Improved Ephemeris Monitoring for GNSS

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ABSTRACT

GNSS performance monitoring is an important component of aviation safety. RAIM, SBAS, GBAS, and ARAIM all meet their safety and availability analyses by assuming certain levels of performance from the GPS L1 C/A signals. In the future, most of these systems will utilize new signals and new constellations. It will be vitally important to verify the level of performance of these additional resources. Currently, GPS flags its integrity status in a variety of methods including broadcast flags in the navigation data as well as by broadcasting alternative codes and/or alternative data bit sequences. Unfortunately, these latter two methods are not necessarily reflected in archived navigation data sets. When a receiver observes NAV data bits that do not pass parity it typically discards the data and the NAV bits are not saved for further evaluation. Aviation receivers are required to set a GPS satellite unhealthy if parity fails on five successive words (3 seconds). However, non-aviation receivers may elect to continue tracking in this situation, which may lead to the appearance that all is well with the satellite.

We propose a new navigation data archive format that saves all of the navigation data bit data regardless of parity checks. This format allows the subsequent detection of non-standard data (NSD) broadcasts. It would also reveal the use of non-standard codes (NSC) that also can be difficult to detect. When an NSC is broadcast, most receivers stop tracking the satellite. This fact is not recorded in navigation data files, but may be seen in the observation files. Further, sometimes receivers cross-correlate the missing satellite's PRN code with another satellite's, and report that observation data as though it came from the satellite broadcasting NSC. This discrepancy can be detected by comparing the expected pseudorange to the observed data. However, this process is cumbersome. By recording the raw navigation data bits, an NSC broadcast becomes more obvious. Either there is a lack of data, which is readily apparent, or the recorded bits correspond to the other satellite being mistaken for the absent PRN. In the latter case, identical bits can be seen for two PRNs. A voting method across multiple receivers can be used to determine which is the true data set. Alternatively, some of the new signals will contain the PRN in the navigation data. This inclusion will make the mistaken record obvious.

INTRODUCTION

This paper proposes a new format to record raw navigation data that will allow a much more rigorous evaluation of the NAV data accuracy and integrity. It fills in some missing pieces of information that currently make it difficult to fully evaluate GPS performance. We further show how these missing pieces of information are used by GPS to maintain the integrity for the users.

We examine some of the recent GPS events and how they were indicated to users via NSD and NSC. We examine the time history of such faults and show that we have to infer the NSD and NSC states. Having direct measurements of such data removes any ambiguity and further allows us to determine the precise time of change over from one set of ephemeris data to the next.

There is a further benefit of recording the raw data bits. Sometimes message formats for the satellites change. For example, when the RINEX format for the GLONASS navigation data was set, GLONASS did not broadcast URA values for its satellites. GLONASS has since changed its operation and broadcasts URA values. Unfortunately, these critical values for aviation are not recorded in any RINEX data sets. By recording the raw data bits, such changes can be more easily accommodated. No information is lost. One simply has to update the tool that translates the bits into their intended values.

GPS LEGACY NAVIGATION MESSAGE ON L1

The legacy navigation (LNAV) message frame has a length of 1500 bits [1] [2]. It is transmitted on the L1 C/A code at a rate of 50 bits per second (bps) and therefore takes 30 seconds to transmit a full frame. Each frame contains five subframes, each consisting of ten 30-bit words. Each word is 30 bits long and contains 24 data bits and six parity bits. The parity bits are used to detect bit errors. Subframes 1 – 3 contain orbit and clock information for the transmitting satellite. Subframes 4 and 5 contain almanac information for all GPS satellites as well as other information. The International GNSS Service (IGS) has defined a NAV message RINEX format to record the legacy navigation message data from the GPS L1 C/A signal [3]. The RINEX data format includes all of the parameters related to the broadcast satellite orbit and clock ephemeris data. However, some of the other information is either not recorded or ambiguously defined.

The navigation data broadcast from the satellites consists of raw bits whose meaning is specified in the corresponding interface specification document [1]. These bits are usually translated into an integer value and then multiplied by a scaling factor to obtain a floating-point value. Depending on machine precision and coding, two receivers may obtain slightly different floating-point representations for the same raw bit pattern. Further, we have seen misinterpretations where the wrong values are recorded to file. For example, we have observed RINEX files where the longitude of ascending node of orbit plane at weekly epoch (Ω_0) and the argument of perigee (ω) were swapped. The former is represented by a capital OMEGA, and the latter by a lower case omega. Clearly, they were confused for each other.

Ephemeris data sets are identified by their issue of data clock (IODC) and issue of data ephemeris (IODE) numbers. The IODC is sent in Subframe 1 and the IODE is in Subframes 2 and 3. Paragraph 20.3.4.4 of [1] defines the relationship 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.*"

In practice, the IODC and the IODE are usually the same number and so the IODE is often not reused within seven days either. The IODE/IODC is treated as the unique identifier of the ephemeris data set and the data content should not change unless this value changes, although violations of this have been observed in the past [4].

Figure 1 contains an example RINEX navigation message data record from a GPS satellite. The top is the actual record with the numerical values, while the bottom identifies the parameters. PN is the 2 digit PRN #, YR is the 2 digit year, MT is the month, DY is the day of month, HR is the hour, MN is the minute and SEC is the second: all corresponding to the broadcast time of clock (TOC). This record is for PRN 1. It has an IODE of 46 and its TOC corresponds to September 30, 2015, 02:00:00 UTC. The actual transmission time of the message (TTOM) was recorded as a time of week (TOW) = 260220 seconds, which corresponds to 00:17:00 UTC on that day. This is an unusual update time as most ephemeris information is changed on the hour mark. This one was apparently

```
 1 15  9 30  2  0  0.0 1.430511474609E-06 6.821210263297E-13 0.000000000000E+00
    4.600000000000E+01-2.446875000000E+01 4.966992609465E-09 6.967783926683E-01
   -1.311302185059E-06 4.723111400381E-03 4.101544618607E-06 5.153652746201E+03
    2.664000000000E+05 1.676380634308E-08 2.100889330268E+00 5.215406417847E-08
    9.626767296585E-01 3.023437500000E+02 4.808965869760E-01-8.489996499575E-09
   -1.842933908452E-10 1.000000000000E+00 1.864000000000E+03 0.000000000000E+00
    2.400000000000E+00 0.000000000000E+00 5.122274160385E-09 4.600000000000E+01
    2.602200000000E+05 4.000000000000E+00

PN YR MT DY HR MN  SEC  Clock Bias (af0)   Clock Drift (af1) Clk Dft Rate (af2)
            IODE             Crs                 Delta n              M0
            Cuc          eccentricity              Cus              sqrt(A)
            TOE              Cic                  OMEGA               Cic
     Inclination (i0)        Crc                  omega            OMEGA DOT
           IDOT          Codes on L2           GPS Week #       L2 P data flag
     SV accuracy (m)      SV health                 Tgd                IODC
           TTOM          Fit interval              spare               spare
```

Figure 1. *Example RINEX GPS legacy navigation data (top) and corresponding format (below)*

changed at 17 minutes past midnight UTC.

What is recorded for TTOM is not the actual first time of transmission of the data, but rather when the receiver first observes the data set. Since the data set takes 18 seconds to transmit, there is uncertainty as to whether this time stamp corresponds to the first bit, the last bit, or some other time stamp. It seems most likely that in this case, the ephemeris data was first transmitted between 00:17:00 and 00:17:18. However, it is possible that it was first transmitted between 00:16:30 and 00:16:48 and not recorded until the end of the full frame. It is also possible that the satellite was not properly observed when it first started broadcasting this ephemeris. If the data were incomplete or the parity bits did not match, the first transmissions of this message could have been discarded. This creates uncertainty as to when a particular ephemeris data set first becomes active. In turn, this leads to ambiguity as to when a fault begins or ends, as we may not know when faulty data was first transmitted or when a health bit is first set to unhealthy.

It is possible for new ephemeris data to start transmission within a frame. For example, Subframe 1 and 2 could correspond to one IODE, but Subframe 3 could be the beginning of a new data set. In such an example, Subframe 3 could be transmitted between 04:00:12 and 04:00:18. The first transmission of the corresponding Subframes 1 and 2 would then occur at 04:00:30 and 04:00:36 respectively. The first possible use of this new data set could occur at 04:00:42. It is not clear what TTOM would be recorded in this event, nor would this unusual sequence be identified in any way by the existing format.

Subframe 1 contains health bits that indicate whether or not the satellite is safe to use. This is the primary mechanism for indicating a satellite fault. However, it takes time before the satellite health bit can be changed. It is only broadcast every 30 seconds and may require a manual upload of data. There are more immediate mechanisms to indicate a satellite fault even when the health bits indicate that the satellite is healthy. The GPS standard positioning service (SPS) performance standard (PS) [5] specifies: "*Alert – Alarm Indications. An otherwise healthy SPS SIS or marginal SPS SIS becomes unhealthy when it is the subject of a SPS SIS alarm indication. The presence of any one of the 9 alarm indications listed below means the information provided by the SPS SIS may not be correct. The SPS SIS alarm indications are defined to include the following:*

(1) The SPS SIS becomes untrackable (e.g., ≥ 20 dB decrease in transmitted signal power, ≥ 20 dB increase in correlation loss):

(a) The SPS SIS ceases transmission.

(b) The elimination of the standard C/A-code.

(c) The substitution of non-standard C/A-code for the standard C/A-code.

(d) The substitution of PRN C/A-code number 37 for the standard C/A-code.

(2) The failure of parity on 5 successive words of NAV data (3 seconds).

(3) The broadcast IODE does not match the 8 LSBs of the broadcast Index of Data Clock (IODC) (excluding normal data set cutovers, see IS-GPS-200).

(4) The transmitted bits in subframe 1, 2, or 3 are all set to 0's or all set to 1's.

(5) Default NAV data is being transmitted in subframes 1, 2, or 3 (see IS-GPS-200).

(6) The 8-bit preamble does not equal 10001011, decimal 139, or hexadecimal 8B."

The first item (accomplished via any of the four sub-bullets) usually results in an untracked signal. However, high elevation angle satellites can have enough power to be tracked when (1c) or (1d) are used. If the satellite is no longer tracked or the power drops by 20 dB, it can be observed in the RINEX observation files, but will not be apparent in the navigation file records. Items (2) and (4-6) will not be necessarily be apparent in either RINEX file although a receiver may elect stop tracking in the event of (2). Item (3) may or may not be captured in the RINEX navigation file. There is a reasonable likelihood that a record with non-matching IODEs and IODC will be discarded rather than recorded.

Thus, there are several integrity alert conditions that are not recorded in the RINEX data, but that are vitally important to determining whether or not a fault has been indicated to the user. This information is essential for evaluating the performance of the GPS satellites. In a later section we will propose a new format to capture this alert information.

GLONASS NAVIGATION MESSAGE

GPS is not the only fully operating constellation. GLONASS also has a full complement of satellites and IGS has defined a navigation message format specifically for GLONASS [3]. Unfortunately, this format was initially defined a long time ago, before GLONASS transmitted a user range accuracy parameter to specify its level of performance. This parameter is required in order to determine the quality of GLONASS performance. However, it is not recorded in any RINEX navigation data files for GLONASS. In order to evaluate GLONASS

```
 1 15  9 30  5 45  0.0-1.498144119978D-04 0.000000000000D+00 2.142000000000D+04
   -1.348158886719D+04 9.845218658447D-01 0.000000000000D+00 0.000000000000D+00
    9.494493164062D+03-2.475769996643D+00 1.862645149231D-09 1.000000000000D+00
    1.945978369141D+04 1.891643524170D+00-2.793967723846D-09 0.000000000000D+00

PN YR MT DY HR MN  SEC  Clck Bias (-TauN) Fqcy Drft (+GammaN) Frame Time (tk)
     X Position (km)    X Velocity (km/s)  X Accel. (km/s^2)     Health (Bn)
     Y Position (km)    Y Velocity (km/s)  Y Accel. (km/s^2)   Frequency Num.
     Z Position (km)    Z Velocity (km/s)  Z Accel. (km/s^2)  Age of Operation
```

Figure 2. *Example RINEX GLONASS navigation data (top) and corresponding format (below)*

performance the accuracy value has to be assumed or obtained from another source [6].

Figure 2 shows example GLONASS data (top) and the corresponding data format (bottom). This data is for the satellite in the first slot and the epoch of ephemeris for is also for the day September 30, 2015, but at time 05:45:00 UTC. Note that GLONASS data is actually transmitted in Moscow time, which is 3 hours earlier than UTC, but the timestamp is converted when recorded to RINEX.

The GLONASS message nomenclature is a little different than GPS. The GLONASS superframe has a length of 7500 bits [7]. It is transmitted at a rate of 50 bits bps and therefore takes 2.5 minutes to transmit a full superframe. Each superframe contains five frames each consisting of 15 100-bit strings. Each string requires 2 seconds to transmit and consists of 85 data bits (including 8 check bits) and 15 timing bits. Strings 1 through 4 contain the "immediate" orbit and clock information for the transmitting satellite. String 4 includes a parameter, called F_T, which describes the expected satellite accuracy (comparable to URA for GPS). However, this parameter was not present when GLONASS RINEX navigation format was first developed.

There is also the possibility of even more significant GLONASS message structure changes in the future [8]. The current message structure does not support more than 24 satellites and GLONASS is interested in one day supporting a greater number of satellites. GLONASS has historically shown a willingness to change its operation by making improvements that are not backwards compatible. It is possible that future changes would not be compatible with the current RINEX GLONASS message structure.

GPS CIVIL NAVIGATION MESSAGE

The GPS civil navigation (CNAV) Message has a flexible structure consisting of 300 bit messages with a 38 bit header section, 238 data bits and a 24 bit Cyclic Redundancy Check (CRC) [9] [10]. A maximum of 64 different message types are supported. The CNAV data rate is 25 bps for L2C and 50 bps for L5.

The new CNAV messages promise greater accuracy by reducing quantization error. They also offer greater flexibility, as the messages are not on a fixed time sequence and new messages can be defined. This flexibility is not as good a fit for the fixed RINEX format. New formats may need to be defined whenever a new message type is created.

The GPS civil navigation message that is to be used on L1C on GPS III satellites (CNAV-2) also has a flexible structure. The CNAV-2 messages consist of an 1800 symbol frame with a 52 symbol subframe 1, 1200 symbol subframe 2, and 548 symbol subframe 3 [11]. The CNAV-2 data rate is 100 sps. Subframe 1 consists of a 9 bit time of interval encoded using a BCH (51,8) code. Subframe 2 consists of clock and ephemeris data, and subframe 3 consists of variable messages. Subframe 2 and 3 are interleaved together and individually encoded with a ½ rate low density parity check (LDPC) as well as a 24 bit CRC.

CNAV-2 clock and ephemeris parameters are the same as those used in the CNAV messages and also offer reduced quantization error. As with the CNAV messages, CNAV-2 subframe 3 messages are not broadcast with any fixed sequence, and additional subframe 3 messages can be defined. Because of the variety of subframe 3 message types and error correction and detection techniques, CNAV-2 may also not be a good fit for the fixed RINEX format.

GALILEO NAVIGATION MESSAGES

Galileo has different navigation message formats depending on the transmitting signal [12]. The F/NAV data is associated with its open service and they are transmitted on the E5a-I frequency signal at a rate of 25 bps. The I/NAV navigation data is associated with both open and the commercial services and is transmitted on both E1-B and E5b-I signals at a rate of 125 bps. Both formats employ forward error correction (FEC) encoding with convolutional encoding rate = 1/2. Thus, there are twice as many symbols per second as there are bits per second.

The F/NAV message consists of a 600 second – 15,000 bit – frame that is composed of 12 50-second subframes that in turn consist of five 10-second pages. Each page has a unencoded 12 symbol synchronization pattern, followed by a 244 bit message containing 6 bits to identify the page type, 208 data bits, 24 CRC bits, and 6 tail bits. Each subframe contains the clock and ephemeris parameters for the satellite as well as almanac information for one and a half other satellites.

The I/NAV message consists of a 720 second – 90,000 bit – frame that is composed of 24 30-second subframes that in turn consist of 15 two-second pages. Each page has two one-second page parts that alternate between even and odd. Each page part has a unencoded 10 symbol synchronization pattern, followed by 114 bits of data and 6 tail bits. Each page part may contains the clock, ephemeris or the almanac information. There are many reserved bits and opportunities for future definitions.

BEIDOU NAVIGATION MESSAGES

BeiDou also has different navigation message formats, but these depend on the transmitting satellite [13]. The D1 NAV data is broadcast at 50 bps and is analogous to the GPS NAV data. The D2 NAV data is broadcast at 500 bps and is analogous to SBAS augmentation data.

The D1 message is very similar to GPS [14]. It is broadcast from the MEO and ISGO satellites and consists of a 720 second – 36,000 bit – superframe that is composed of 24 30-second frames, that in turn consist of five six-second subframes. Each subframe has ten 30-bit words. Each word has 24 bits of data and 4 parity bits. Like GPS, subframes 1-3 have clock and ephemeris information for the broadcasting satellite, while subframes 4 and 5 have almanac information for the other satellites.

The D2 message is BeiDou GEO satellites and consists of a 360 second – 180,000 bit – superframe that is composed of 120 three-second frames, that in turn consist of five 0.6-second subframes. Each subframe has ten 30-bit words. As for D1, each D2 word has 24 bits of data and 4 parity bits. Subframe 1 has the basic NAV information of the broadcasting satellite, subframes 2-4 have integrity and differential correction information, and subframe 5 has almanac, ionospheric grid point data, and time offsets from other systems.

SBAS AND OTHER NAVIGATION MESSAGES

SBAS satellites broadcast correction and integrity information at 500 symbols per second [15]. The signal uses FEC with ½ convolutional encoding resulting in 250 bps. Each message is 1 second long and consists of 14 header bits, 212 data bits, and 24 CRC bits. Multiple messages are defined and any message can be transmitted at any second. There are many available message types that have not yet been defined.

There are regional augmentation systems such as Japan's quazi-zenith satellite system (QZSS) [16] and the Indian regional satellite system (IRNSS) [17], that also have different message structures. These signals should also be preserved for examination.

PROPOSED RAW BIT RINEX DATA RECORD

The RINEX navigation message format was not intended to analyze satellite faults or to diagnose unusual behavior in their operations. They were simply intended to capture the basic navigation data so that receivers could form position fixes. More often than not they are not even used, as most IGS users want the higher precision post-processed ephemeris data. Nevertheless, it has been a useful tool for investigating satellite performance. However, we interested in now doing better, and that requires capturing more information.

We propose to create a new format that captures all of the raw bits, regardless of signal power, parity check, matching IODEs/IODCs, or any other consistency checks. Instead the raw bits should be recorded according to the output of the tracking loop. We will later perform evaluations after first capturing the data to file. In post-processing we will vote among multiple recorded files from different receivers and perform other consistency checks. If there is unusual/inconsistent behavior, only later will we be able to tell if it came from the satellite or from the receiver.

```
G33 15  9 30  2  0  0.0 C1C 46.31 8BFF2FF7C26ECFA0DEACB6A2B0401DB5F076CC277ABC4
7F593C48BEF8224D4D3AAAAAAAAAAAAAAAAAAAAAAAAAAAA48294ABB713E2D8F171F0CDD164C6E24
22D982D95861312360EF775E51C63612FF9035D002ABA                   DCA6C85FE899347
3D332364E62EF7146949B31456814C0EB7937F88379A65F0EEC145A2B1A7CBEE5B30B87E99DC923
E05555555555555555555576D1226DC0686AA460F215375FE0B468F6F4BA8BA22F208EA357F2DA
6367193694494D


SNN YR MT DY HR MN  SEC OCD DB       Raw Bits
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Figure 3. *Example of proposed RINEX raw navigation data bits (top) and corresponding format (bottom)*

Figure 3 shows an example of the data capture that we recommend. It uses the RINEX 3.0 conventions [18] starting with S for satellite system identifier, in this case G for GPS. See Table 1 for the full list of options. NN for PRN number (here it is PRN 33 as it is fictitious data). Next are the 2-digit year, month, day, hour, minute, and second: all corresponding to the broadcast time of the first bit of the data. Next is the observation code (OCD). Here we are proposing to use C to indicate the data comes from the code, 1 for the L1 signal, and C for the C/A code. This format allows the recording of NAV data from different signals (e.g. L1 P-code, L2 civil signal, etc.). Next, is the signal to noise ratio in dB-Hz (also at that initial epoch) and finally the raw data bits stored as hexadecimal characters. The raw data bits should be synched to the starts of the frames (or messages for CNAV). Note that Figure 3 shows the text as wrapping around several lines, but in reality the hex characters are one long string on a single line.

We recommend that each data record correspond to one full frame for GPS LNAV or for GLONASS or five GPS CNAV messages. Thus, there would be one record per tracked signal every 30 seconds (or every minute for GPS L2C which has half the data rate).

Each hexadecimal character represents four raw NAV data bits. In this example the first two characters are 8B which in binary is 10001011 and is the expected preamble. So the first bit of the frame starting at 02:00:00 UTC is 1, the next bit is 0, etc. An LNAV frame consists 1,500 bits and requires 375 hex characters to be fully represented. In this made up example, we have inserted some unusual events. Non-standard data would typically be alternating 1's and 0's. These would appear as 0101 (or hex '5') or 1010 (or hex 'A') depending on which bit started the sequence. A long series of all 5's or all A's indicates NSD.

Non-standard code would result in a complete loss of tracking, as represented by the blank spaces in the raw data set. Typically, NSC could last longer than thirty seconds. An untracked satellite would presumably have no corresponding record. Its absence would indicate a loss of tracking. If NSC is not initiated right at a thirty-second boundary, then some data bits for the frame would be recorded, but the blank spaces would tell us to within four bits when NSC was initiated. If we wanted to, we could define other characters to specify partial bit patterns (e.g. G could represent xxx0, H could be xxx1, etc.), but at the moment it seems unnecessary to determine NSC transitions to better than four bits (0.08 seconds).

If NSC does not prevent tracking, but reduces the SNR by 20 dB-Hz, this should be reflected in the SNR. Here we have assumed that NSC will typically last longer than 30 seconds. As an alternate we could include the SNR at several time steps as part of the specification. For example, we could have it recorded every six seconds.

This proposal means that raw data records will be much larger than current navigation data files. Instead of recording ephemeris data only when it changes, now it is recorded continuously, even when it does not change from one thirty-second frame to the next. One possibility is to add an indicator that the raw bits have been received but are identical to a previous record. The hexadecimal representation causes the record to be smaller than the existing RINEX navigation record. The high repetition rate should also lead to efficient compression of the file. However, there is no doubt that the uncompressed file will be substantially larger than existing files.

There are still many other details to work out for this proposal. For signals with FEC, should the raw symbols

Constellation	Identifier
GPS	G
GLONASS	R
SBAS	S
Galileo	E
BeiDou	C
QZSS	J
IRNSS	I

Table 1. *Satellite system identifiers*

Const.	Signal	Obs. code	Symbols per second	Bits per second (bps)	Frame length	Subframe length	Word length
GPS	L1 C/A	C1C	50 (sps)	50 (bps)	1500 bits (30 sec)	300 bits (6 sec)	30 bits (0.6 sec)
	L2	C2S	50 (sps)	25 (bps)	-	-	300 bits (12 sec)
	L5-I	C5I	50 (sps)	50 (bps)	-	-	300 bits (6 sec)
	L1C	C1S	100 (sps)	~49 (bps)	883 bits (18 sec)	9 bits (0.5 s), 600 bits (12 s), 274 bits (5.5 s)	-
GLONASS	L1 C/A	C1C	50 (sps)	50 (bps)	1500 bits (30 sec)	-	100 bits (2 sec)
Galileo	E5a-I	C5I	50 (sps)	25 (bps)	15,000 bits (600 sec)	1,250 bits (50 sec)	250 bits (10 sec)
	E1-B	C1B	250 (sps)	125 (bps)	90,000 bits (720 sec)	37,500 bits (30 sec)	125 bits (1sec)
	E5b-I	C7I	250 (sps)	125 (bps)	90,000 bits (720 sec)	37,500 bits (30 sec)	125 bits (1sec)
	E6-B	C6B	1000 (sps)	?	?	?	?
BeiDou	B1I	C2I	50 (sps)	50 (bps)	1500 bits (30 sec)	300 bits (6 sec)	30 bits (0.6 sec)
SBAS	L1 C/A	S1C	500 (sps)	250 (bps)	-	-	250 bits (1 sec)

Table 2. *Data formats for many of the different signals*

be stored or just the decoded bits? We recommend the latter as there is less ambiguity associated with the FEC decoding. However other communities may find value in recording the raw symbols. Should each record contain 30 seconds worth of data regardless of the message format? We face a choice of having each record correspond to a fixed amount of time, a fixed amount of data, or to the different frame or superframe sizes.

Note that there are some previous examples of raw data bit recording. The Helmoltz Center in Potsdam Germany (http://isdc.gfz-potsdam.de) records the raw GPS data bits for use in radio occultation processing. Unfortunately, they do not store the data in the event of parity failure. Nevertheless, this is a valuable archive of data. In addition, UNAVCO has defined a similar BINEX format (http://binex.unavco.org/binex.html). However, it only records 75 bytes corresponding to subframes 1-3 and does not include the parity bits. These examples indicate that there may be a general interest in recording the raw data and we hope to identify more interested parties.

GPS ALERT EVENTS

To demonstrate the potential benefit of capturing this information we turn to two historical GPS events that have been described previously [19]. Figure 4 shows a clock event on PRN 8 that occurred on November 5, 2009. The top plot shows the measured instantaneous user range error (IURE) as computed from the 300+ observation files from IGS. Also shown is broadcast URA value multiplied by 4.42. GPS defines the satellite to be in a fault state when the IURE exceeds 4.42 x URA for more than six seconds. As can be seen in the figure, at approximately 18:45 the error exceeds this bound, but he satellite continues to indicate that it is healthy (represented by the cyan line). A little after 19:00 the signal is no longer recorded in the observation files.

We do not know why the signal is no longer tracked. It could be due to any of the previously described fault alerting mechanisms. A little before 19:30 data is again recorded for the satellite and new ephemeris information is recorded indicating that the satellite is unhealthy (magenta line).

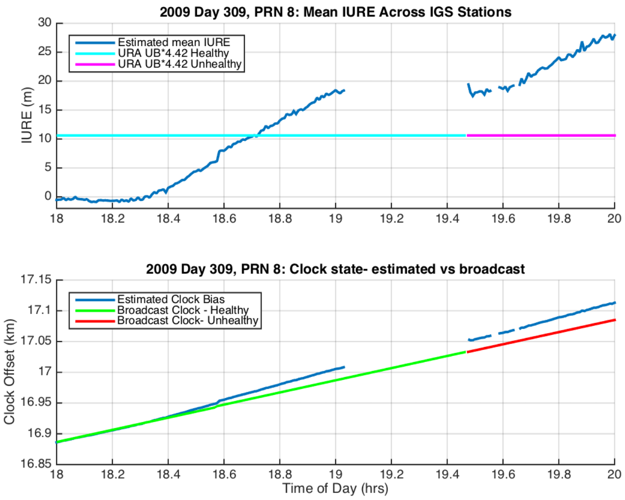

Figure 4. *Measured IURE and URA (top) and measured vs. broadcast clock bias (bottom) for PRN 8 on November 5, 2009.*

We are very interested in the timing of events when transmission of a trackable signal resumes. Given that the data loss is relatively brief (less than 30 minutes), the prior ephemeris is still within its period of validity. There would be a period of time when a receiver could use the faulty range measurements with this old ephemeris data set, before it receives the new health flag. Precisely when the new health flag arrives, in relation to when the signal can be tracked, is very important. The health flag is only broadcast once every 30 seconds. If the transmission resumes immediately after the regular broadcast time, then the fault can be present for nearly 30 seconds. Additionally, if there are bit errors shortly after transmission resumes, it may take even longer to successfully receive the new flag.

Having the raw data bits would let us precisely obtain the length of time between transmission restart and health flag reception. We also may be able to obtain some statistics for probability of garbled transmission around this restart time.

Figure 5 shows a similar event that occurred in 2010 on PRN 30. The bottom portion of Figures 4 and 5 show the estimated clock error from the observations vs. the broadcast parameters in the ephemeris data. As can be seen in both cases, the clock starts to drift away from its previous rate of change. The first reaction appears to be to switch to some form of NSC. Roughly half an hour later standard code returns and the ephemeris is updated to one where the health bit indicates the satellite is unhealthy.

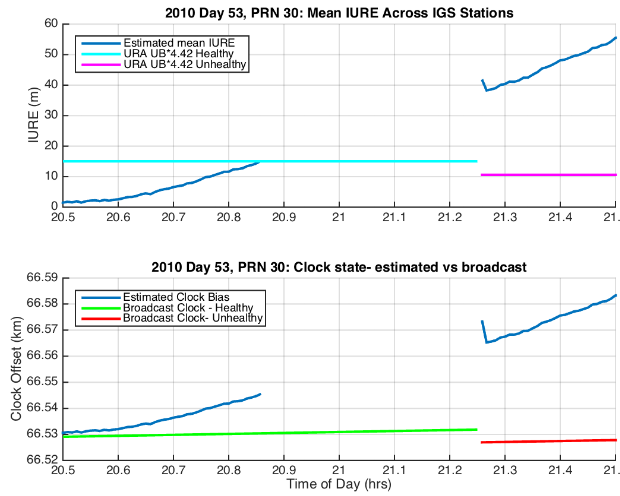

Figure 5. *Measured IURE and URA (top) and measured vs. broadcast clock bias (bottom) for PRN 30 on February 22, 2010.*

CONCLUSIONS

Recording all of the raw bits allows post-processing to correctly determine what information was broadcast from each satellite at any given time. This allows for non-standard data transmissions to be properly recognized as well as identifying any possible data glitches. Additionally, the initial time of transmission for every broadcast ephemeris can be correctly determined, allowing for a more precise determination of fault duration.

Further, we would have the ability to record all data regardless of any future changes that may occur. If a constellation redefines bits or specifies use of previously reserved bits, it will be recorded in these data files. After recording, a new converter can be written to recover the data content and convert it to floating-point values. It also would capture any future CNAV messages. Thus, this proposed format provides wide margin against future constellation message design changes.

There are still many details to harmonize if this proposal is to become a standardized format. We welcome input and discussion from interested parties on how best to proceed and to identify specific elements that should be included in the format.

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