Anomalous behavior of the 'Issue of Data, Clock' (IODC) and 'Issue of Data, Ephemeris' (IODE)

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SUMMARY

This paper informs the reader about the recent anomalous behavior of the 'Issue of Data, Clock' (IODC) and 'Issue of Data, Ephemeris' (IODE) parameters in the GPS broadcast Legacy Navigation (LNAV) messages and compares that anomalous behavior against the required behavior defined by IS-GPS-200H and by the GPS Standards and Recommended Practices (SARPs). The extent to which the IODC parameter behavior violated the 'IODC minimum repeat time' constraint in IS-GPS-200 and the mitigations which have been put in place to remedy this behavior are described. The IODE parameter behavior, which is critical for integrity purposes, is also shown as having violated the related 'IODE minimum repeat time' constraint on one occasion, though GPSOC has not to date received reports of any anomalous operational manifestations resulting from the constraint violation.

1. INTRODUCTION

This paper informs the reader about the anomalous behavior of the 'Issue of Data, Clock' (IODC) and 'Issue of Data, Ephemeris' (IODE) parameters in the Legacy Navigation (LNAV) messages broadcast by the GPS Block IIF (GPS IIF) satellites detected during calendar year 2015.

2. BACKGROUND

2.1 Discovery and Identification of the Anomalous Behavior

Since the beginning of 2015 the Centre National d'études Spatiales (CNES) has reported 12 instance of IODC parameter violations to the U.S. Coast Guard Navigation Center (NAVCEN). These 12 violating instances of the IODC/IODE parameters were spread across four separate occasions in 2015 and are summarized in Table 1.

Table 1. IS-GPS-200 IODC Constraint Violations in 2015 per CNES

Space Vehicle (SVN)	PRN Code	Occasion Start Date	Constraint Violated	Instances	Shortest Violating Time
GPS IIF-2 (SVN 63)	1	1 Jan 2015	IODC repeat time	5	1 Day
GPS IIF-2 (SVN 63)	1	7 Jan 2015	IODC repeat time	1	6 Days 16 Hrs
GPS IIF-1 (SVN 62)	25	11 Mar 2015	IODC repeat time	1	22 Hrs
GPS IIF-4 (SVN 66)	27	15 Mar 2015	IODC repeat time	5	22 Hrs

2.2 IS-GPS-200 IODC and IODE 'Minimum Repeat Time' Constraints

As described in IS-GPS-200H, the IODC is a ten-bit term contained in subframe 1 of the broadcast LNAV messages which indicates the issue number of the satellite clock correction parameter data set. The IODC provides the user with a convenient means of detecting any change in the clock correction parameters. Similarly, the IODE is an eight-bit term contained in both subframe 2 and subframe 3 of the

broadcast LNAV messages which indicates the issue number of the satellite ephemeris parameter data set. The IODE provides the user with a convenient means of detecting any change in the ephemeris parameters, as well as ensuring that subframe 2 and subframe 3 contain a consistent set of satellite ephemeris parameters. The IODE is provided in both subframes 2 and 3 for the purpose of comparison with the eight least significant bits (LSB) of the IODC term in subframe 1. Whenever these three terms do not match, a data set cutover has occurred and new data must be collected.

Paragraph 20.3.4.4 of IS-GPS-200H defines the minimum repeat time between IODC and IODE values as follows:

> *The IODE is an 8 bit number equal to the 8 LSBs of the 10 bit IODC of the same data set. The following rules govern the transmission of IODC and IODE values in different data sets:*
> *(1) The transmitted IODC will be different from any value transmitted by the SV during the preceding seven days; (2) The transmitted IODE will be different from any value transmitted by the SV during the preceding six hours.*

For IODC, the 'minimum repeat time of seven days' constraint allows the IODC to be used in conjunction with the untruncated GPS week number as a unique identifier of every subframe 1-2-3 data set broadcast by the satellite for archiving purposes. The IODC 'minimum repeat time of seven days' constraint is not related to integrity. For IODE (and for the eight LSBs of the IODC), the 'minimum repeat time of six hours' constraint allows users to ensure they are operating with a matched/consistent set of subframe 1-2-3 data broadcast by the satellite and are unaffected by potential data set cutover ambiguities. Since using an unmatched/inconsistent set of subframe 1-2-3 data can result in unpredictably large errors, the IODE and eight-LSBs-of-IODC 'minimum repeat time of six hours' constraint is essential for ensuring integrity.

To access IS-GPS-200 visit http://www.gps.gov/technical/icwg/.

3. ANALYSIS

Once the most recent anomalous behavior report from CNES was received, the GPS Directorate along with engineers from 2 SOPS, Lockheed Martin, Boeing, and Aerospace (hence forth included in the term "GPSD Team") began an analysis of the reported IS-GPS-200 violations. This effort centered around the confirmation of the IODC repeat times, characterization of the IODC behavior along with the related IODE behavior, and then as appropriate, identifying the root cause of the anomalous behavior as well as implementing effective short and long-term re-mediations.

3.1 Confirm IODC Repeat Times and Characterize IODC/IODE Behavior

The GPSD Team first examined the historical archive of LNAV messages broadcast during 2015 and were able to confirm the accuracy of the CNES observations. The search was then expanded to cover all LNAV messages broadcast by GPS satellites over the past several years. This research discovered a total of 14 occasions where a GPS IIF satellite broadcast LNAV messages with a sequence of anomalous repeating IODC and IODE values. In each case, the anomalous behavior was correlated with a preceding upload of LNAV data to the affected GPS IIF satellite (roughly one to seven days earlier) which did not complete in a normal manner.

The first GPS IIF satellite (SVN-62/PRN-25) was launched on 28 May 2010. The GPSD Team discovered in the available data that the first instance of anomalous IODC/IODE behavior occurred in the LNAV messages broadcast by that GPS IIF satellite on 27 February 2011 wherein the LNAV message repeated an IODC/IODE pair previously broadcast 4.3 days earlier on 23 February 2011. This repetition violated the 'minimum repeat time of seven days' constraint for IODC, but even though anomalous, it did not violate the 'minimum repeat time of six hours' constraint for IODE. Two other IODC violations (but not IODE violations on this occasion) were also traced to the non-normal upload completion which occurred on 23 February 2011. This sort of behavior following a non-normal GPS IIF upload completion was seen in all 14 occasions since 2010 where there was a sequence (one or more) of anomalous repeating IODC values that violated the 'minimum repeat time of seven days' constraint. During this same analysis, the GPSD Team also discovered one occasion where there was a single instance of an anomalous repeating IODE value (and IODC value) which violated the 'minimum repeat time of six hours' constraint for IODE. In this instance, the IODC/IODE pair repeat time was 0.8 hours.

The single instance of IODC/IODE values violating the IODE 'minimum repeat time of six hours' constraint in the LNAV messages broadcast by SVN-62/PRN-25 on 20 March 2014 was interesting in several ways. Not only was this the only violation of the IODE 'minimum repeat time' constraint, the observed IODC/IODE pair repeat time of 0.8 hours was more than 20 times shorter than the next shortest IODC/IODE pair repeat time observed which was 16.4 hours. This was also the only instance of anomalous repeating IODC/IODE values where none of the clock correction parameters in subframe 1 (i.e., a_{f0}, a_{f1}, a_{f2}, and T_{GD}) had any change whatsoever. The only change to the LNAV message in this particular case was a 16-second shift in the clock data reference time (i.e., t_{oc}). Similarly, this was also the only instance where 60% of the ephemeris parameters in subframes 2-3 had no changes (the remaining 40% had changes which clearly constituted an IODE constraint violation).

The exhaustive historical analysis revealed:

- that the IS-GPS-200 violations were limited to 14 occasions where the broadcast IODC values from GPS IIF satellites violated the IODC 'minimum repeat time of seven days' constraint,

- that only one of the 14 occasions included an instance where the broadcast IODE value (and 8 LSBs of the broadcast IODC value) also violated the IODE 'minimum repeat time of six hours' constraint,

- that the single instance where the IODE 'minimum repeat time of six hours' constraint was violated involved subframe 1-2-3 clock and ephemeris parameters with negligible changes such that the resulting ambiguities were inconsequential,

3.2 Root-Cause Analysis

The GPSD Team conducted a root-cause analysis after all IODC/IODE 'minimum repeat time' constraint violation occurrences were identified. The team conducting the analysis compared the different occurrences for commonalities. Each of the violations occurred after a GPS IIF NAV upload experienced some form of communications interruption which led to a particular type of non-normal upload completion. In each of these non-normal upload completions, the communications interruptions resulted in the command sequence timing out and requiring the re-execution of the transmit (XMT) NAV protocol.

The XMT NAV protocol is unique for the GPS IIF satellites because they use two superblocks of upload data instead of multiple small blocks of upload data like prior generation satellites. This difference is why the error was only observed in the GPS IIF satellites and not systemically in all the satellites. When the GPS IIF command sequence timed out, the GPS Operational Control System (OCS) IODC/IODE

database did not properly update to indicate use of the specific IODC/IODE values contained in the uploaded data. As a result, those specific IODC/IODE values were still flagged in the OCS IODC/IODE database as predicted. When the next LNAV upload was generated the flags were set to available, and then those specific IODC/IODE values were used in generating a subsequent upload within seven days. This reuse is what resulted in the IS-GPS-200 violations.

4. WAY FORWARD

4.1 Mitigations

During the course of the analysis, the GPSD Team identified two short-term mitigations. The first short-term mitigation is an operational procedure designed to check the OCS IODC/IODE database following every GPS IIF LNAV upload. The operation procedure identified specific IODC/IODE values contained in the LNAV upload flagged in the IODC/IODE database as predicted. If found, these values were flagged as used prior to the next LNAV being generated. This mitigation was discontinued upon implementation of the Long-Term Solution.

The second, Short-Term mitigation was an operational change to the IIF navigation upload anomaly procedures. In the event that the GPS IIF LNAV upload experiences an interruption due to a communications outage, this change ensured that the OCS operators could update the OCS database such that IODC/IODE values that potentially made it into the space vehicle were flagged correctly in the IODC/IODE database as used.

4.2 Long-Term Solution

The root cause analysis traced the reason for failing to properly update the IODC/IODE database during non-normal upload completions with GPS IIF satellites to a problem with the NAV upload software in the OCS. A permanent coding fix has been developed and was deployed onto the OCS system as part of a pre-planned software release in May 2015.

In addition to the OCS software solution, the GPSD Team is also investigating possible ways to add ‘user expectation-based’ monitoring and validation of the LNAV message content in advance of the GPS Next-Generation Operational Control System (OCX) – perhaps by using the OCS monitoring system or an independent organization.

SUMMARY

The anomalous IODC/IODE behavior in the LNAV messages broadcast by the GPS IIF satellites which led to the IODC values violating the ‘minimum repeat time of seven days’ constraint in IS-GPS-200 was infrequent and IODE values violating the ‘minimum repeat time of six hours’ constraint was even more infrequent. Historical analysis shows that there were a total of 14 uploads with IODC values that violated IS-GPS-200 which were sent to GPS IIF satellites since the first GPS IIF satellite was launched in May 2010. To place this number in context, there were more than 80,000 navigation uploads performed by the OCS across the GPS fleet since the current version of the OCS software became operational in September of 2007. Recognize that 14 uploads out of 80,000 uploads equates to less than 0.02% upload error rate. This anomalous behavior and the resulting IODC parameter violations of IS-GPS-200 constraints went undetected over the nearly 3.5-year period of time from May 2010 until March 2014. Recurrence of the broadcast IODC/IODE values violating IS-GPS-200 constraints is now prevented by a permanent long-term correction.

The GPSD Team would like to acknowledge and thank the French Government, especially those individuals at CNES, who detected this issue, as well as our European Commission and Federal Aviation Administration colleagues who brought these violations to the attention of the GPSD. The GPSD remains committed to providing the premier positioning, navigation, and timing solution to all of our global users.