Investigation into September 2020 GPS SVN 74 Performance Anomaly

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ABSTRACT

On September 20, 2020, GPS Space Vehicle Number (SVN) 74 exhibited unusual behavior that appears to have led to anomalous behavior for some GPS users. This paper investigates the observed signals in order to characterize the broadcast signal behavior over the course of the event. Investigations like this are critical to understanding the potential impact of such events on safety-of-life applications using GPS. In particular, Advanced Receiver Autonomous Integrity Monitoring (ARAIM) has associated requirements to monitor signal behavior and predict future performance levels including accuracy and fault probabilities. The first question that arose from the initial reported behavior was whether or not the event constituted a major service failure as defined in the GPS Standard Positioning Service Performance Standard (GPS SPS PS)[1]. As it turns out, the answer was not so easily determined. GPS has many different methods to indicate an alarm to the user, that if employed will successfully indicate to the user that the satellite should not be included in their position solution computation. Among these methods are an absence of a trackable signal and the use of alternative data patterns in the navigation message. A difficulty with determining whether these indicators were used is that they are not always recorded into data archives and may be confused with network outages or other data loss mechanisms. Although the alarm may result in the loss of data, the absence of data does not guarantee the presence of an alarm.

We need to be able to rule out other explanations for data loss in the archival records. We therefore need to obtain and scrutinize the measured carrier to noise ratios and raw navigation data bits in order to firmly establish the presence and timing of these different alarm mechanisms. This paper describes the signal behavior observed indicating different health states and also describes the transition characteristics between each state. We will describe some of the reported receiver behaviors and which mechanisms were used to protect users from the potential use of misleading data.

INTRODUCTION

On September 20, 2020, two Notice Advisory to Navstar Users (NANUs) were issued describing an outage on SVN 74 (PRN 04) during the first part of that day. These NANUs specified an outage period between (hour:minute:second) 00:31:00 and 05:47:00 GPS time. We later learned of large reported pseudorange errors on this satellite and reports of invalid position estimates via Automatic Dependent Surveillance–Broadcast (ADS–B) data that occurred within this time period. We began investigating this satellite in more detail in order to determine whether the satellite had exhibited faulted behavior or whether users may have reacted badly to unexpected behavior. SVN 74 is the first Block III satellite and therefore may have characteristics not previously seen on other GPS satellites. The question of whether or not the satellite was faulted is an important one. The GPS SPS PS [1] allows for the possibility of excess error on the GPS range measurement, but such behavior is expected to be rare (less often than once per 100,000 satellite operating hours). In fact, the last observed such fault occurred June 17, 2012 [2], so any new fault would be a noteworthy event. However, if it was not a fault, then many receivers may have still had an adverse reaction to what was broadcast, and we may need to take action to ensure that receivers are better prepared to operate under similar events in the future. We also examined the response of the Wide Area Augmentation System (WAAS) [3] and saw that the satellite either set to “Not Monitored” or to “Do Not Use” during the time period of interest. “Not Monitored” is used when the satellite is insufficiently observed and WAAS cannot confidently determine its level of performance. “Do Not Use” is broadcast when the satellite is set to unhealthy or when the satellite appears to be exhibiting a large error.

ADS-B REPORTS

We received reports that a few dozen aircraft over the United States reported invalid positions between approximately 03:38 and 04:15 Universal Time Coordinated (UTC). UTC time is 18 seconds earlier than GPS time due to a difference in leap seconds. These aircraft reported that a parameter called Navigation Accuracy Category – position (NACp) was below 8. A NACp of 8 corresponds to 93 m [4]. Smaller values correspond to larger uncertainties and all equipment are required to meet values of 8 or higher. We collected data from Opensky [5] and saw that most of these aircraft had NACp values of 0 which indicates that positioning accuracy is greater than 10 nautical miles or unknown. Most aircraft in the airspace did not experience any problem, which indicates that whatever the cause it was geographically widespread but limited to a minority of GPS receivers. The affected tracks as shown in Figure 1 also correlated well with the footprint of SVN 74. This indicated that the cause was likely associated with SVN 74, but that most of the GPS receivers were capable of recognizing and rejecting the problematic component.

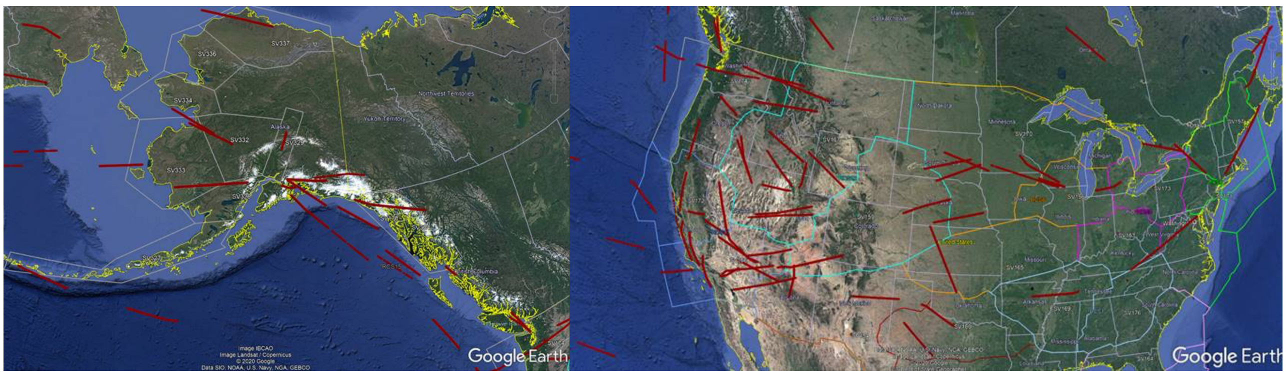

Figure 1 Tracks showing locations where aircraft reported poor positioning (NACp < 8) via ADS-B (courtesy Andy Leone at the FAA SBS program office)

IGS DATA

We next turned to data from the International Global Navigation Satellite System (GNSS) Service (IGS) [6] to collect raw tracking data including carrier to noise ratio (C/N_0) data. The IGS network consists of over 350 globally distributed GNSS receivers. We downloaded 30 second data from all available receivers for September 20, 2020. Of this set, 228 received data between 00:00 and 06:00 from PRN 04. As can be seen in Figure 2, essentially all receivers ceased tracking the L1 C/A code between 00:31:30 and 03:38:00 and then again between 05:33:30 and 05:46:30. The red crosses in the left-hand figure show that there was some reported data during these gaps, but none of it was continuous with data before or after, and all of it demonstrated a significant drop in C/N_0. Most likely the data in the gap is the result of cross-correlation with a different PRN code. Thus, we think it most likely that the normal L1 C/A PRN code ceased transmission during these gaps. It may have been replaced with an alternate code or ceased transmission altogether.

The right-hand plot in Figure 2 also shows the L5 C/N_0 data. Here we see that this signal ceased at the same starting time for the first gap but did not resume until 04:40:30. For the second gap, the start and stop times match those of the L1 C/A code. There were no reported measurements of L5 in either gap. This could be because there were fewer overall L5 measurements or that the L5 signal has better cross-correlation rejection. According to the GPS interface specifications for L1 C/A [7] and L5 [8], several methods are defined in Section 6.4.6.2.1 (Common Alarm Indications) to provide warnings that signals are unusable:

> *The following alarm indications are common to all code signals.*
> *The code signal becomes untrackable (e.g., ≥ 20 dB decrease in transmitted signal power, ≥ 20 dB increase in correlation loss):*
>> *(a) The code signal ceases transmission.*
>> *(b) The elimination of the standard code (e.g., gibberish code).*
>> *(c) The substitution of non-standard code for the standard code (see paragraph 3.2.1.6)*

Thus, it appears that during these data gaps, the normal PRN 04 codes were removed in order to indicate that the satellite was not to be used. Note that the L1 code did return at 03:38, about the same time that the ADS-B data reported GPS positioning errors.

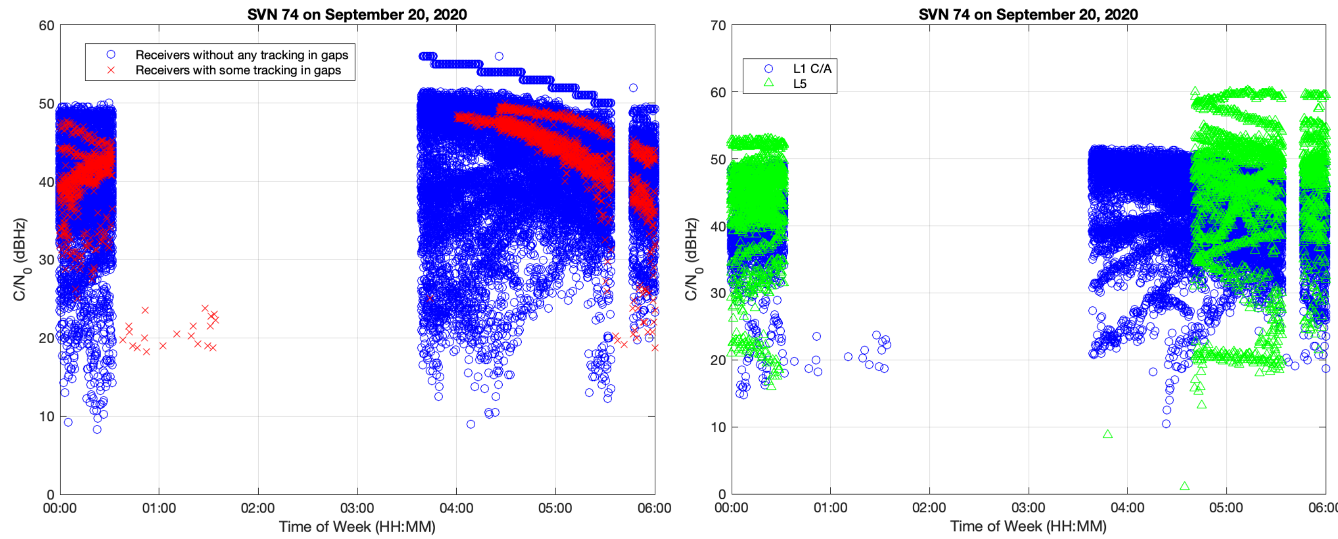

Figure 2 Measured L1C/A C/N0 (blue circles) and L5 C/N_0 (green triangles) from IGS stations that could observe SVN 74 between 00:00 and 06:00 on September 20, 2020. The red crosses show all of the data for stations that reported data during the outage period

NAVIGATION DATA BITS

We next turned to examining the data content on the signal once it returned to its normal power levels around 03:38. Figure 3 shows the received raw data bits shortly after a receiver at the William J. Hughes FAA Technical Center in Atlantic City, New Jersey began tracking the L1 C/A signal again. The first number is the GPS time of week in milliseconds and the next number is a 75-character hexadecimal representation of a 300-bit subframe of navigation data. Each subframe consists of ten 30-bit words including six parity bits at the end of each. Parity is calculated using information from the current and previous words. The first 15 characters in the figure represent the first two words of each subframe. These include a preamble (`8B`), telemetry information, timing information, and parity bits [7]. The next 60 characters represent words three through ten. These have all been set to `A` which is hexadecimal for ten or binary '1010'. These words all fail parity indicating that they do not contain any useful ephemeris or almanac data. However, there is even greater significance to the value `A`.

```
13128000,8B500027EEE5B4CAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13134000,8B500027EEE3A3CAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13140000,8B500027EEE1EC0AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13146000,8B500027EEDFD4CAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13152000,8B500027EEDDCC4AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13158000,8B500027EEDBB78AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13164000,8B500027EED9AF0AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13170000,8B500027EED7EB8AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13176000,8B500027EED5DD0AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13182000,8B500027EED3CA0AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13188000,8B500027EED1BE4AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13194000,8B500027EECFA10AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13200000,8B500027EECDEECAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13206000,8B500027EECBD7CAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13212000,8B500027EEC9CF4AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13218000,8B500027EEC7B04AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13224000,8B500027EEC5A8CAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13230000,8B500027EEC3E88AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13236000,8B500027EEC1DE0AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13242000,8B500027EEBFCB4AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
13248000,8B500027EEBDBF0AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
```

Figure 3. Time of week in milliseconds and raw subframe navigation data in hex from 03:38:48

According to Section 6.4.6.2.2 of [7] the Specific Alarm Indications on the (C/A-Code) consist of:

(a) The failure of parity on 5 successive words of LNAV data (3 seconds) (see paragraphs 20.3.5 and 40.3.5).
(b) The broadcast IODE does not match the 8 LSBs of the broadcast IODC (excluding normal data set cutovers, see paragraph 20.3.3.4.1).
(c) The transmitted bits in words 3-10 in subframe 1, 2, or 3 are all set to 0's or all set to 1's.
(d) Default LNAV data is being transmitted in subframes 1, 2, or 3 (see paragraph 20.3.2).
Alternating ones and zeros will be transmitted in words 3 through 10 in place of the normal LNAV data
(e) The 8-bit preamble does not equal 100010112, decimal 139, or hexadecimal 8B (see paragraph 20.3.3).

Thus, we see that according to mechanism (d) a series of alternating ones and zeros in words three through ten of the first three subframes also indicate that a satellite is not safe to use. This bit pattern also causes the parity of words three through ten to fail also triggering mechanism (a). We should note that the last two bits of word ten are always '`00`' in order for the parity of word one of the next subframe to pass. This is why we see that the final character of the subframe is '`8`' instead of '`A`'. The final four bits of the subframe are '1000' instead of '1010' in order to ensure that the next word passes parity. Nevertheless, this pattern is the specific condition identified in (d).

After more than half an hour, the satellite begins transmitting valid subframes four and five. Figure 4 shows the received raw data bits starting from time 04:25:18. The alternating ones and zeros pattern continues until subframe four starting at 04:25:48 when we see normal data for that and the next subframe. These pass parity, but then the alternating ones and zeros resume again for subframes one, two, and three exactly as specified above. It may appear confusing, but the bit pattern presented here does correspond to the specified alarm condition and the satellite still should not be used.

```
15918000,8B500027EB43BB0AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
15924000,8B500027EB41A38AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
15930000,8B500027EB3FE18AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
15936000,8B500027EB3DD70AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
15942000,8B500027EB3B4BCAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
15948000,8B500027EB393F85D0D1ABF1B8FB48FD4E004D7BC97D101993CF16B5204A081C694C680095400000
15954000,8B500027EB372C447747150E41A7C502ADFFFA8432EC55964C5FD8143A60901705E4C400B6800000
15960000,8B500027EB35638AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
15966000,8B500027EB335A8AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
15972000,8B500027EB31420AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
15978000,8B500027EB2F3185E271060E7F412EFD4300DD7BCED61588AF38236CE15E8ECBBFC4A00094000000
15984000,8B500027EB2D290482D009F1BB9F4F02C1FF1A8435A56FAE29763F59725FF5A687CC1BFFA9000000
15990000,8BB8404FEB2B618AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
15996000,8BB8446014D6ADCAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
16002000,8B500027EB274C0AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
```

Figure 4. Time of week in milliseconds and raw subframe navigation data in hex from 04:25:18

Shortly thereafter, the satellite begins transmitting valid data for all subframes. Figure 5 shows the received raw data bits starting from time 04:29:30. Now all of the data is valid and none of the alarm conditions specified above are met. However, the data includes a health flag which now indicates that the satellite has been set unhealthy and therefore should not be used. Thus, from about 03:38 onwards (we did observe the alternating ones and zeros pattern before in the data in Figure 3, but the receiver had not yet synchronized the data to its proper subframe), the transmitted navigation data bits indicated an alarm status to the user via alternating ones and zeros and then through the health flag.

```
16170000,8B4E20D01510990AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
16176000,8B4E30601512AF8AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
16182000,8B4E407FEAEB424AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA800000
16188000,8B4E70A81516C4076AAAA9AAAAAA957A1A048857676ABDBA342DB63747817BAD26C9BD6B42800000
16194000,8B4E802FEAE725C4F68EE87182394EFD3000328435F0B88E431D09638BE8E0D9A30C6BFF37000000
16200000,8B4E909FEAE56A01310FEA9DC8B71124693F9839F7491045308FAF016D47FF00239447B46D000000
16206000,8B4EA048151CA10BCFAA8CF41E3E1E94ED1ABC127FFEC6AE03D505AEE87FF2E91EB7E92AFE000000
16212000,8B4EB0F8151EB98FFFB7CB4401C717FFE5D807720057C15518BD6EF3CA4AFFA87BCD0C43CF000000
```

Figure 5. Time of week in milliseconds and raw subframe navigation data in hex from 04:29:30

This new ephemeris data set continued to indicate that the satellite was unhealthy until time 05:33:37 which corresponds to the second data gap in Figure 2. Once again, all signals ceased to be tracked until 05:47:18 when all signals again resumed normal transmission. The navigation data did not contain any alarm conditions and now broadcast a new ephemeris data set that indicated that the satellite was healthy. This concluded the anomaly event and from this time forward the satellite operated normally and as expected.

FIT INTERVAL

The last valid, healthy ephemeris to be broadcast before the event had an Issue of Data Ephemeris (IODE) equal to 141. It was first broadcast beginning at 00:00:00 for the day and was last broadcast at 00:31:30. Anyone who received that data could continue to use it afterwards provided they were able to track the PRN code. GPS typically broadcasts the same ephemeris data set (identified by its IODE) for a period of two hours and then replaces it with a new data set. Each data set has a specified curve fit interval which is the period of time the data can be safely used. Section 6.2 of [7] provides the following definition:

> *6.2.1 User Range Accuracy. User range accuracy (URA) is a statistical indicator of the ranging accuracies obtainable with a specific SV. URA is a one-sigma estimate of the user range errors in the navigation data for the transmitting satellite. It includes all errors for which the Space and Control Segments are responsible. It does not include any errors introduced in the user set or the transmission media. While the URA may vary over a given subframe fit interval, the URA index (N) reported in the NAV message corresponds to the maximum value of URA anticipated over the fit interval.*

The curve fit interval for most data sets, including IODE = 141, is four hours. It was broadcast starting at 00:00:00 with a reference time of ephemeris of 02:00:00 which means that it could safely be used until 04:00:00. Normally it would have been replaced at 02:00:00, except that the satellite stopped transmitting at 00:31:46. Thus, when the satellite resumed transmission on PRN 04 around 03:38, a receiver that still had a copy of the data set with IODE = 141 could have resumed use of the satellite again, if they ignored the alarm indications in the raw navigation data bits. But they would have stopped using that data set after 04:00:00 when the ephemeris information was outside of its curve fit interval. Thus from 04:00:00 onwards there was yet another mechanism to indicate that the satellite should not be used.

SATELLITE CLOCK AND ORBIT ERROR

The next question that we had is: what did the satellite orbit and clock errors look like during this anomaly period? We compared the broadcast ephemeris data sets against a post-processed precise ephemeris set from the National Geospatial-Intelligence Agency: Office of Geomatics [9]. These data sets appear to have some ability to track through non-standard codes and data sets. Figure 6 shows the orbital errors (radial, along-track, and cross-track) in the top plot, the clock error in the middle plot, and the IODE values in the bottom plot. As we can see, the first IODE of the day (141) is the only available data set until the unhealthy data set (IODE = 188) is broadcast at 04:29:30. It is also evident that the orbital errors begin to grow rapidly after 04:00 which is beyond the curve fit interval. However, we also notice that the clock error exceeds 325 m around the time transmission resumes. This error remains present until it is corrected by the IODE = 188 data set. A new healthy data set (IODE = 189) begins transmission at 05:46:30. At 06:00:00 it is replaced by another healthy data set (IODE = 190) and the normal pattern of behavior resumes.

We can see that if a receiver had access to the IODE = 141 data, and did not correctly interpret the navigation message data bit indications, they would have experienced a large pseudorange error. Users who correctly interpreted those bits would have been fully protected. We therefore do not consider this event to be an integrity fault as it was properly annunciated according to the interface specification.

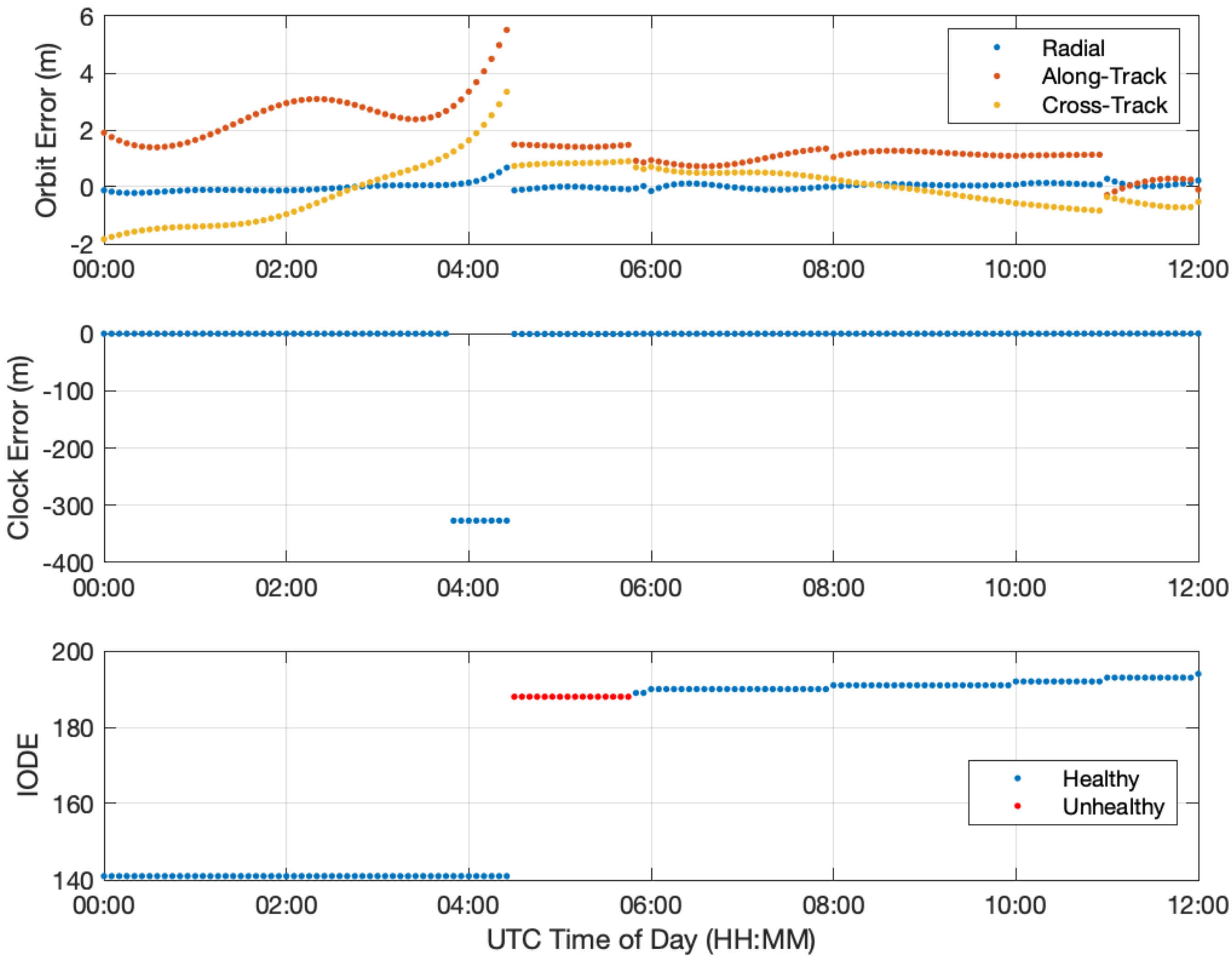

Figure 6 Broadcast ephemeris versus precise ephemeris for SVN 74 between 00:00 and 12:00 on September 20, 2020.

EFFECT ON WAAS

We next looked at data from WAAS to see how it reacted to the event. Figure 9 shows the satellite location (left) while various confidence parameters were broadcast. The User Differential Range Error (UDRE) indicates the confidence that WAAS had in the corrected ranging accuracy of a satellite. It also flagged the satellite as “Not Monitored” or “Do Not Use” [10]. The right-hand side of the figure shows the UDRE values in more detail (blue circles). It also shows the UDRE values for SVN 74 on the previous day when no anomaly was present. At the beginning of the day, the UDRE value started at 5.25 m and decreased as the satellite came into view of more of the WAAS network. However, at 00:31:47 the satellite was suddenly set to “Not Monitored” as result of all of the reference stations ceasing to track the signals from this satellite. The previous day’s data indicates that the satellite’s UDRE normally would have continued decreasing to its floor value of 3 m. At 04:30:34 WAAS set the satellite to “Do Not Use” in response to receiving the new ephemeris data set that was flagged as unhealthy. At 05:44:07 it switches back to “Not Monitored” as again all reference stations stopped providing tracking information on the satellite. Finally, at 05:52:00 it could begin broadcasting a numerical UDRE once it had time to evaluate the ranging and navigation data. We were able to use the WAAS data to determine transition times of the GPS signals and WAAS UDRE values to within one second.

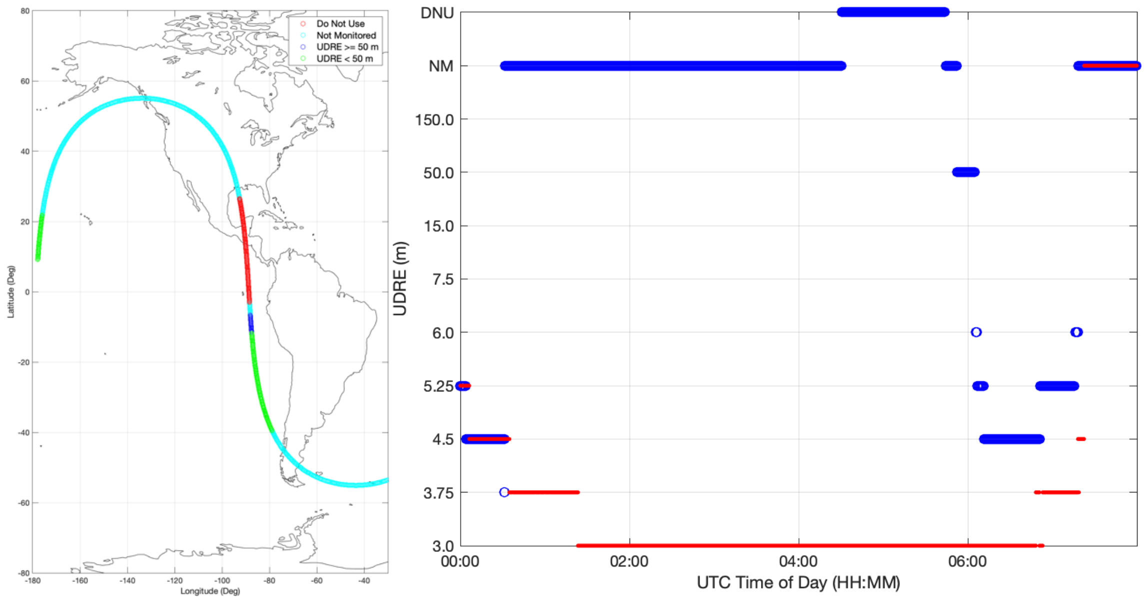

Figure 7. SVN 74 location and WAAS UDRE status (left) and UDRE values versus time (right) where the red lines are for September 19 and the blue circles are the values for September 20, 2020.

Figure 8 shows the impact of the satellite anomaly on WAAS performance. On the left is the normal performance with all satellites set healthy as observed on September 19, 2020. On the right is the performance on the anomaly day. Unfortunately, the satellite was lost while it was the highest satellite in the sky for much of this period. Such satellites are extremely valuable for resolving the vertical positioning component. Losing SVN 74 had a significant impact on the Vertical Protection Level (VPL) over Alaska for at least half an hour. Fortunately, horizontal positioning was not nearly so affected.

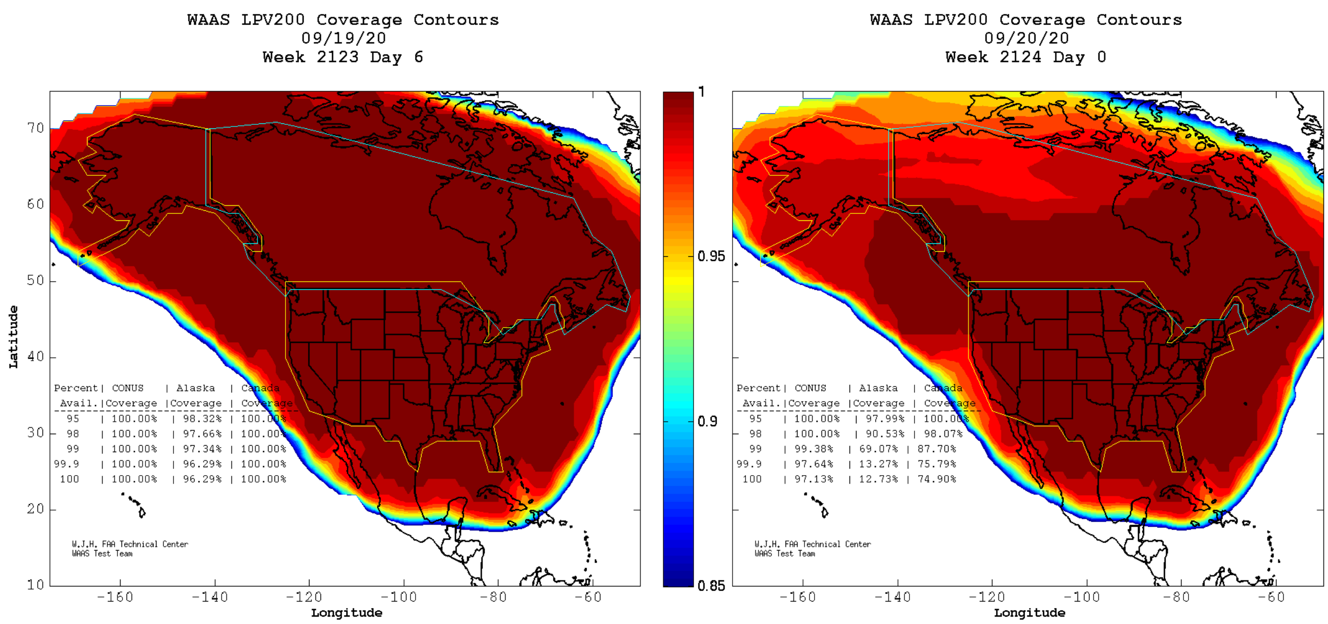

Figure 8. WAAS LPV-200 availability for September 19 (left) and September 20, 2020 (right).

RECEIVER LOGIC

We now return to the ADS-B data and look to see how the receivers operated during the event. The left-hand side of Figure 9 shows the locations of affected flights (13 out of 256 recorded flights) over California between 03:00 and 05:00. The middle plot shows the status of the reported positioning (red indicates a NACp = 0 and invalid positions, green indicates NACp > 7 and valid positions). As we can see, the majority of the red points are contained between 03:38 (when broadcast resumed with a large bias) and 04:00 (when the IODE = 141 data timed out). Flight # 7 seems to always be bad and upon further inspection showed a position on the ground not near to any airport (the points just below the "O" in CALIFORNIA). Its problems likely have nothing to do with SVN 74. The right-hand side of Figure 9 shows a zoomed in view near the start of the event. Here we see repeating patterns every six seconds. The dashed lines are six seconds apart and mark the start of each new subframe. As can be seen, it appears that each receiver oscillates between good and bad position estimates over the course of each subframe during this period, however there are at least two different patterns: whether it is good at the beginning and bad at the end, or bad at the beginning and good at the end. Our supposition is that the receiver may be reacting differently to the two valid initial words of each subframe and the eight final words that fail parity. The receiver may declare the satellite unusable after word seven when it fails five parity checks in a row and then good again after the reception of word one. This pattern then repeats the next subframe. When the satellite is used, the fault is likely detected, and the position is declared invalid. It appears that there may be varying delay on when the satellite is included in the position solution and when it is removed. Some receivers may also have an exclusion capability and this may also affect the timing and resilience against this anomaly. It appears that most of these receivers did correctly recognize the fit interval limits and stopped trying to use this satellite after 04:00. It is not clear why flights 6 and 9 continued to have invalid positions after 04:00.

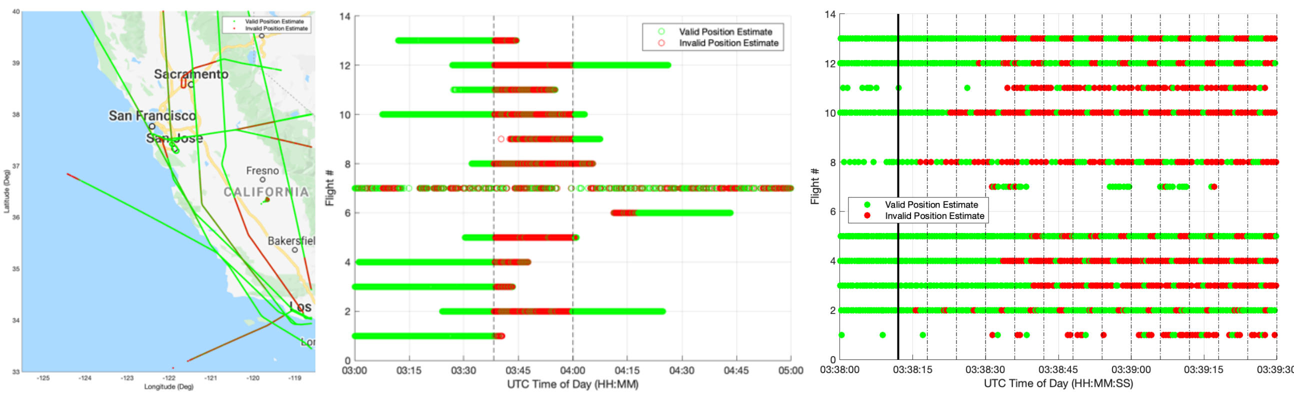

Figure 9. Reported locations of flights with invalid position data (left), reported position status as a function of time (middle), and zoomed in (right), the vertical dashed lines enclose the times when the clock error was present, but only indicated by non-standard data.

Aviation receivers are supposed to be robust against the alarm mechanism used between 03:38 and 04:30. However, methods to recognize the alarm via alternating ones and zeros is not fully specified, for example, reacceptance criteria are not described. The receiver Minimum Operational Performance Standards (MOPS) language has changed over time. The initial Receiver Autonomous Integrity Monitoring (RAIM) MOPS (DO-208) from 1991 stated in Section 2.2.1.11 on satellite selection:

> *The equipment shall provide the capability to:*
>
> > ...
> >
> > *b) determine the suitability of each satellite for use by data content including all appropriate parameters such as "health" status, complete almanac data, correct ephemeris and correctness of parity.*
> >
> > *c) remove satellite from use when not suitable.*

This specification certainly could lead to the behaviors that we saw above. More recent MOPS specifically include the alarm mechanism used in this event. DO-229 (from versions B through F from 1999 – 2020) and DO-316 (from 2009) state in Section 2.1.1.5.5 specifying the GPS UNHEALTHY designation:

> *The equipment shall [R229-101] designate any GPS satellite as GPS UNHEALTHY if the GPS satellite navigation message meets any of the following conditions:*
>
> > ...
> >
> > *b) Failure of parity on 5 successive words (3seconds);*
> >
> > ...
> >
> > *f) Default navigation data [alternating one's and zero's] is being transmitted in subframes 1, 2, or 3*

Here the alarm mechanism is specifically called out, but again it does not necessarily make it clear when the satellite may be used again. For example, would the bit pattern seen in Figure 4 allow usage again during valid subframes four and five? It is important to clarify both the alarm conditions and the reacceptance conditions. The latest Dual-Frequency Multi-Constellation (DFMC) Space-Based Augmentation (SBAS) MOPS, ED259, contains new requirements that should offer significantly better protection and clarity against similar events in the future. One new requirement is:

> **[REQ:207]** With ABAS provided integrity monitoring, the equipment shall only use a GPS satellite in the position solution if the following conditions are all met:
>
> *a) the satellite CEI data set in use has been decoded and processed within the last 5 minutes and*
> *b) the GPS broadcast time is within the curve fit interval of the CEI data set in use.*

Thus, the ephemeris data needs to have been received within the last five minutes. In addition, the curve fit interval is explicitly included in the MOPS requirements. When the large pseudorange error began at 03:38, the last valid ephemeris transmission was more than three hours earlier. This requirement would have prevented the continued use of IODE = 141. Another issue that we recognized is that if a user has some corrupted bits during the usage of the C/A alarm mechanisms (c) or (d) the user may fail to recognize them. Since these patterns already fail parity, a user would not know if they have an incorrect bit that interrupts the received alternating ones and zeros pattern. Thus, we want to define an implementation to recognize their usage even if the bits are not all correctly received. The following language has been recently proposed:

> *With FDE provided integrity monitoring, the equipment shall only use L1 measurements from any GPS satellite in the navigation solution if the following conditions are all met:*
>
> *a) 6-bit health word in subframe 1 equal to binary 000000; and*
> *b) Four or less successive L1 LNAV word failures of parity; and*
> *c) L1 LNAV User Range Accuracy index strictly less than 8; and*
> *d) Bit 18 of the LNAV HOW equal to 0; and*
> *e) Each of the last received L1 LNAV subframes 1, 2 and 3 has at least two words among words 3-10 with bits different from all 0s and from all 1s; and*
> *f) Each of the last received L1 LNAV subframes 1, 2 and 3 has at least two words among words 3-10 different from Default Nav Data (i.e. 101010101010101010101010101010 for words 3-9 and 101010101010101010101010101000 for word 10) and from their binary inversion (010101010101010101010101010101 for words 3-9 and 010101010101010101010101010100 for word* 10)*; and*
> *g) Subframe preamble is equal to decimal 139, or hexadecimal 8B.*

This language allows for the possibility of corrupted words and defines the reacceptance criteria as all three of the most recently received subframes 1, 2, and 3 need to be clear of the alarm indications.

ANOMALY TIMELINE

The full anomaly time frame is provided in Table 1. The satellite began the day normally with healthy operation using IODE = 141. From 00:31:42 until approximately 03:38 GPS time all signals were determined to be untrackable. Between approximately 03:38 until 04:30 the L1 C/A signal was trackable but the navigation bits exhibited non-standard data (NSD) behavior that indicated the presence of an alarm. From approximately 04:30 until 05:33 the satellite was trackable, the navigation data bits conformed to standard behavior, and the satellite health bits indicated that it was unhealthy and therefore still not to be used. Between 05:33:37 and 05:46:30 the satellite again became untrackable on all signals. Finally, at approximately 05:46:30 the satellite again became trackable and broadcast valid navigation bits and was set healthy. The L5 and L2C signals experienced a larger initial gap as they did not return from it until 04:40:30. The civilian navigation (CNAV) message structure [8][11] on these signals is different from the legacy navigation (LNAV) message structure on L1. The CNAV curve fit interval is just three hours. Therefore, neither of these signals experienced a time period where there was an active ephemeris data set and a trackable signal. There was no need for any navigation data based alarms.

At 00:17 NANU #202042 was issued declaring that the satellite will be unusable from time 00:31:00 onwards. At 05:42 NANU #202043 was issued stating that the satellite was unusable between 00:31:00 and 05:47:00. These are interesting as they came out 14 minutes before the start and five minutes before the end of the anomaly, respectively. This was not a planned event, as the NANUs were provided with very little advanced notice. However, the operators had at least some advanced notice of the differing states of the satellite. Such service interruptions are not entirely uncommon. Between January 1, 2000 and September 30, 2020 there were 1,105 outages (about 53 per year or 1.7 per satellite year), 812 of these were scheduled outages and 293 were unscheduled. The outage rate has decreased over time and for the one-year period between October 1, 2019 and September 30, 2020 there were 28 outages, 22 were scheduled and 6 were unscheduled. So, the current rate is approximately half of the longer-term average.

Table 1. Timeline of Events

Time	TOW	L1 PRN Code?	L1 LNAV Data	L5 PRN Code?	L5 CNAV Data	ARAIM Status	WAAS UDRE
00:00:00	0	Yes	Begin broadcast of IODE = 141	Yes	Valid data	Healthy	5.25 m
00:00:48	48	Yes	Earliest time MOPS receiver can validate IODE = 141	Yes	Valid data	Healthy	5.25 m
00:02:18	138	Yes	WAAS Correction uses IODE = 141	Yes	Valid data	Healthy	5.25 m
00:17:00	1020	Yes	Valid with IODE = 141 NANU #202042 issued	Yes	Valid data	Healthy	4.5 m
00:31:42	1902	No	-	No	Code and data unavailable	Unusable	3.75 m
00:31:47	1907	No	-	No	-	Unusable	Not Monitored
03:38:15 - 03:38:30	13095 - 13110	Yes	NSD	No	-	Unusable	Not Monitored
03:50:00	13800	Yes	NSD	No	-	Unusable but with 327 m clock error	Not Monitored
04:00:00	14400	Yes	NSD, IODE = 141 outside of fit interval	No	-	Unusable	Not Monitored
04:25:48	15948	Yes	Begin broadcasting valid subframes 4 & 5 (subframes 1-3 remain invalid)	No	-	Unusable	Not Monitored
04:30:00	16200	Yes	Begin broadcast of valid subframes 1-3 with IODE = 188	No	-	Unhealthy	Not Monitored
04:30:34	16234	Yes	Valid Data IODE = 188	No	-	Unhealthy	Do Not Use
04:40:30	16830	Yes		Yes	Valid data	Unhealthy	Do Not Use
05:33:37	20018	No	Code and data unavailable	No	Code and data unavailable	Unusable	Do Not Use
05:42:00	20520	No	NANU #202043 issued	No	-	Unusable	Do Not Use
05:44:07	20647	No	-	No	-	Unusable	Not Monitored
05:46:30	20790	Yes	Begin broadcast of IODE = 189	Yes	Valid data	Unhealthy	Not Monitored
05:47:18	20838	Yes	Earliest time MOPS receiver can validate IODE = 189	Yes	Valid data	Healthy	Not Monitored
05:52:00	21100	Yes	Valid Data IODE = 188	Yes	Valid data	Healthy	50 m

CONCLUSIONS

Given our analysis, the September 20, 2020 event on SVN 74 did not constitute a major service failure. The satellite used a variety of notification methods to indicate that the satellite was not to be used between 00:31:42 and 05:46:30. It began by ceasing transmission of the normal signals and then utilized Non-Standard Data (NSD) to alarm the satellite when the L1 C/A code first returned. Thirty minutes after the old ephemeris information had timed out (beyond its curve fit interval) a new ephemeris was broadcast that set the satellite to unhealthy. The signals again ceased normal transmission and finally the satellite returned to normal operation. Figure 10 depicts this sequence of events. While this was unusual satellite behavior, specified alarm mechanisms were used the entire time in order to indicate that the satellite should not be used. When investigating the MOPS language describing the usage of such mechanisms, we realized that the language should be improved to clarify how to robustly detect the use of NSD and how to determine when it no longer applied. Language had already been placed into the DFMC SBAS MOPS that would have prevented any possible use of the satellite during the periods with large pseudorange errors. Further language has been proposed to reliably detect any future instance of NSD. As this represents the first Block III satellite we might expect to see similar alarm sequences in the future, especially as more Block III satellites enter into service.

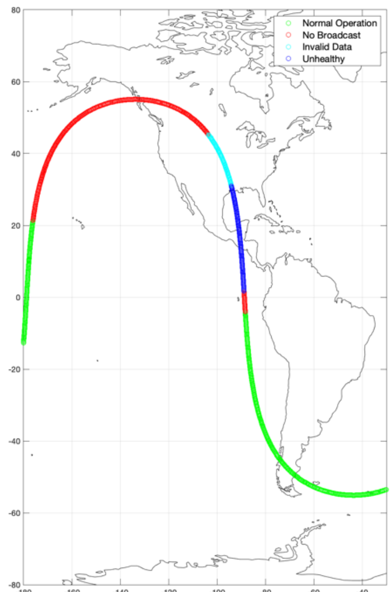

Figure 10. Satellite locations and the different health indications used

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