples below threshold. An interesting result for AGC enabled is that at even high duty cycles of 80% the non-blanked channel continued to track the underlying L5 signal.

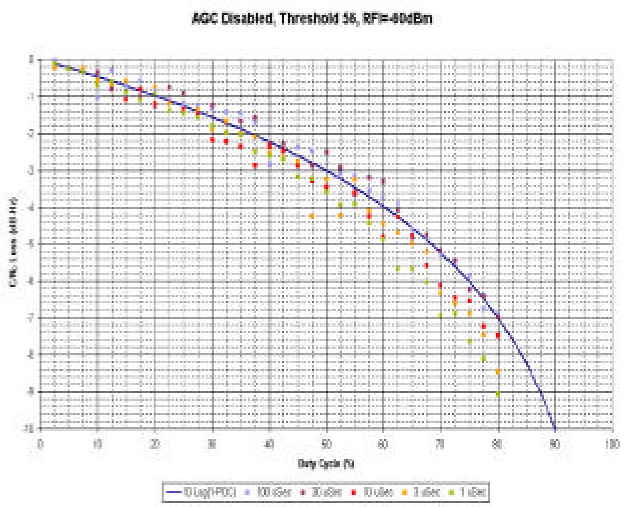

Figure 12. C/N_0 Loss vs. Pulse Duty Cycle with AGC Disabled

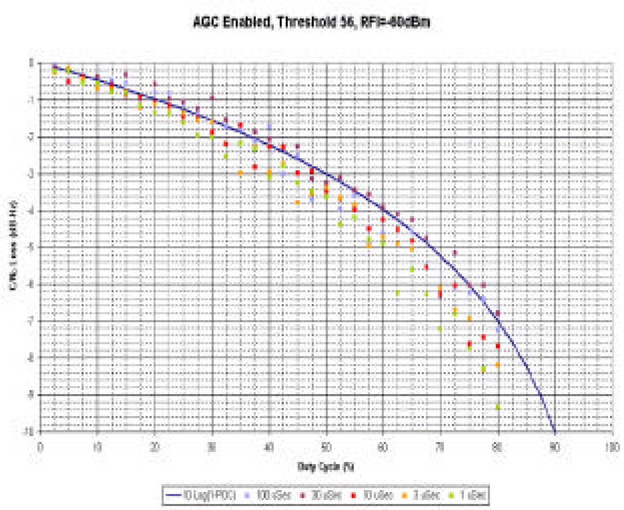

Figure 13. C/N_0 Loss vs. Pulse Duty Cycle with AGC Enabled

The ability for the receiver to continue to operate with a significant number of samples removed can be attributed to the robustness of the signal design.

SUMMARY

The development and testing of an L5 receiver that implemented IGEB Working Group 1 recommendations has demonstrated the feasibility of building such a receiver using current receiver technology. Digital pulse blanking has been shown to perform in accord with theory while using a simple method of blanking on a sample-by-sample basis. An interesting finding has shown that AGC operation can be reliable as long as only non-blanked samples are used to update the AGC.

Further testing of this receiver is planned and is expected to include:

1. Additional tests in a laboratory setting using additive white gaussian noise.
2. Flights over areas predicted to have dense pulse interference environments that expose the L5 receiver to pulsed interference environments.
3. Simulated DME/TACAN pulsed interference environments.
4. JTIDS simulator tests using various dense pulsed interference scenarios performed in cooperation with JSC.

ACKNOWLEDGEMENTS

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