PRN-21 Carrier Phase Perturbations Observed by WAAS

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BIOGRAPHY

Mr. Stephen Gordon received a B.S. in EE from Bucknell University. He began working on the FAA WAAS program in 1999 focusing on testing of system performance during the development phase of the system. For the past two years, he has worked for the WAAS Operations Group where he monitors for, and investigates anomalies.

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Mr. 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 nine years concentrating on GPS applications in support of the FAA WAAS program. Previously he worked at ESL Inc. from 1984 to 1990 and Harris Corporation from 1978 to 1982.

Dr. Thomas N. Morrissey is employed with Zeta Associates Incorporated and currently performing data analysis and simulation in support of the FAA WAAS and GCCS programs. He previously worked for Eikonix Corporation, Codex Corporation, the US Government, and served in the US Army. He received a BSEE and a Ph.D. in EE from the University of Notre Dame and an SMEE from MIT.

Mr. Frank Lorge received his BSEE from Drexel University. He has over thirty years experience working for the FAA on communications, navigation, surveillance and automation systems. He has worked on the WAAS program since 1998, and since 2001 has also served as the GPS Civil Test Director.

ABSTRACT

PRN-21 experienced numerous periods of anomalous or degraded performance over the past three years where the Wide Area Augmentation System (WAAS) set this satellite Not Monitored or increased the User Differential Range Error (UDRE). Setting the satellite to Not Monitored or to a higher UDRE value limits the utility of this satellite in the WAAS service. Investigation of these events indicated PRN-21 exhibited carrier range perturbations that sometimes resulted in receiver subframe parity failures, adjustments of L1 and L2 carrier of approximately half cycle over a few seconds, or complete loss of carrier tracking. These subframe and carrier tracking anomalies were investigated and were also observed in other receivers besides those used in the WAAS network.

These anomalous PRN-21 events have been occurring approximately twice per month and are observed and tracked by normal WAAS system monitoring. PRN-21 is a GPS Block II-R satellite that was launched on March 31, 2003. Other GPS satellites exhibit similar carrier phase behavior but they typically are GPS Block II-A satellites and events do not occur with this frequency. This paper characterizes the events occurring with PRN-21 and shows that PRN-21 exhibits this anomalous behavior more frequently than other GPS satellites. It is anticipated this paper will be of interest to others that

perform precision processing of GPS data as well as those that monitor GPS satellite performance.

INTRODUCTION

The Wide Area Augmentation System (WAAS) is a safety critical system that augments GPS by providing additional ranging with geostationary earth orbit (GEO) satellites, improved accuracy with differential corrections, and safety with integrity monitoring. The WAAS reached its initial operating capability in July 2003 and now consists of 38 reference stations, three master stations, and four uplink stations supporting two wideband L1/L5 GEO satellites. WAAS reference stations are located throughout the Continental United States, Hawaii, Alaska, Puerto Rico and internationally with stations in Mexico and Canada.

Monitoring of WAAS for purposes of identifying anomalous performance and providing field support necessary to maintain service recently transitioned from the prime contractor to the FAA Aeronautical Center located in Oklahoma City. This FAA monitoring identified PRN-21 as having its WAAS User Differential Range Error (UDRE) increased or set Not Monitored excessively in April 2008 (this type of performance is also referred to as UDRE bumping). The UDRE provided by WAAS is a measure of clock and ephemeris error and represents a 3.29 sigma overbound of the true error. Setting the satellite's UDRE to a higher value or to Not Monitored limits the utility of this satellite for the WAAS Service. This PRN-21 feature of frequently being set to a higher UDRE value when well viewed by the WAAS network is not typical of other GPS satellites. Moreover, PRN-21 is a GPS block II-R satellite that was launched on 31 March 2003 and therefore is relatively new compared to most of the GPS satellites currently on orbit. This makes the observed performance even more noteworthy.

This paper details investigations conducted by the FAA on PRN-21 to isolate anomalous performance and compares PRN-21 to other GPS satellites. Additionally, the paper suggests a new requirement that could be imposed on future GPS satellites to limit this type of performance.

INITIAL WAAS INVESTIGATIONS

Several PRN-21 events were investigated to various levels of detail to first understand the cause of WAAS degrading this satellite's UDRE and then to isolate the source. The investigations utilized primarily WAAS network data and focused on events from 2008. The PRN-21 events from 19 June and 26 April are considered representative of this analysis and are discussed in greater detail below.

19 June 2008

On 19 June 2008, PRN-21's UDRE was set Not Monitored by WAAS on two separate occasions within approximately one hour during a period when the satellite was well viewed by the WAAS network. Figure 1 shows the WAAS broadcast UDREI ("I" indicates a UDRE index value) for PRN-21 from 19 June and Figure 2 shows the number of WAAS reference stations viewing this satellite. The UDREI for this event transitioned to an index value of 14 on two occasions when the satellite was nearly at the center of its pass over the WAAS network. (A UDREI of 14 indicates the satellite is set Not Monitored by WAAS.) Another observation from Figure 1 is that after the satellite was set Not Monitored it took approximately 20 minutes for the satellite to return to its UDRE value prior to the anomalous condition.

Investigation of receiver measurement data from the reference station located at Kansas City indicated the WAAS high pass filter algorithm used for cycle slip detection [1] tripped at the times the UDRE was set Not Monitored. The high pass filter algorithm (see Equation below) provides an estimate of carrier range at the current epoch (Φ_{HPF}) based on the four previous carrier range measurements (Φ_{t-x}). This filter estimate is differenced with the measured carrier range at the current epoch and then compared with a threshold to determine if a cycle slip occurred. Figures 3 and 4 show the difference between the filter estimate and current L1 and L2 carrier range measurement (residual) for PRN-21 for this 19 June event. (Cycle slip detection in WAAS uses the high pass filter only for the L2 frequency but L1 is shown in this example to demonstrate that L1 exhibited similar behavior.) The two periods that correspond to PRN-21 being set Not Monitored are clearly evident in the high pass filter results. This particular event resulted in the 0.3 meter high pass filter cycle slip threshold being exceeded which in turn causes most WAAS measurement processing to restart for this satellite. Detecting a cycle slip and having WAAS measurement processing restart is consistent with the UDRE transitioning to a higher value and then gradually returning to its original level due to warm up times associated with measurement processing algorithms.

$$\Phi^{i}_{HPF}(t) = 4 \cdot \Phi^{i}(t-1) - 6 \cdot \Phi^{i}(t-2) + 4 \cdot \Phi^{i}(t-3) - \Phi^{i}(t-4)$$

To further isolate performance in the 19 June event, the period highlighted as "Evt #1" in Figure 3 was detrended by fitting L1 carrier range with a 3rd order polynomial.

Figure 5 provides an expanded view of Evt #1 and compares high pass filter residuals with the fit of L1 carrier range over a 300 second period. Note the 3rd order polynomial was estimated with data excluded during the phase perturbation period so as not to corrupt the results. The L1 carrier range with the polynomial removed shows the L1 carrier range trended off by approximately half an L1 cycle and then 'jumped' back to its original value approximately 12 seconds later. WAAS cycle slip processing protects against half cycle slips so the detrended carrier range data showing this level of carrier range perturbation is consistent with the cycle slip trip detection.

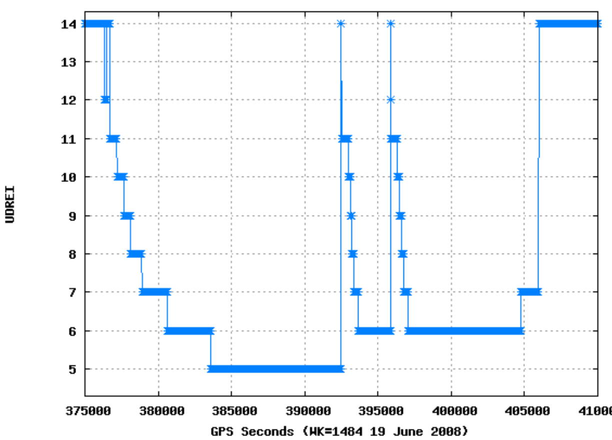

Figure 1. WAAS Broadcast UDREI for PRN-21 on 19 June 2008

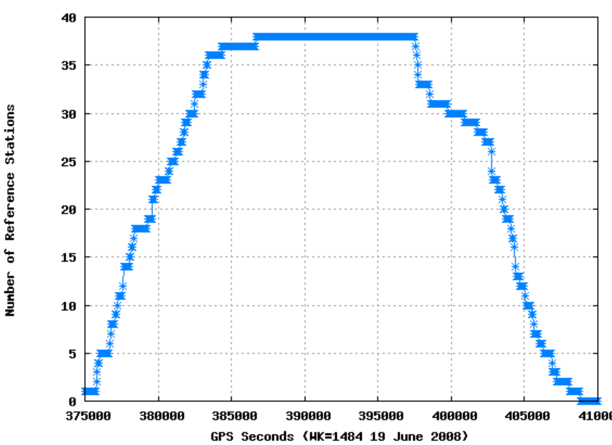

Figure 2. Number of WAAS Reference Stations Viewing PRN-21 on 19 June 2008

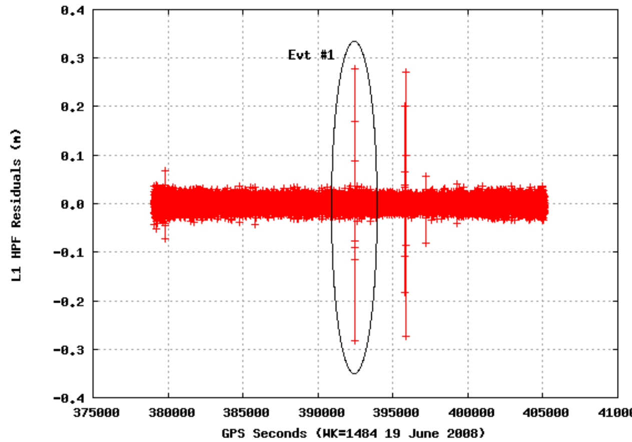

Figure 3. L1 High Pass Filter Residuals for Kansas City on 19 June 2008

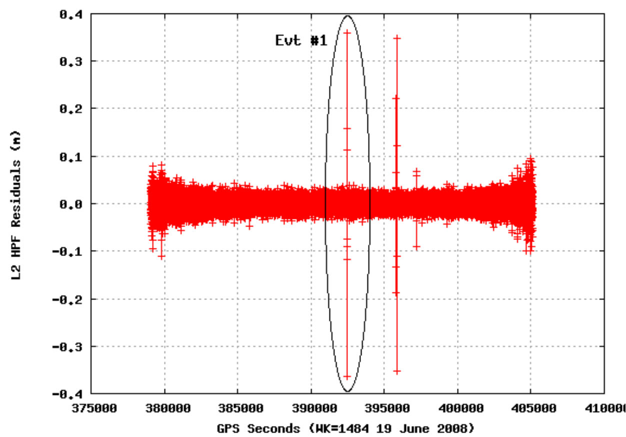

Figure 4. L2 High Pass Filter Residuals for Kansas City on 19 June 2008

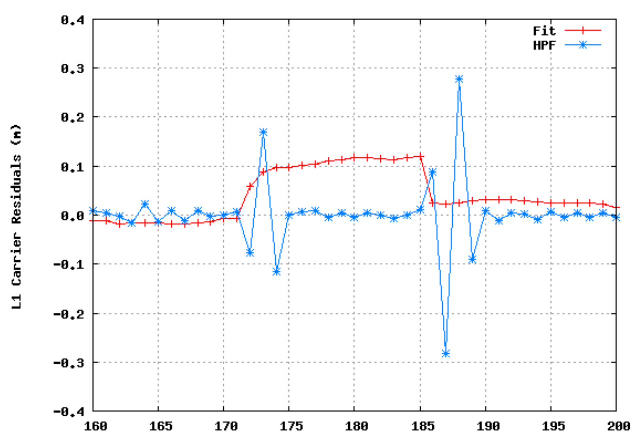

Figure 5. Comparison of L1 Carrier Range with the Polynomial Removed and High Pass Filter Residuals for Kansas City on 19 June 2008

26 April 2008

The 19 June event provided evidence that PRN-21 UDRE bumping was associated with anomalous carrier performance. The 26 April event was investigated in greater detail to provide additional characterization of the anomalous behavior and also to determine whether this performance was a satellite issue or possibly some other concern such as the WAAS reference station environment. The 26 April event was of particular interest because unlike 19 June, the anomalous carrier performance persisted for a more extended period.

To demonstrate PRN-21 UDRE bumping was not caused by WAAS hardware or some peculiarity in the reference station environment, additional comparisons were made between receivers at different reference stations. It is important to note for this comparison that each WAAS receiver operates independently of all other receivers in the WAAS reference station network. Comparisons across reference stations were conducted using three reference stations with significant geographic separation. Figures 6 and 7 show PRN-21 L1 and L2 high pass filter residuals from WAAS reference stations located in Mexico City, Kansas City and Minneapolis. As shown in these Figures, the behavior across these stations is nearly identical. These results indicate that UDRE bumping for PRN-21 were caused by the satellite and not some environmental feature at WAAS site(s).

Figures 8 and 9 provide additional characterization of the 26 April event by showing L1 and L2 carrier range difference and pseudorange performance. Figure 8 shows PRN-21 L1 minus L2 carrier from the Kansas City reference station and demonstrates that the receiver is cycle slipping frequently during the period of elevated high pass filter residuals. Since the L1 minus L2 carrier difference is commonly used for precision GPS processing, this difference value would be invalid during this period. Figure 9 shows L1 code minus carrier corrected for dual frequency ionosphere computed with carrier range. The Figure compares code minus carrier data for the same three stations used previously and suggests the anomalous behavior primarily impacts carrier and not pseudorange since no significant perturbations are evident in this data.

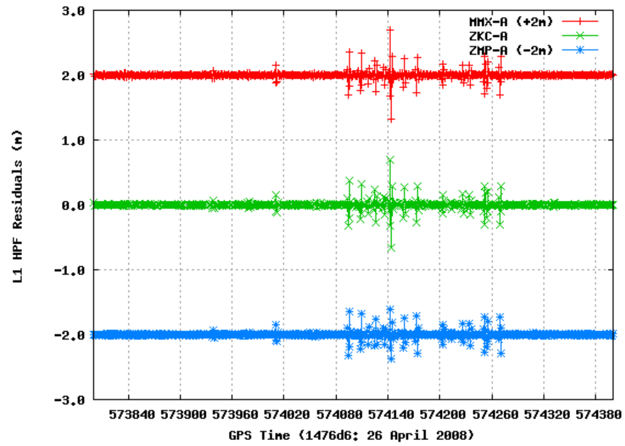

Figure 6. PRN-21 L1 HPF Residuals for Mexico City A, Kansas City A, and Minneapolis A

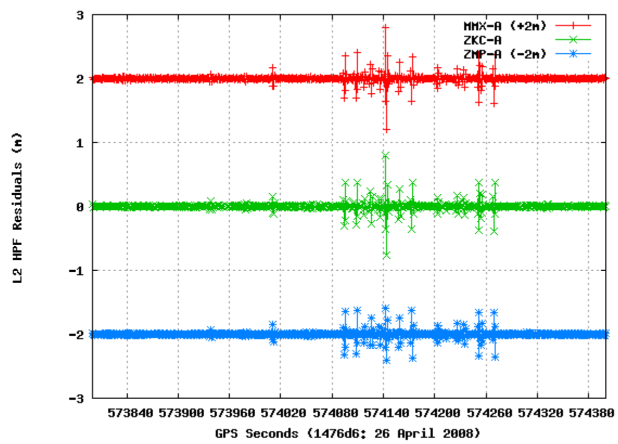

Figure 7. PRN-21 L2 HPF Residuals for Mexico City A, Kansas City A, and Minneapolis A

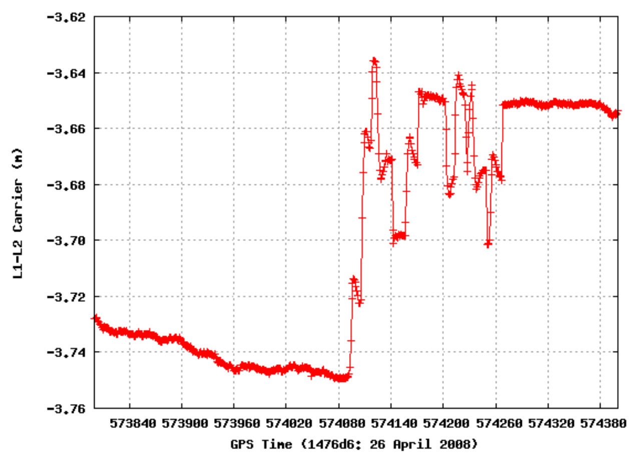

Figure 8. PRN-21 L1-L2 Carrier for Kansas City A Reference Receiver

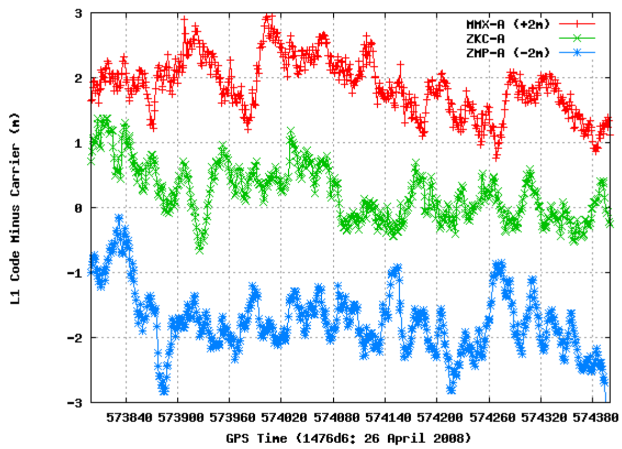

Figure 9. PRN-21 L1 Code minus Carrier for Mexico City A, Kansas City A, and Minneapolis A

The analysis for 26 April has focused thus far on PRN-21 ranging performance. An additional analysis was accomplished using two WAAS reference receivers at Zeta Associates Inc. in Fairfax, Virginia to investigate the impact of PRN-21 performance on data demodulation. The WAAS receivers output GPS navigation data with their RAWGPSSUBFRAMEWP data logs. A single log contains one of the five subframes of GPS data that contains 300 bits of information. Every six seconds the next subframe is output and therefore subframes 1 through 3 are repeated every 30 seconds. The 300 bits are organized as 10 separate words of 30 bits each where the first 24 bits of each word are data bits followed by 6 bits of parity. As the data stream is received, the receiver computes parity and compares it against the demodulated data to determine whether or not there are any parity errors present. Parity errors are counted and output with each log.

For the 26 April event GPS navigation data was recorded by the two independent receivers at Zeta. The data set below shows summary information from subframe 3 during a time period that coincided with one of the anomalous carrier events. It includes the time of the subframe, if parity passed (value of 0) or failed (value of 1), and 60 bits from words 1 and 2 from subframe 3 represented as hexadecimal. The data highlighted in color are bits that are inverted with respect to the actual desired values. At a time of 574092 it is clearly evident that a bit inversion took place within the very first 30-bit word. The first 16 bits (8B07) match those from prior and subsequent subframes but starting at bit 17, bits were inverted. In most cases once bits were inverted they remained inverted for the remainder of the subframe. Although in this example the bit inversions occurred at the same time as the cycle slip, this has not always been the case.

Receiver #1

Week	SOW(secs)	ParFail	Words 1 and 2
1476	574002.000	0	8B07104514974D4
1476	574032.000	0	8B071045148D480
1476	574062.000	0	8B07104514834E4
1476	574092.000	1	8B07EFBAEB86B7B
1476	574122.000	0	8B071045146F464
1476	574152.000	1	8B07104514654F8
1476	574182.000	1	8B071045145B4CC
1476	574212.000	0	8B0710451451450
1476	574242.000	0	8B07104514474B0
1476	574272.000	0	8B071045143D444

Receiver #2

Week	SOW(secs)	ParFail	Words 1 and 2
1476	574002.000	0	8B07104514974D4
1476	574032.000	0	8B071045148D480
1476	574062.000	0	8B07104514834E4
1476	574092.000	1	8B07EFBAEB86B7B
1476	574122.000	1	8B071045146F464
1476	574152.000	1	8B07104514654F8
1476	574182.000	1	8B071045145B4CC
1476	574212.000	0	8B0710451451450
1476	574242.000	0	8B07104514474B0
1476	574272.000	0	8B071045143D444

CONFIRMATION USING CORS

Since all receivers used in the analyses to this point were WAAS reference receivers, there was some question as to whether other receivers were experiencing the same carrier tracking issues or navigation bit errors with PRN-21. The performance of the two WAAS reference receivers located at Zeta was compared with receivers found in the Continuously Operating Reference Stations (CORS) network operated by the National Geodetic Survey (NGS). The CORS receivers were a Leica GRX1200GGPRO receiver located in Alexander City, Alabama and a Trimble NetR5 located in Columbus, Ohio.

Receiver performance was compared for the two events observed on 19 June (the event shown in Figures 1 through 5). Receivers' responses using the high pass filter algorithm were compared for both L1 and L2 measurements. The L1 responses from all four receivers are shown in Figure 10 for GPS time 392471, which corresponds to the first event on this day. Clearly all four receivers reacted at the same time while the Leica receiver did not output a measurement for PRN-21 for one second and also indicated it had cycle slipped. Both of the G-II receivers also exhibited elevated HPF residuals 15 seconds later. Also shown in this plot in green are the times when one of the G-II receivers output inverted navigation bits. Figure 11 shows a similar plot but for the later time of 395820 and it also indicates that each of the four independent receivers had an unusual response in carrier phase. This comparison demonstrates PRN-21 anomalous performance was detected by other receivers in addition to WAAS reference receivers.

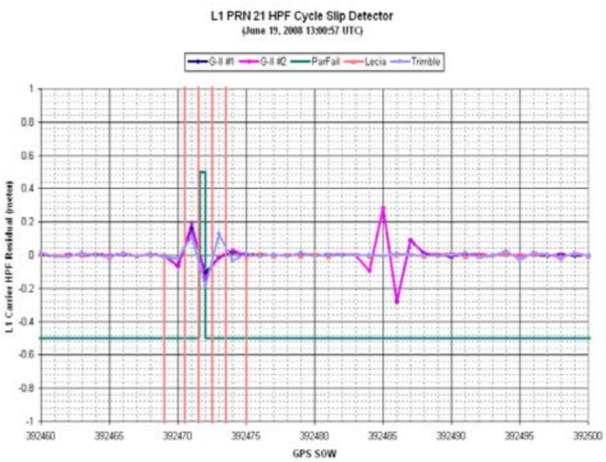

Figure 10. June 19, 13:00:57, Four Independent Receivers

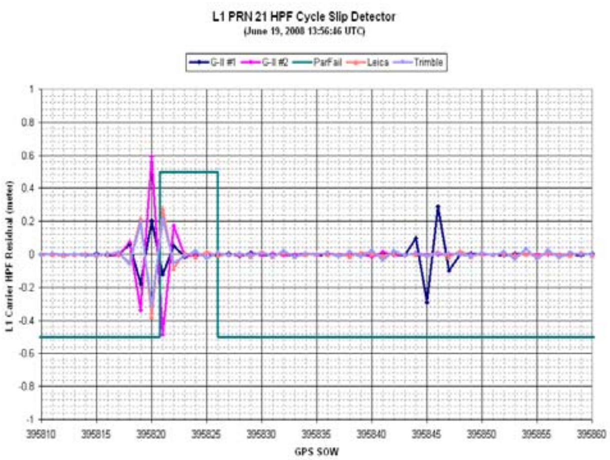

Figure 11. June 19, 13:56:46, Four Independent Receivers

COMPARISON TO OTHER GPS SATELLITES

The investigation of PRN-21 demonstrates this satellite exhibits anomalous carrier performance that is sometimes accompanied with navigation bit errors. The frequency of these anomalous events was determined by analyzing GPS data collected continuously since March 2005 at Zeta for any GPS subframe parity failures as reported by a WAAS reference receiver. Besides the anomalous carrier performance observed with PRN-21, subframe parity failures can be caused by other issues such as a weak signal or possibly an error in transmission. To eliminate the effects of weak signals, only GPS satellites with an elevation of at least 10 degrees were considered in the analysis. Figure 12 shows the time, date and PRN number of any GPS subframe containing a parity failure since March 2005.

All of the satellites have experienced subframe parity failures. However, PRN-21 and to a lesser extent PRN-4, clearly stands out from the rest of the constellation. The parity failures for PRN-21 appear to have begun late in 2005 and became more frequent in June of 2006. The rate of occurrence of PRN-21 parity failures experienced at Zeta is approximately one event per week but as shown in Figure 12 this rate is clearly not uniform. The satellite is in view above the 10 degree elevation mask at Zeta for approximately 5.5 hours each day and the parity failures have been detected at many different satellite elevations and relatively high C/N_0. PRN-4 (SVN 34) has also experienced numerous parity failures but this satellite is a Block II-A launched on 28 October 1993 and therefore not considered as noteworthy as PRN-21 (SVN 45) which as mentioned previously is a more recent Block II-R. A high number of parity failures also were detected for PRN-5 (SVN 35), a Block II-A launched 30 August 30 1993, but most of these occurred between January and March 2008 and at satellite elevations near 10 degrees and low C/N_0. PRN-5 was decommissioned on 26 March 2009.

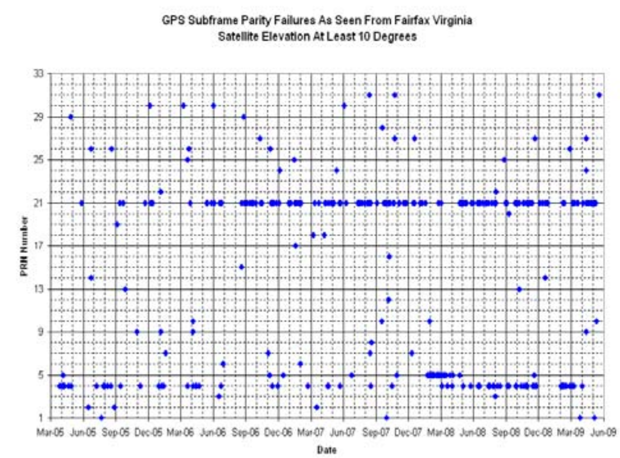

Figure 12. Comparison of GPS Satellite Parity Failures observed at Zeta Associates

IMPACT ON WAAS

The availability of WAAS Service is directly related to the Dilution of Precision (DOP) [2] and number of satellites available to the WAAS user. To determine the impact of PRN-21 events, the availability of WAAS Localizer Performance with Vertical guidance (LPV) service in the Continental United States and Alaska was analyzed for several events along with availability of Lateral Navigation and Vertical Navigation (LNAV/VNAV) and Localizer Performance with Vertical guidance with 200 ft decision altitude (LPV-200) services. The impact of PRN-21 carrier perturbations and navigation bit errors to these WAAS service levels were generally determined to be negligible. This can be seen in the LPV WAAS coverage comparisons provided in Figures 13 through 16 for 18-19 June 2008. June 18 represents baseline WAAS performance with no PRN-21 events and June 19 with the PRN-21 events discussed earlier. The differences in coverage are very small.

The impact on WAAS service is mitigated by the fact that GPS constellation has been very robust during the time period analyzed in this paper with 28-30 satellites healthy and available to WAAS users. If the GPS constellation was to degrade as described by the recent US Government Accountability Office (GAO) report [3], the impact of PRN-21 events would become more significant to WAAS users. According the GAO report, the probability of having 24 available satellites significantly decreases after 2010 and if this were to occur, the performance of PRN-21 would be amplified. This is especially true for WAAS since, as shown earlier, these momentary carrier anomalies result in a degraded UDRE that typically lasts for 20 minutes after each event.

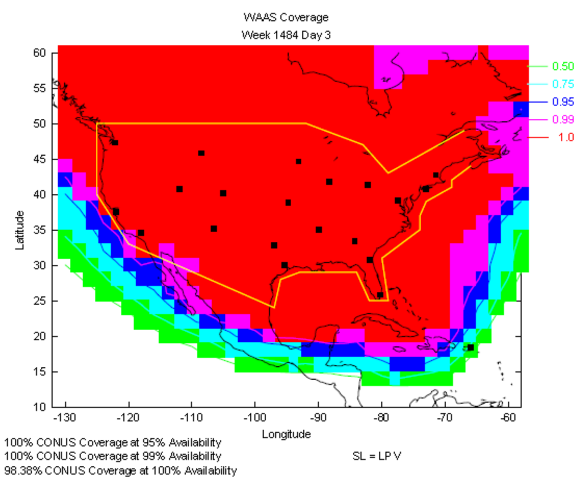

Figure 13. WAAS on 18 June 2008 (Baseline)

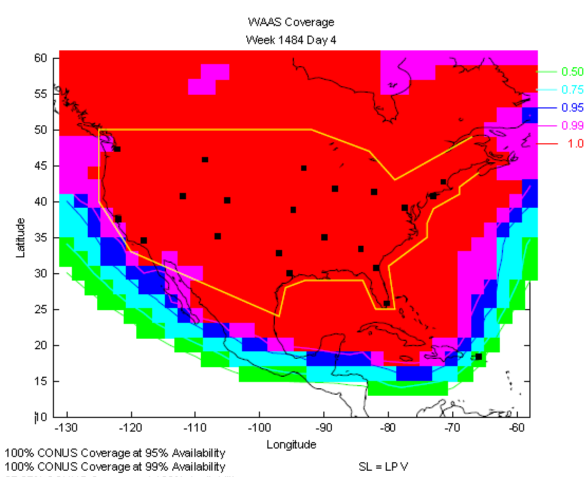

Figure 14. WAAS Coverage on 19 June 2008

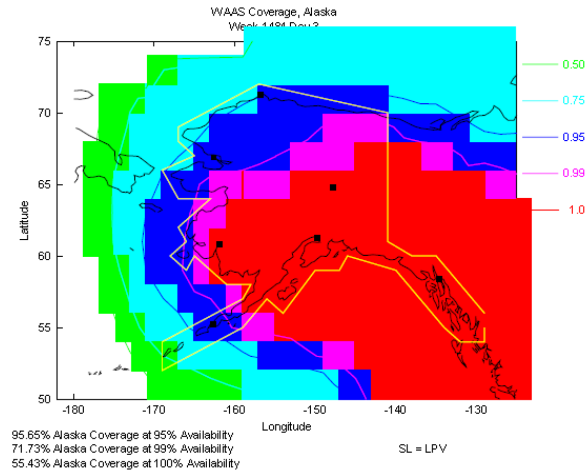

Figure 15. Alaskan Coverage for 18 June 2008 (Baseline)

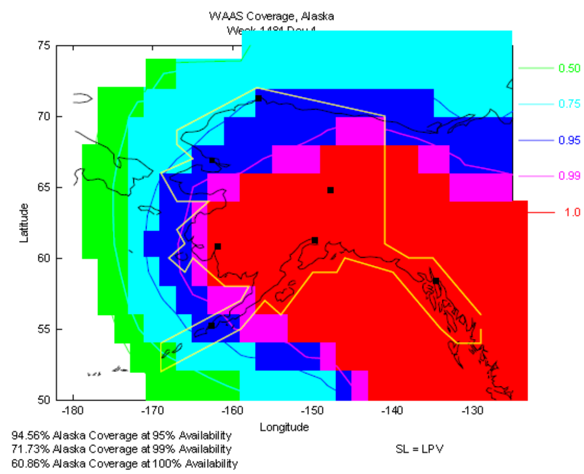

Figure 16. Alaskan Coverage for 19 June 2008

NEXT STEPS

The performance exhibited by PRN-21 does not appear to violate any GPS interface specification requirement. However, PRN-21 carrier phase performance is clearly anomalous when compared with other GPS satellites. This performance would result in more pronounced service impacts as described in the previous section if it were representative across the GPS constellation. The root cause of PRN-21's carrier perturbations and corresponding navigation bit errors is still under investigation at the GPS Wing and at 2SOPS. A clear explanation of PRN-21 performance would assist GPS augmentation providers and high accuracy users to properly address the continuity and availability risks for their applications.

The lack of an explicit requirement controlling this performance is considered a GPS specification weakness, especially given the heavy reliance in almost all precision GPS applications on carrier range processing. To assist in closing this weakness, a new requirement is proposed that could be applied to future GPS developments such as GPS-III. The current DRAFT wording proposed for a new IS-GPS-200/705/800 Phase Continuity Requirement is:

While a satellite is broadcasting standard L1 P(Y) code, standard L1 C/A code, standard L2 P(Y) code, standard L2 CM or standard L2 CL code signals, there shall be no discontinuities that exceed 10 degrees (TBR), as measured over any interval up to and including 10 seconds, in the respective L1 P(Y), L1 C/A, L2 P(Y), L2 CM or L2 CL carrier phase other than those attributable to the binary state of the modulating signals (with verbiage changed as necessary for L5 in -705 and for L1C in -800).

The 10-degree threshold is used as a placeholder for the phase discontinuity value but ideally the value chosen should satisfy the following two conflicting requirements: 1) the specified phase discontinuity value should be *small enough* to protect a wide range of User receivers under typical operating conditions. Parameters that must be considered include Phase Lock Loop (PLL) order and bandwidth, C/No level, maximum receiver dynamic stress, and receiver phase noise characteristics; and 2) the specified phase discontinuity value should be *large enough* to be detected with high confidence via a suitable monitoring architecture. Key parameters of this architecture include PLL order and bandwidth, number and distribution of monitoring stations, number of monitoring receivers at a given station, minimum expected receiver C/No and phase noise levels, phase jump detection methodology, and allowed probabilities of false alarm and of missed detection.

The analysis needed to more fully understand these trades between protecting all Users and robust monitoring has just commenced. The next steps will include formulation of reasonable false alarm and missed detection probabilities and apply these to specific monitoring architectures.

CONCLUSIONS

FAA monitoring of WAAS identified PRN-21 as having its WAAS UDRE increased or set Not Monitored excessively in April 2008. Several PRN-21 events were analyzed in detail and demonstrated the observed performance was caused by anomalous carrier performance with this satellite. The anomalous carrier events often were accompanied with navigation bit errors. These results were further confirmed with CORS data from receivers different than those used in WAAS.

Analysis of historical data since 2005 from all GPS satellites demonstrated that PRN-21 carrier performance is clearly different than other GPS satellites. The carrier performance observed with PRN-21 has the potential of degrading WAAS service but the robustness of the current GPS constellation has thus far limited any such degradations. The impacts of PRN-21 type performance would be far more pronounced if this performance were to become more common but without knowledge of the cause it is not possible to estimate the likelihood of this possibility.

The paper also introduced a possible requirement to address carrier continuity that could be applied to future GPS satellite developments. Further investigation into the details of this requirement will be the focus of future effort.

ACKNOWLEDGMENTS

The authors would like to acknowledge that this effort was sponsored in part by the FAA satellite program office and that the WAAS coverage plots were provided by the FAA Technical Center.

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[3] “GAO Report to the Subcommittee on National Security and Foreign Affairs, Committee on Oversight and Government Reform, House of Representatives - GLOBAL POSITIONING SYSTEM - Significant Challenges in Sustaining and Upgrading Widely Used Capabilities”, GAO-09-325, April 2009