GPS Receiver Impact from the UTC Offset (UTCO) Anomaly of 25-26 January 2016

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BIOGRAPHIES

Karl Kovach is a Senior Project Leader within the Navigation Division of The Aerospace Corporation in El Segundo, CA. Karl has over 35 years working on various aspects of the GPS program, including 3 years as the Air Force Officer-in-Charge of the GPS Control Segment when it was at Vandenberg AFB, CA (1983-1986). Karl received his BS degree in Mechanical Engineering from UCLA in 1978.

Philip Mendicki is a Senior Project Engineer within the Navigation Division of The Aerospace Corporation, supporting the GPS Directorate and the 2nd Space Operations Squadron. He has been involved in the operation and development of GPS Space and Control Segments since 1998. He holds a B.S. in Applied Physics from The United States Air Force Academy.

Ed Powers received his BS and MS degrees in Electronic Engineering and Instrumental Science from the University of Arkansas in 1984 and 1987, respectively. In 1987, he joined the U.S. Naval Research Laboratory as an engineer working on the GPS satellite clock development program, GPS UE testing and advanced GPS timing systems. In 1997, he joined the U.S. Naval Observatory (USNO) in Washington, D.C., and is the GNSS and Network Timing Operations Division Chief responsible for development of improved precise time synchronization and GPS timing.

Brent Renfro is a Program Manager within the Space and Geophysics Laboratory of Applied Research Laboratories, The University of Texas at Austin (ARL:UT). He has a Bachelor's degree in Physics from Wabash College and a Master's degree in Computer Science from The University of Texas at Austin. Mr. Renfro has been involved in development of systems for collecting and processing GPS data since 1979.

ABSTRACT

On 25-26 January 2016, Global Positioning System (GPS) users experienced a rare anomaly in GPS operations. For several hours, multiple satellites broadcast information regarding the offset between GPS time and coordinated time universal (UTC) in a manner that did not conform to the GPS signal interface specification (IS-GPS-200). This paper describes what data was broadcast at what times and the manner in which the contents of the signal did not conform to the specification. We discuss the scope of problems reported and the classes of users that were possibly subject to problems. We describe the impact of the anomaly with respect to public assertions made by the U.S. government in the GPS Standard Positioning Service Performance Specification. We describe how the existing interface specification provides sufficient information to detect the non-conforming data such that receivers can protect against such faults in the broadcast data.

INTRODUCTION

On 25-26 January 2016, GPS users experienced a rare anomaly in operations. For several hours, multiple satellites broadcast information regarding the offset between GPS time and UTC in a manner that did not conform to the GPS signal interface specification (IS-GPS-200[1]).

The flaws had no impact on GPS positioning and navigation. However, some GPS timing receivers that use the broadcast UTC correction information to derive UTC time experienced difficulties. Examination of the broadcast data combined with a review of the interface specifications show how the flawed broadcast data could have been detected and rejected by receivers.

Even though the flawed data could have been rejected, there are improvements that could be made to both the GPS control segment and to GPS receivers to reduce the likelihood of such problems in the future. Suggestions for several such improvements are listed at the end of the paper.

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DEFINITION OF TERMS

To maintain clarity, the following terms will be used throughout the paper.

GPS Time (t_{GPS}) - A smooth and continuous timescale that started on midnight of 5/6 January 1980 and continues into the indefinite future. GPS time is used for all GPS positioning and navigation calculations. It is usually expressed in terms of Week Number (WN) since the beginning of t_{GPS} and Time of Week (TOW) since most recent Sat/Sun crossover. All week numbers provided in the navigation message are truncated representations of the full GPS WN.

Coordinated Universal Time (UTC, t_{UTC}) – UTC is the legal basis of timing for the United States and most industrial countries as specified in public law and as part of the Treaty of the Meter which establishes a uniform set of weights and measures. UTC is not continuous in that it is occasionally adjusted by leap seconds which are needed to keep UTC linked to the rotation of the earth.

CNAV – The GPS Civil Navigation message; i.e. the message defined in IS-GPS-200 Section 30 and in IS-GPS-705[2].

LNAV – The GPS Legacy Navigation message; i.e. the message defined in IS-GPS-200 Section 20.

UTC(USNO) – UTC as maintained by the United States Naval Observatory (USNO).

UTCO data set – The set of four UTCO parameters (WN_t, t_{ot}, A_0, and A_1) in subframe 4 page 18 (SVID 56) of the LNAV message.

t_E - GPS receiver's estimate of current GPS TOW.

UTCO reference time, t_{ref} – The reference time of a UTCO data set; the point in t_{GPS} represented by the properly resolved WN_t and t_{ot} parameters.

UTCO, Δt_{UTC} – The UTC Offset. The difference between t_{GPS} and t_{UTC} at a given moment. The UTCO broadcast by GPS allows the user to convert between GPS time and UTC(USNO).

UTCOE - UTC Offset Error. The error in the UTCO prediction provided in the navigation message and the true UTCO as measured by U.S. Naval Observatory (USNO).

SPECIFICATIONS AND STANDARDS

The UTC data set for LNAV is defined in IS-GPS-200 Section 20.3.3.5.1.6, Figure 20-1 (sheet 8), and Table 20-IX. The interpretation of the LNAV data set is described in IS-GPS-200 Section 20.3.3.5.2.4. The location of the parameters within subframe 4, page 18 (SVID 56) is shown in Figure 1. The parameters of the UTC data set are highlighted.

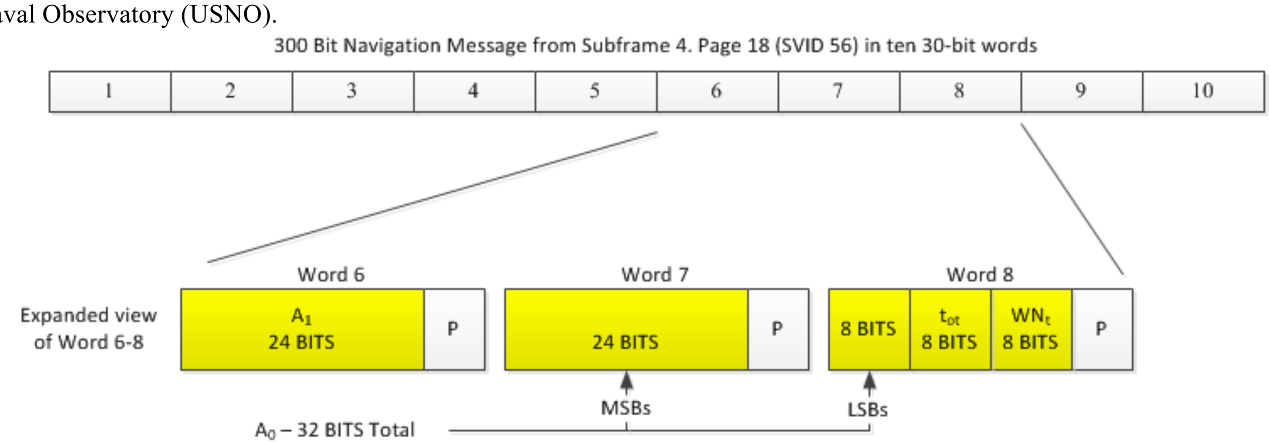

Figure 1 - Location of LNAV UTCO Parameters

Table 1 is an abbreviated version of IS-GPS-200, Table 20-IX, that summarizes how to convert the bits within the navigation message into quantities that may be used in calculations. While not discussed further in this paper, the interpretation of the WN_t parameter has an additional complication. The WN_t has only 8 bits. This implies a range of values from 0-255, which is insufficient to represent the full GPS week number. The receiver must consider both the broadcast value of WN_t and the current GPS week in order to derive a WN_t that accounts for this truncation and week number rollovers.

Table 1 - Summary of UTC Parameters

Parameter	No. of Bits	Scale Factor (LSB)	Units
A_0	32*	2^{-30}	seconds
A_1	24*	2^{-50}	sec/sec
t_{ot}	8	2^{12}	seconds
WNt	8	1	weeks

*- *Parameters so indicated shall be two's complement.*

There are two places in the Standard Positioning Service Performance Standard (SPS PS)[3] where assertions regarding the UTCOE are provided:

- Section 3.4.4 UTCOE Accuracy - ≤ 40 nsec 95% Global Average UTCOE during Normal Operations at Any AOD.
- Section 3.5.4 UTCOE Integrity - The assertion states a ≤ 1 x 10^{-5} probability over any hour of the SPS SIS Instantaneous UTCOE exceeding ±120 nsec tolerance without a timely alert during Normal Operations. There are a number of additional conditions and constraints.

PURPOSE OF THE UTCO PARAMETERS

The UTCO parameters are provided to the users via the navigation message for two reasons:

- The parameters allow a GPS receiver to output time referenced to UTC. Internally, the receiver should conduct all position/navigation/timing computations in t_{GPS}. However, the UTCO parameters allow the receiver to translate the receiver t_{GPS} solution into a human-readable t_{UTC} output.
- The parameters allow a GPS receiver to accept UTC for initialization. In such cases, the receiver needs the UTCO parameters to translate t_{UTC} to t_{GPS} for internal use.

The UTCO parameters allow GPS to provide a UTC timing service that supports a large number of timing uses and applications around the world. Additionally, many navigation users require UTC to time stamp navigation data. The UTCOE of GPS is typically much better than the ±40 nsec 95^{th}% specified in the SPS PS. This is illustrated in Figure 2.

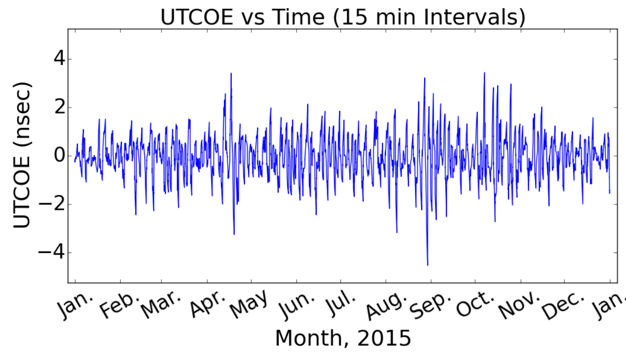

Figure 2 - UTCOE Performance of GPS

BROADCAST OF ANOMALOUS UTCO DATA

Beginning at 23:26:18 on 25 January 2016, flawed UTCO data was broadcast in LNAV by one or more GPS space vehicles (SVs) until 13:11:18 on 26 January 2016 when the valid UTCO data was once again present on all SVs. Overall 15 SVs were affected. A list of the affected SVs and the times that the data were transmitted is provided in Table 2. The flawed data set is denoted by the label "EE" in Table 2.

Table 3 provides a summary of all the unique UTC data sets broadcast on 24-25 January. Figure 3 is a graphical representation of when each data set shown in Table 3 was broadcast by a particular SV. The labels in the legend correspond to the dataset labels in Table 3.

As some users noted anomalous behavior, reports came to the U.S. Coast Guard Navigation Center and the GPS Operations Center. These reports were forwarded to the GPS system operators, who in turn stopped upload activities as they investigated the reports, identified and resolved the problem, and restored proper UTCO data. Taken together, Table 2 and Figure 3 illustrate the intense activity undertaken by the GPS system operators once they became aware of the flawed data. Typically, GPS SVs are uploaded once/day. There are 30 SVs so that works out to about 1.25 uploads/hr. During the period of roughly 11:30-13:00 of 26 January 2016, 15 SVs were uploaded, for a rate of 10 uploads/hr.

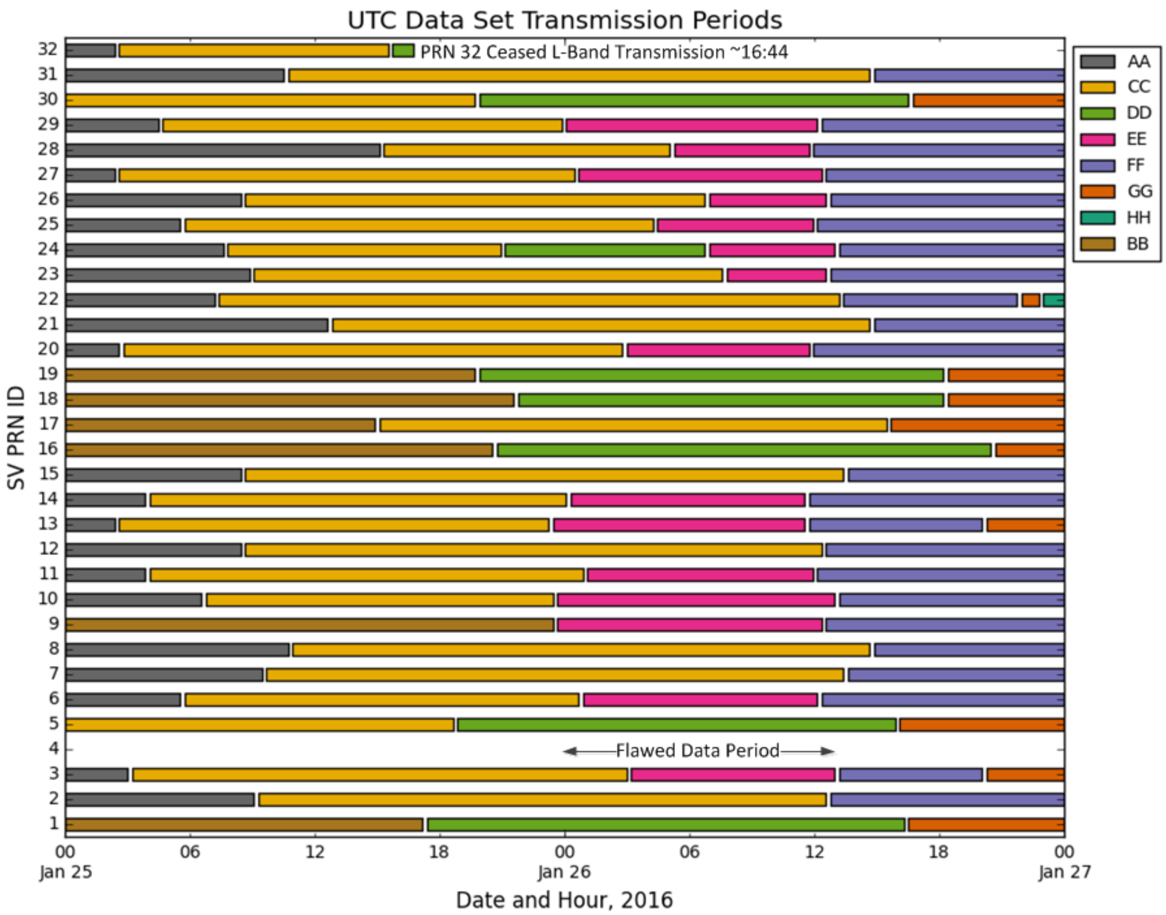

Figure 3 - Graphical Representation of UTC Data Set Cutovers for 25-26 January 2016
Note: Data set "EE" is the flawed data set

WHAT ABOUT CNAV?

The UTCO data sets broadcast in the pre-operational CNAV message were nominal throughout the period examined. There were no anomalous UTCO reference time values and no unusual values for A_0/A_1. Given the pre-operational nature of CNAV at the time of this event, these data sets will not be discussed further.

INTERPRETING THE DATA

The UTC offset data provides an offset and a rate of change at a given epoch (the UTC reference time). The receiver uses that information along with the time of interest (t_E) in the following equation from IS-GPS-200 20.3.3.5.2.4 in order to derive the UTCO:

$$\Delta t_{UTC} = \Delta t_{LS} + A_0 + A_1 (t_E - t_{ot} + 640800 (WN - WN_t)).$$

where

- Δt_{LS} – Current leap second
- WN – current full GPS week number
- WN_t – Week number of the UTCO reference time
- t_{ot} – Seconds of week of the UTCO reference time

In the context of this equation, it is important to note that the navigation message contains various representations of the full GPS week number, each of which is truncated at 8 bits or 10 bits. In this equation, WN is not the 10-bit value broadcast in subframe 1, and WN_t is not the 8-bit value of WN_t. Instead, WN and WN_t refer to full GPS week number values after accounting for truncations and rollovers. Taken together, t_{ot} and WN_t are the UTCO reference time (t_{ref}) for the UTCO data set.

Table 2 - Summary of UTC Offset Data Set Transmissions with Flawed Data, 25-26 January 2016

SVN	PRN	Start Time for Flawed Data: First Transmission	Start Time for Flawed Data: First 900s Epoch	Time Restored	Last Bad 900s Epoch	Duration (hh:mm)*
69	3	01/26 03:11:18	01/26 03:15	01/26 13:11:18	01/26 13:00	10:00
67	6	01/26 00:53:48	01/26 01:00	01/26 12:33:48	01/26 12:15	11:30
68	9	01/25 23:38:48	01/25 23:45	01/26 12:21:18	01/26 12:30	13:00
73	10	01/25 23:38:48	01/25 23:45	01/26 13:11:18	01/26 13:00	13:30
46	11	01/26 01:06:18	01/26 01:15	01/26 12:08:48	01/26 12:00	11:00
43	13	01/25 23:26:18	01/25 23:30	01/26 11:43:48	01/26 11:30	12:00
41	14	01/26 00:16:18	01/26 00:30	01/26 11:43:48	01/26 11:30	11:00
51	20	01/26 02:58:48	01/26 03:00	01/26 11:56:18	01/26 11:45	9:00
60	23	01/26 07:46:18	01/26 08:00	01/26 12:46:18	01/26 12:45	5:00
65	24	01/26 06:56:18	01/26 07:00	01/26 13:11:18	01/26 13:00	6:15
62	25	01/26 04:26:18	01/26 04:30	01/26 12:08:48	01/26 12:00	7:30
71	26	01/26 06:56:18	01/26 07:00	01/26 12:46:18	01/26 12:45	5:45
66	27	01/26 00:41:18	01/26 00:45	01/26 12:33:48	01/26 12:30	11:45
44	28	01/26 05:16:18	01/26 05:30	01/26 11:56:18	01/26 11:45	6:15
57	29	01/26 00:03:48	01/26 00:45	01/26 12:21:18	01/26 12:15	11:30

** - Measured from "First 900s Epoch" to "Last Bad 900s Epoch" inclusive of both.*

Table 3 - Unique UTC Offset Data Sets for 25-26 January 2016

Data Set ID*	Earliest Transmission	t_{ref} (mm/dd/yy hh:mm:ss)	A0 (sec)	A1 (sec/sec)
AA	01/24 00:08:48	01/26/16 16:51:12	-6.51925802e-09	-1.15463195e-14
BB	01/24 17:26:18	01/26/16 16:51:12	-1.86264515e-09	5.32907052e-15
CC	01/24 22:51:18	01/27/16 16:44:48	-9.31322575e-10	5.32907052e-15
DD	01/25 15:43:48	01/27/16 16:44:48	0.00000000e+00	1.24344979e-14
EE	**01/25 23:26:18**	**05/11/14 00:00:00**	**-1.36960298e-05**	**1.24344979e-14**
FF	01/26 11:43:48	01/28/16 16:38:24	1.86264515e-09	1.24344979e-14
GG	01/26 15:41:18	01/28/16 16:38:24	-1.86264515e-09	-8.88178420e-16
HH	01/26 22:58:48	01/29/16 19:56:48	-2.79396772e-09	-8.88178420e-16

** - Label used in Figure 3 and Table 4 to denote each set of data*

To illustrate the use of this equation, Table 4 provides the results of evaluating this equation at 00:00:00 26 January 2016 for each of the data sets shown in Table 3. The right-hand column of Table 4 provides the UTCO ignoring the contribution of the leap second. Table 4 shows agreement at the nsec level between all the data sets with the exception of the flawed data set (EE). The result for the flawed data set is in disagreement by five orders of magnitude.

Table 4 - UTCO Values at 00:00 on 26 January 2016 From All UTCO Data Sets Transmitted any Time 25-26 January 2016

Data Set ID*	Δt_{UTC} (sec)	Δt_{UTC} - Δt_{LS} (nsec)
AA	16.9999999978	-2.18597052
BB	16.9999999942	-2.18597052
CC	16.9999999983	-1.71303327
DD	16.9999999982	-1.82399162
EE	16.9999869754	-13024.56689670
FF	16.9999999990	-1.03091225
GG	16.9999999983	-1.65596248
HH	16.9999999975	-2.49997356

** - See Table 3*

Note that the UTCO value in Table 4 from data set EE is approximately -13.0 usec. This is noticeably different than the A_0 value of -13.7 usec shown for data set EE in Table 3. The difference is due to the role of A_1 in the Δt_{UTC} equation. In the case of the flawed data set, the A_1 term is being propagated for 625 days to derive the value in Table 4. Even a very small rate of change contributes a noticeable effect over a long period. If the user ignores the A_1 term, the UTCO will be increasingly inaccurate the further the evaluation time moves from the UTCO reference time. For example, in Table 4 if the A_1 term is ignored for data set EE, the result will be -13.7 usec rather than -13.0 usec.

The evaluation time used in the previous paragraph was arbitrarily chosen as a specific t_E that fell within the period of the anomaly. To examine the degree of agreement between the UTCO data sets further, the UTCO was computed for each unique data set for all of 24-30 January 2016 (Week 1881). Each data set was evaluated from the time of first transmission by any SV until the time it was last transmitted by any SV. This was done at a 15 min. evaluation interval. The results (modulo Δt_{LS}) are shown in Figure 4. Results from the flawed data set are omitted because they are far offscale.

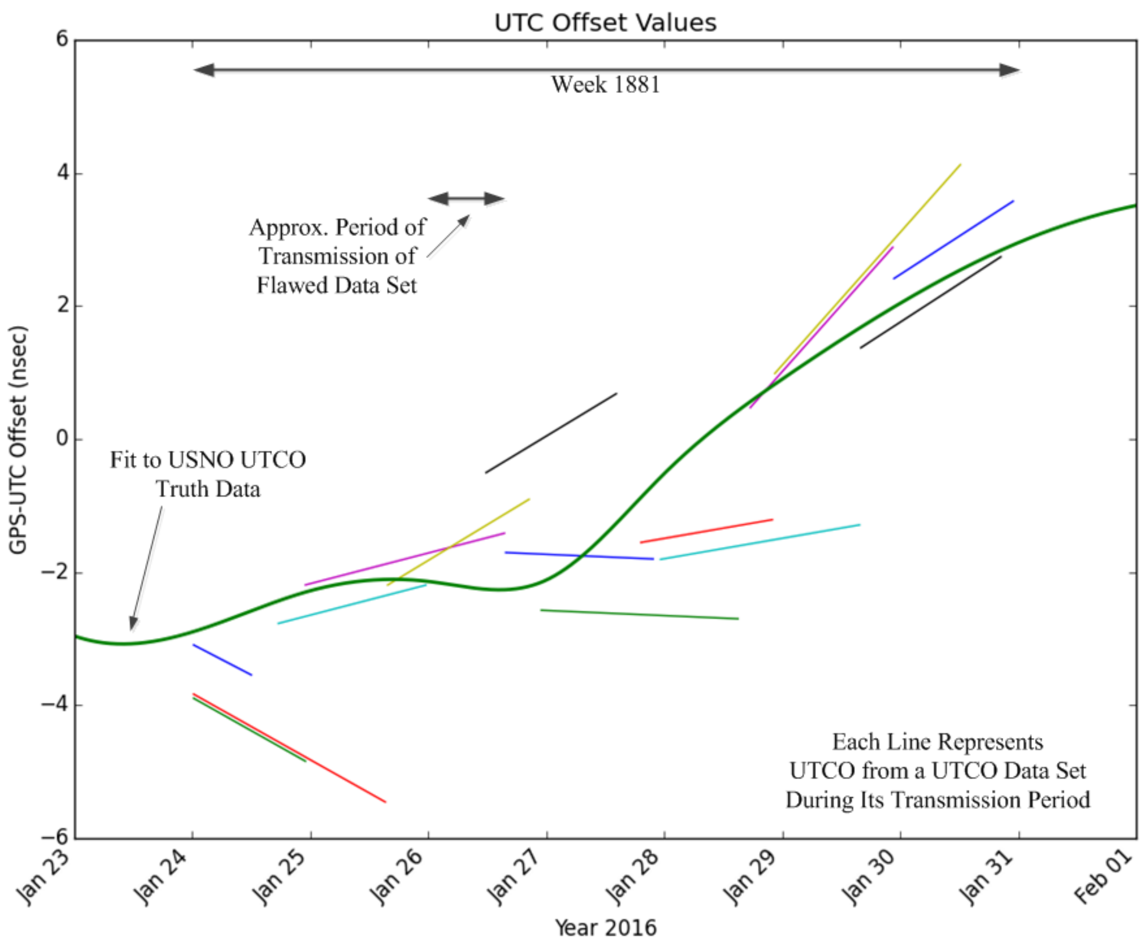

Figure 4 - UTC Offset As a Function of Time for Various UTC Data Sets (Flawed Set Excluded)

The actual UTCO as estimated by USNO was not the cause of these anomalies. USNO estimates the timing difference between GPS Time and UTC(USNO). This data is provided to GPS operations daily, which is used to align GPS Time (modulo whole second differences) and build the UTCO correction message. GPS Time is specified to be kept within one microsecond of UTC(USNO) modulo whole second offset. Over the past 20 years GPS Time has been kept within 10 nanoseconds of UTC(USNO) modulo whole second differences. After applying the UTCO message, a GPS user receiver can produce a representation of UTC accurate to within a few nanoseconds of UTC(USNO). Figure 4 includes a cubic spline fit to the daily observations.

During this UTCO anomaly, all users worldwide always had access to at least one correct UTC data set in addition to the flawed data set through the time period the flawed data set was being broadcast. This was confirmed by overlaying a one degree grid on the Earth and determining the number of unique UTC data set transmissions visible at each grid point at every 30s interval.

The flawed data set exhibited characteristics that were clearly in conflict with IS-GPS-200. The UTCO reference time associated with data set "EE" in Table 3 is well in the past with respect to the time period in which it was transmitted. The UTCO fit interval is illustrated in Figure 5. The normal curve fit for UTCO data sets is 144 hrs (6 days). The UTCO reference time is nominally 70 hrs after the start of the curve fit interval (subject to least significant bit representation limitation). (This definition is in IS-GPS-200 Section 20.3.4.5, Table 20-XIII).

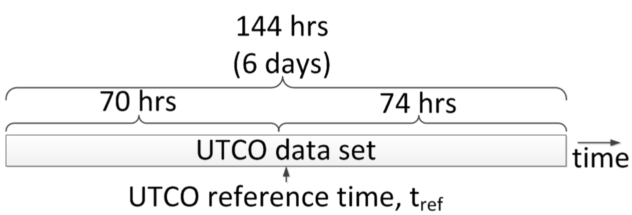

Figure 5 - UTCO Data Set Fit Interval

IS-GPS-200 provides the following guidance on fit intervals in 20.3.4.4:

> "Each data set nominally remains valid for the duration of its curve fit interval."

The antithesis is also true, each data set should be regarded as invalid outside the duration of its fit interval. If circumstances dictate it must be used, degraded performance beyond that stated in the SPS PS may be the result.

The fit interval implied by the reference time of data set EE is the period from 02:00 8 May 2014 to 02:00 14 May 2014 (almost two years in the past). No part of this fit interval overlaps the transmission period of data set EE. Therefore, this data set should have been judged invalid by receivers as the data set was received.

In general, a UTCO data set should not be used outside its' curve fit interval. The exceptions are in situations when the entire constellation is operating in extended operations mode (which has never happened) and when a receiver is resuming operation after a long period off (e.g. more than a week). In the latter case, an aged UTCO data set that was previously collected and stored may be used temporarily to provide an initial estimate of the current UTCO. As always, the results may be degraded when data are used outside their curve fit interval.

SELECTING UTC DATA SETS

As seen in Figure 4, multiple unique data sets are being transmitted at any moment. A given user may have three or more data sets to choose from considering only the data sets currently being transmitted. IS-GPS-200 does not contain explicit guidance on how the user is to select between data sets.

This realization led to discussion on possible algorithms for selecting UTC data sets in a resilient manner. The following algorithm takes into account the description of healthy SVs as described in SPS PS 2.3.2 and the time requirements in IS-GPS-200 20.3.4.5

Select the data set with the following characteristics:

a. *The data set is currently being broadcast by a healthy SV with an elevation angle of 5 degrees or greater.*
b. *The data set has a t_{ref} that is in the range (current time) $\leq t_{ref} \leq$ (current time + 72 hours).*
c. *The data set has a t_{ref} corresponding to the latest time of those fulfilling conditions (a.) and (b.).*

There are some limitations to this approach.

1. It assumes the user is tracking more than one SV; ideally all SVs in view.
2. It disallows the use of stored data and requires the collection and examination of each page 18, subframe 4 that is broadcast.
3. The algorithm guards against "unreasonably early" and "unreasonably late" data, but does not guard against data sets with reasonable t_{ref} values but invalid A_0/A_1 values.

Figure 6 illustrates the UTCOE obtained for the GPS week that includes 25-26 January 2016 using this selection algorithm. The UTCOE remains within ±2 nsec and no excursions are present despite the flawed data set.

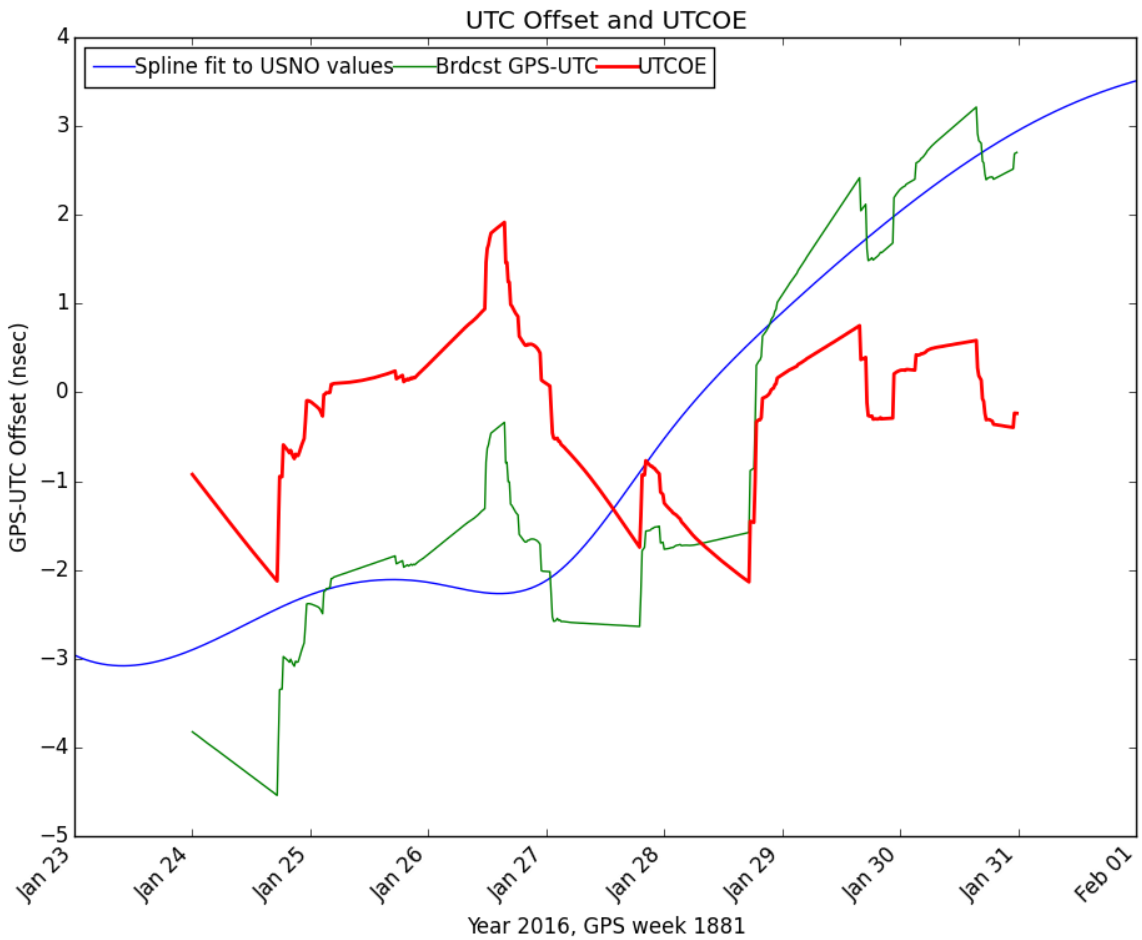

Figure 6 - USNO UTCO, GPS broadcast UTCO, and UTCOE for GPS Week 1881 (24-30 January 2016)

IMPACT TO USERS

Despite the flawed data set, there were no impacts to GPS positioning and navigation. Furthermore, GPS time (t_{GPS}) was unaffected. Only a subset of the functions that make use of the GPS-UTC offset were affected.

- A user initializing a receiver from a cold start would not be affected by a -13 usec error in the GPS-UTC offset. That is not large enough to impact initial SV acquisition.
- Many precise timing and time interval (PTTI) users were adversely affected by the -13 usec error induced by the flawed data. However, a significant number of user receivers recognized the flawed UTCO data and did not use the anomalous UTCO data.

Of the latter two categories, the specific impact was dependent on how the user equipment and/or data processing were implemented (e,g. -13.0 usec or -13.7 usec).

In broad terms, the large majority of GPS users were not impacted by this anomaly. However, a small but very high-value community saw the impact quite clearly.

MEANING WITH RESPECT TO IS-GPS-200

Broadcast of a UTCO data set with a UTCO reference time in the past is a violation of the requirement that the UTCO reference time shall represent a time 70 hours in the future at the time of first broadcast.

MEANING WITH RESPECT TO THE SPS PS

There was no violation of the accuracy assertion in the SPS PS for receivers that honor the UTCO data set fit interval. However, a receiver that ignores the IS-GPS-200 requirement regarding the fit interval for the UTCO data sets may have seen up to 13.5 hours of UTCOE values that were greater than the ±40 nsec accuracy assertion. Typically, the accuracy assertions are evaluated for 30 day periods. Therefore, 36 hours of UTCOE values above the threshold would be required to violate the 95th% statistic. (There are 30 days X 24 hours/day X 0.05 = 36 hours.)

There was no violation of the integrity assertion for receivers that honor the UTCO data set fit interval. This assertion is stated as a by-SV metric. As shown earlier, a receiver that rejected UTCO data sets outside their fit interval would never select the flawed data. However, a receiver that ignores the IS-GPS-200 requirement regarding the fit interval for the UTCO data sets may have seen up to 15 UTC data sets that violated the ±120 nsec NTE threshold.

GOING FORWARD

Several improvements to GPS are possible in order to prevent a recurrence of this anomaly or, at the least, further reduce the impact of any future anomalies.

1. There are a number of data checks that can be performed in the control segment after an upload is prepared and prior to the moment the data are uploaded to each SV. Such a tool can be implemented relatively quickly as an off-line process while a fully integrated tool is added to the system requirements for the future.
2. The GPS Directorate is undertaking development of a new appendix to the SPS PS in which best practices for handling GPS data within receivers will be addressed. This will provide a means of communicating to users "how to" information that is not appropriate for interface specifications but useful in understanding appropriate interpretation of the specifications.
3. In the long run, improved monitoring is needed. In the case of this particular anomaly, the operators were unaware of the problem until external user reports arrived at 2SOPS. Once the operators became aware of the anomaly, further uploads ceased, the cause was identified, and the flawed data set updated as quickly as practical.

Each of these approaches should be undertaken with an eye to addressing more than the anomaly currently under consideration, but looking for additional possible fault conditions that may be addressed in advance.

CONCLUSION

A rare combination of events led to the computation of an incorrect UTCO data set. Over the course of 8 hours, 15 satellites were uploaded with this incorrect UTCO data. Once the GPS system operators received word of the problem, uploads stopped until the problem was corrected, and over the next few hours all satellites were uploaded with correct UTCO information. GPS position and navigation were unaffected by this anomaly. Timing users with receivers that implement fit interval checks on the UTCO data sets were unaffected. The root cause has subsequently been addressed and additional actions are being considered.

REFERENCES

[1.] Navstar GPS Space Segment/Navigation User Interfaces, IS-GPS-200, Revision H. http://www.gps.gov/technical/icwg/, dated Sep 24, 2013

[2.] Navstar GPS Space Segment/Navigation User Interfaces, IS-GPS-705, Revision D. http://www.gps.gov/technical/icwg/, dated Sep 24, 2013

[3.] Standard Positioning Service Performance Standard, 4th Edition, 2008, http://www.gps.gov/technical/ps