Comparison of Continuity and Integrity Characteristics for Integrated and Decoupled Demodulation/Navigation Receivers

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BIOGRAPHY

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Abstract

Signal fault events such as momentary blockages on low elevation satellites could jeopardize the continuity and integrity of GPS guidance. Classical receivers are especially vulnerable given their isolated error detectors and loop filters for each channel. By contrast, an integrated receiver's correlator data on all satellites is optimally tested and combined leading to a substantial suppression of cycle slippages during signal faults. The trade between continuity and integrity becomes more favorable with additional satellites/pseudolites. Proving this assertion required the integrated receiver's tracking performance be verified with differing signal geometries since, analogous to RAIM, performance is geometry dependent.

The classical decoupled receiver structure is contrasted with the integrated approach for a variety of geometries and signal faults. A signal fault continuity (SFC) definition is established encompassing accuracy and vertical protection limit (VPL) values to be satisfied during and immediately after signal fault events. Each satellite constellation is scanned to identify times of greatest vulnerability. In blockage testing geometries for which a sequential blockage on the two lowest elevation satellites could lead to SFC loss are identified. In spoofing tests the disrupted satellite was selected on the basis of VPL maximization.

In both blockage and spoofing tests the conventional receiver consistently loses continuity, whereas a high fraction of the time the integrated design provides seamless tracking, even with the difficult geometries. The impact of faults introduced at random times throughout the day is also ascertained, with substantial improvement for the integrated technique.

Introduction

Differential GPS has scored impressive successes in demonstrations of category III aircraft approach and landing **[1-3]**. However, signal fault events such as momentary signal blockages could jeopardize the continuity and integrity needed for this stringent landing category. Indeed, instances of momentary losses of low elevation satellites on final approach have been reported **[4, 5]**, suggesting that as more experience is gained with these systems additional safeguards may be desired. Some researchers have suggested inertial reference combining or aiding to offset the impact of reception events on continuity and integrity **[6]**. A less expensive alternative appears to be improved integration of receiver signal tracking and navigation elements.

Classical GPS receivers recover their carrier phase and pseudorange parameters from independent satellite tracking channels, with raw correlator data processed in separate error detectors. By contrast, in integrated receivers correlator data from all satellites is jointly monitored and combined **[7-9]**. A more complete statistical model as well as high quality differential corrections at an earlier point in the receiver permits rapid response to signal quality conditions, and seamless tracking across faults. With cycle slippages to some degree suppressed during signal fault events, the trade between continuity and integrity becomes more favorable. Unlike the classical structure, as additional satellites/pseudolites become visible the signal tracking performance improves on all satellites .

In order to better understand and evaluate receiver performance in the precision approach regime we first establish a signal fault continuity (SFC) criteria. Following this signal blockage scenarios are developed, and the two architectures are evaluated for periods of poor geometry with low elevation blockages and spoofing. The performance of the two processors is ascertained by a full tracking simulation, including tracking non-linearities. The paper concludes with an analysis of continuity for faults appearing at random times throughout the day.

Performance Criteria

In establishing a useful notion of continuity for short-duration signal fault events the classical DDN GPS avionics structured shown in **Figure 1** was examined. The individual tracking loops responsible for each satellite are protected by local lock monitors (LLM's) where the onset of carrier mistracking is detected by comparing local residuals against a break-lock threshold. These detections are conveyed to the central navigation filter where defective carrier or carrier smoothed code data is blocked prior to navigation. The LLM's are limited in their effectiveness since external data such as differential corrections, navigation state variables and satellite geometry are ignored in their decision making processes. Consequently a second line of defense is needed, the central fault detection and exclusion (FDE) algorithm. While the LLM can respond to signal reception events such as blockage, attenuation and the like, it is the job of FDE to backstop these decisions, and to detect other errors unrelated to signal blockage and spoofing, such as spacecraft or DGPS ground segment problems. Given an internal alarm condition from either or both LLM and FDE elements the avionics must decide whether a continuation of the approach is warranted. The avionics will primarily consider two factors:

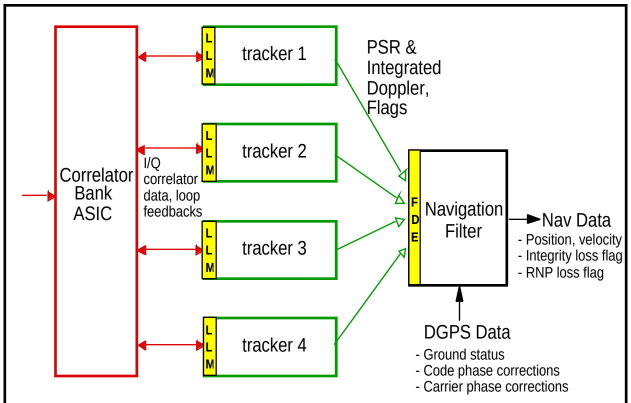

Figure 1 Classical Decoupled Demodulation/ Navigation (DDN) structure

- With the faulty tracking channel excluded is the estimated vertical navigation system error (NSE) be tolerable, and

- With the faulty tracking channel excluded is the computed vertical protection limit (VPL) still adequate.

The receiver's decision is very dependent on available geometry and the required NSE and VPL system specifications. In many circumstances the affected satellite may simply be excluded for the remainder of the final approach, with predicted NSE and VPL values sufficient to meet all landing safety requirements. As will be shown however there are a substantial number of geometries where a signal mistracking detection and channel exclusion event results in a loss of NSE or VPL. Such a circumstance is shown generically in **Figure 2**. Following a reception event and detection/exclusion, estimated NSE and VPL degrade. While perhaps tolerable for the short period of signal fluctuation the loss of NSE or VPL may persist for an unacceptably long period needed for reliable recovery and repair of the affected channel. Recovery following the event is not instantaneous, and during this interval system continuity is lost. Certainly one solution is to supplement the GPS avionics with IMU inputs, at a cost and complexity unacceptable to many users **[6]**. Another alternative is to suppress cycle slippage and mistracking for the duration of the signal fault event, thereby reducing the tracking loop recovery and repair time to zero. As one would anticipate the ability to accomplish this seamless tracking depends very much upon the satellite geometry available at the onset of the signal fault event.

The alternative structure is shown in **Figure 3**. The major difference from **Figure 1** is a single central processor for evaluation, weighting and processing of raw I and Q outputs from all available satellites. This approach has been studied previously **[7-9]**. The weighting of raw data is varied rapidly in proportion to estimated signal strength and quality. With a full system state model involved in raw data evaluation, phase detection and correlator control, the structure offers a better chance of early fault detection and exclusion of faulty data, without tracking disruption. The internal covariance model carried forward is very useful in predicting performance. However its validity in the difficult reception conditions warrants a full non-linear tracking simulation and/or hardware bench test. In this paper the simulation technique, **Figure 4**, incorporates an analytical model for the correlator bank followed by operational receiver software. Signal fault events of various types are accurately introduced, including blockage, spoofing, and narrow and wide-band interference. We now turn to a comparison of receiver structures.

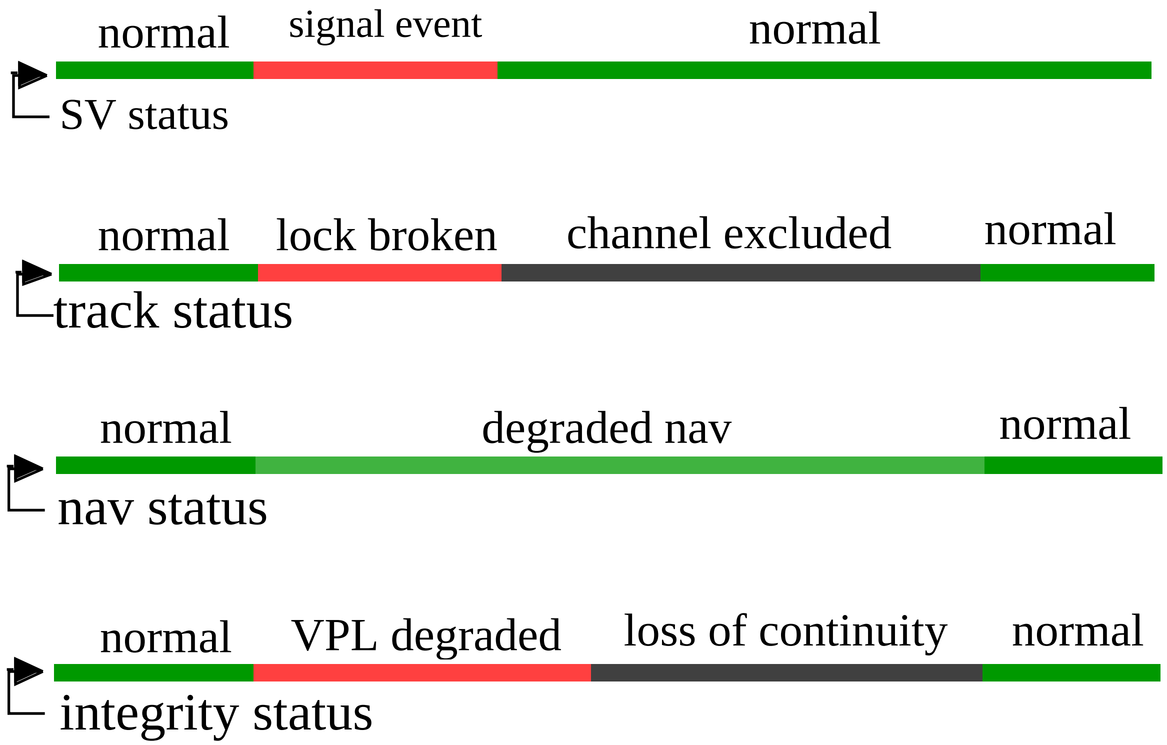

Figure 2 Typical Loss of Continuity Failure Mode

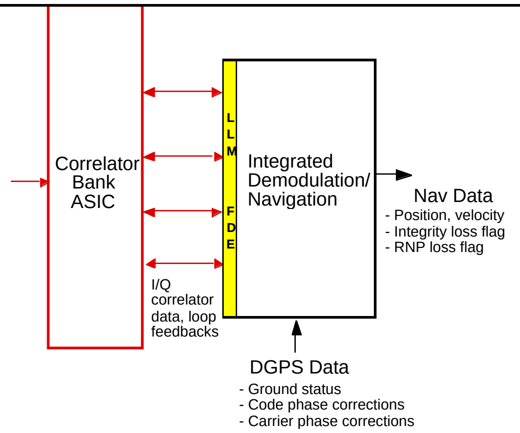

Figure 3 Integrated Demodulation/Navigation (IDN) structure

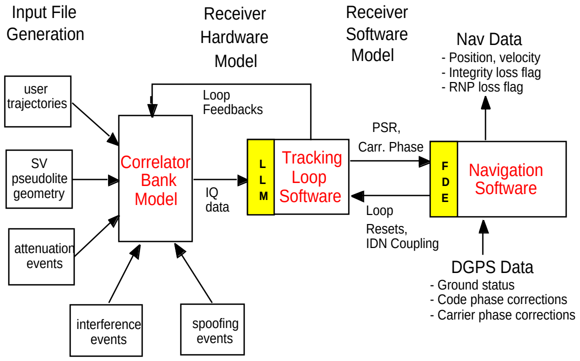

Figure 4 Signal Environment Receiver Simulator

Blockage Tests

While the frequency of occurrence of short attenuation events on final approach due to vehicle blockage or other events has as yet to be carefully studied, it seems that low elevation satellites are most likely to be affected. Therefore a basic outage scenario consisting of attenuations on the lowest two satellites was introduced. Starting with a converged carrier phase navigation solution good to 0.1 meters, the first satellite was attenuated by 20 dB for a duration of two seconds. Following signal amplitude recovery the second satellite was attenuated by the same duration, followed by recovery. In both cases the amplitude fluctuation rate was 100 dB/sec, demanding responsive amplitude estimation and gain adaptation.

In order to further challenge the receivers a geometry screening was carried out in order to ascertain “poor” geometries, those for which mistracking on both attenuated satellites would result in a VPL value greater than 0.5 meters, 95 percentile. The fault detection false alarm rate was 10^{-5}. VPL computations were carried out using well established techniques **[10,11]**. Under these difficult reception condition many candidate “poor” geometries were identified for simulation. Those geometries not so identified would not have resulted in excessive VPL, and loss in SFC continuity, unless false alarms occurred in either the LLM or FDE stages of the receiver. In the present tests these false alarm induced continuity losses were dominated by true outage events and were thus ignored. Three different constellation scenarios were screened: the existing 25 satellite constellation, at 15 and 7.5 degree mask angles, and the 25 satellite constellation at a 7.5 degree mask angle with four satellites removed .

Simulation runs and results were then grouped by number of satellites tracked prior to the signal fault introduction. During receiver simulations continuity was declared lost under the SFC definition if vertical NSE was greater than 0.3 meters following the reception event. The ability to maintain SFC continuity was tabulated for all three constellation assumptions, and averaged to determine overall the continuity versus number of available satellites prior to the reception event. The results are shown in **Figure 5**. It should be noted that in all cases the

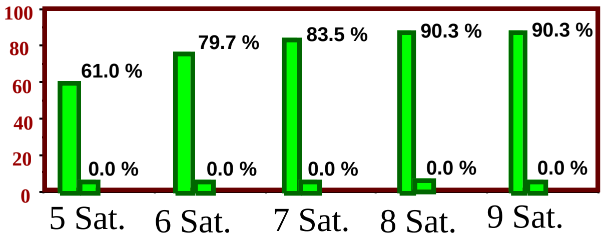

Figure 5 Continuity Results with Blockages on Worst Case Satellites

Table 1 Blockage Continuity Results, Averaged over All Sample Times

25 SV 7.5 deg. elev.	IDN	99.7 %
	DDN	98.7 %
25 SV 15 deg. elev.	IDN	92.5 %
	DDN	77.6 %
21 SV 7.5 deg. elev.	IDN	99.1 %
	DDN	93.5 %

DDN structure failed, its success rate with screened geometeries being zero. The most common failure mode being a mistracking on both satellites and a subsequent loss after channel exclusion of the 0.5 meter protection limit. By contrast the IDN structure suppressed signal mistracking in many cases, providing continuous service throughout the severe double blockage 79 percent of the time given six satellites. Even with just five satellites prior an event, when any outage immediately results in unbounded VPL and continuity loss, service is continued 62 percent of the time.

In those situations in which IDN fails to suppress mistracking there is a potential for integrity loss. However these false dismissals are protected in two ways. First, the snapshot fault detection available at the start of the event is used upon amplitude recovery at event conclusion to verify whether the fault suppression was successful. Secondly, and more significantly, the central phase error covariance model maintained by IDN reflects the entire signal amplitude history.

Finally, the overall results for each of the three constellations for both good and bad geometries, sampled over 24 hours at five minute intervals, is shown in **Table 1**. Instead of worst case values, these can be interpreted as probabilities of maintaining continuity with the introduction of a signal fault at some random time of day. Perhaps most dramatic in comparing the two receivers is a continuity improvement from 78 percent to 92 percent, for the 25 satellite geometry at a 15 degree mask, and from 93 to 99 percent for the 21 satellite geometry at 7.5 degree mask.

Spoofing Tests

Spoofing presents a somewhat different challenge to the signal processor. By definition the spoofer is able to generate a GPS look alike signal on one or more satellites. With the exception of an extremely sophisticated spoofer able to generate just the right Doppler-delay offset needed to convince the avionics of a valid position, spoofing is easily detectable and excluded. However, this still poses difficulties for continuity. First, the receiver must properly identify the channel damaged by the spoofer. This may require sufficient geometry to support both fault detection and exclusion in the central processor, since the LLM by may fail if the loop is captured. Secondly, assuming the bad channel to be identified, the remaining satellites may be insufficient to support either the accuracy or VPL conditions needed for SFC.

The spoofer in our simulations was tuned to appear in the central delay-Doppler cell of the correlator bank for a two second period, its maximum amplitude equal to the true signal amplitude. Prior to carrying out simulations three constellations were screened. At each time sample point the visible satellites were scanned to find the one which, when removed from the constellation, led to the worst vertical protection limit (VPL). As previously all faulted geometries with a VPL greater than 0.5 meters were flagged for full receiver simulation. Thus, for the selected geometries, once signal mistracking takes place continuity is lost.

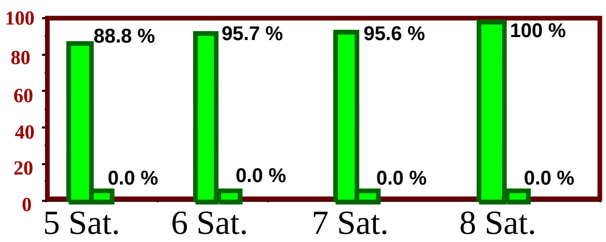

Figure 6 Continuity Results with Spoofer on Worst Case Satellite

Figure 6 summarizes continuity for the selected "poor" spoofing geometries. In all cases the DDN structure fails to provide continuity. The

IDN however is able to detect and suppress the effects of the spoofer, with full VPL and accuracy recovery upon termination of the spoofing event. With five satellite geometries the success rate is at 89 percent, rising to 96 percent with six satellites.

As for blockage the continuity statistics associated with introduction of a spoofer at a random time of day are also of interest, **Table 2.**

Table 2 Spoofing Continuity Results, Averaged over All Sample Times

25 SV 7.5 deg. elev.	IDN	99.96 %
	DDN	99.69 %
25 SV 15 deg. elev.	IDN	99.29 %
	DDN	93.73 %
21 SV 7.5 deg. elev.	IDN	99.93 %
	DDN	98.71 %

The most dramatic effects are seen with the 25 satellite constellation, at 15 degree mask, with the SFC increasing from 93.7 to 99.3 percent in switching from DDN to IDN processors. Note that in making this comparison we've made the optimistic assumption in favor of DDN that the LLM and central FDI are sufficient for exclusion of the spoofed satellite. Strictly speaking this may require that DDN have available the stronger geometry needed for fault exclusion, thus further degrading average performance.

Conclusion

As more experience is gained in Cat III approaches under a variety of aircraft and airport environmental conditions, robust techniques for signal tracking may be required. An attractive approach, with respect to both performance and cost, is full integration of the receiver's demodulation and navigation functions. This IDN technology appears to be especially effective in scenarios with rapid signal blockages and spoofing, allowing for near seamless tracking with difficult geometries. Preliminary results also indicate some jamming margin improvement. In summary, the GPS constellation offers us a great deal of strength in overcoming signal faults without loss of continuity, provided we apply wisely all available information in the signal tracking process.

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