Coordinating GPS Calibrations Among NIST, NRL, USNO, PTB, and OP

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Abstract—**Reviewing calibration results over the history since early 1980's among several labs shows very mixed results. The best stabilities of GPS receivers, as given by calibrations, are of the order of a few nanoseconds or better over a year, though many results are quite a bit worse. Absolute calibrations show similar potential, though there are problems. We conclude that more calibrations and standard methods are needed.**

I. INTRODUCTION

The purpose of this paper is to evaluate the status of GPS receiver delay calibrations, for a subset of receivers that support the generation of international atomic time (TAI). We first discuss historical and current methods for calibrating receivers. Then we look at the history of differential receiver calibrations in order to estimate receiver stabilities for the receivers in use at the time. Our last consideration of differential calibrations is to compute closures of calibration values by use of the most recent available data. These data give a measure of consistency of differential calibrations for use in current receivers. Finally, we discuss the history, use and potential for absolute calibrations.

GPS data are used in various ways for comparing clocks for generating TAI. All of these comparison methods are differential. We use the data to determine the difference between UTC(lab) among the labs that contribute to TAI. The delays through receivers need to be calibrated differentially in order to reference the data to a laboratory's UTC measurement plane. The best way to do this is with the use of a portable GPS receiver as a calibration system. The method is to do a series of common-clock, short-baseline calibrations between a travelling receiver and the primary receivers of different labs.

For example, to calibrate the differential delay between laboratory A (lab A in the following) and laboratory B (lab B), we could start with a portable system at lab A. To achieve a common-clock short-baseline calibration, one connects the travelling receiver to the same clock signals as the primary receiver, measuring the delay in the reference signal from the lab's UTC reference plane. We will discuss the details of a common-clock short-baseline calibration later. In principle, one collects data from the same satellites, measured against the same clock in two receivers with separate antennas, positioned near each other. With proper calibration of reference signals and coordinates, the difference in the measurements should be due only to the difference in the receiver systems, mainly the delays in the antennas, antenna cables and receivers. Evaluating these data allows us to determine the difference in the delays between each pair of systems. The sequence, in practice, would be to first measure the travelling receiver against the primary system at lab A, which we denote Trav-SysA (1). The travelling system is then brought to lab B, where we measure Trav-SysB. We then bring the travelling system back to lab A, where we determine a closure measurement of Trav-SysA (2). This closure gives a measure of any systematic shift in the delay of Trav during the trip. Typically, we then conclude that the difference in primary receivers is:

SysB – SysA= (Trav-SysA(1) + Trav-SysA(2))/2 - (Travs-SysB).

The actual value of SysB-SysA must be accompanied by the uncertainty of this measurement. We will discuss methods used for determining this in later sections.

There are many laboratories that contribute GPS data in support of generating TAI. There are also several different types of receivers, several different formats for the data, and several different methods for processing these data. In all cases, the differential receiver delays are crucial for

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determining the values for UTC(lab A) – UTC(lab B). These delay values cannot be determined remotely. Either differential measurements must be made *in situ* against another receiver, or an absolute calibration of the receiver system must be done, which requires interrupting service. Differential calibrations appear to be the most accurate and convenient method of measuring these relative delays, though an absolute calibration is required for the total delay of one receiver system. Campaigns of calibrations have been done historically, and seem to be required at ongoing intervals to maintain accurate time transfer. We discuss in this paper the status of current differential and absolute calibrations, various hardware and software methods for performing calibrations, and possibilities for the way forward to best use GPS receivers and data in support of TAI.

II. MEASUREMENT TECHNIQUES FOR CALIBRATION

GPS receivers for timing from 1980 on used a 1 pps signal as a reference. GPS time was measured against this 1 pps usually by use of a time-interval counter. Calibration involved measuring this reference 1 pps against the reference plane for time of the lab [1]. With the advent of receivers that used a 5 MHz or 10 MHz frequency signal as the reference signal, calibration became more complicated. Receivers measure GPS signals against a zero-crossing of the 5/10 MHz. This zero-crossing is determined by a 1 pps signal. So, in addition to knowing the offset of the 1 pps from the reference plane, the so-called tic-to-phase needs to be measured. Complicating this, some receivers lock an internal oscillator to the external frequency, and use that for a reference. Determining the internal reference point may be somewhat ambiguous. The internal reference point may be more than the next internal zero-crossing from the reference 1pps, or indeed may precede it, since the processing is usually digital. In addition, there are tic-to phase zones where the reference point may slip forward or backward a cycle. These forbidden zones may not be near to the value when the measured external tic-to-phase is close to zero. Figure 1 gives a block diagram illustration of the aspects involved with calibrating a frequency-reference receiver.

Some receivers can have a 1 pps out that is derived directly from the internal frequency reference with a fixed delay from the lock point. In that case, it may be possible to use that signal to eliminate any ambiguity for the reference zero-crossing in the receiver.

Thus we see that there are several measurement techniques possible for calibration. In addition, the question of biases in time-interval counters has been considered [2]. One recommendation has been to use a travelling time-interval counter along with the travelling receiver to minimize uncertainties due to counter error.

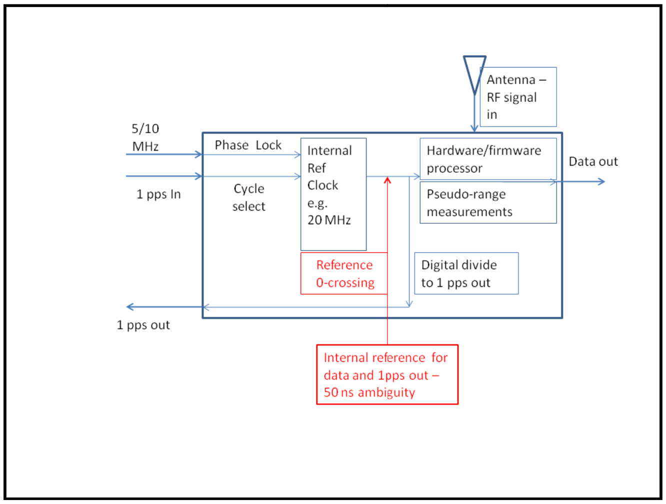

Figure 1. Block diagram of the timing functions in a modern GPS or GNSS receiver that measures the received pseudo-range against an internal oscillator, which in turn is locked to an external frequency reference. This illustrates the difficulty in unambiguously finding the the reference point.

III. PROCESSING CALIBRATION DATA

Historically, there have been two different frequencies that have delays through the receiver, L1 and L2, with C/A and P codes modulated on these frequencies, P code not being originally intended for civilian use. While these are the frequencies of most interest to the timing community historically, a new frequency specifically designed for civilian use, L5, is appearing in the new GPS constellation, as well as a version of the C/A code on L2 called L2C. There will also be other constellations of interest. The Russian system, GLONASS, has been available for some time. Though less used for various reasons, GLONASS may become more used for TAI generation as it is modernized. There are also the European system, Galileo, and the Chinese system, Compass or Beidou 2, which are being developed.

There are several formats that data can be taken in and several methods for processing these data. The CGGTTS format [3] provides 13 minute averages every 16 minutes, with all delays from the satellite removed and the times of the on-board satellite clock adjusted for GPS time. For a short-baseline common-clock comparison, as a minimum, pseudo-range data must be adjusted for the range delay, the delay of the signal from the GPS satellites to the receivers. If exact common-view computations are done this is enough. However, the CGGTTS format uses only the C/A code for the main data, the Reference-GPS data. If there are P code on L2 carrier (P2) data, measured ionosphere values are a deterministic combination of both P2 and C/A code data. It is possible to use the combination of Reference-GPS and measured ionosphere data types to compute the differential delays for both the C/A code and the P2 code.

The format called RINEX (for Receiver INdependent EXchange format) [4] has been developed to provide detailed data for flexible processing options. RINEX data are instantaneous pseudo-range data, and are typically recorded every second to every 30 seconds. This format can store data for all codes from all constellations. It is managed and updated by the International GNSS Service (IGS), and version 3 should provide flexible capability. However, it requires more storage space and processing than the CGGTTS data, which are already pre-processed. Minimal processing for common-clock short-baseline calibrations would be software that corrects only for the range delay from the satellites to the receivers, then differences these data between receivers matching exact common-view data, i.e. exactly matching satellites and transmission times between receiver data. This processing gives the differential calibration for the maximal density of data, with the minimum of extraneous processing.

In the timing community, it is most common to use either of two software systems for processing RINEX data. The P3 software reads RINEX files and outputs a CGGTTS format using either the C/A or P codes on L1 (C1 or P1) and the C/A or P2 codes on L2 (C2 or P2). The P3 data type is the ionosphere-free combination of P1 or C1 and P2 (C2 is available on a very limited number of satellites at this time). This format can, in principal, be used for differencing any of these codes individually, with 13 minute averages every 16 minutes. In practice, the usual output from the software allows for using the P3 combination and the value of the measured ionosphere to derive calibration values. Alternatively, one can use Precise-Point Positioning (PPP) [5,6] software to estimate the value of local clock against IGS system time at both locations for every reference time in the RINEX files. This uses carrier-phase smoothing of the code measurements, fixed local coordinates, and IGS post-processed estimates of satellite orbits to give an optimal estimate of the receiver's reference clock. While the PPP software produces perhaps the most precise estimates of user clock against system time, using it to compute differences for a local calibration introduces terms that do not cancel between receivers, due to the smoothing and averaging techniques.

Thus there are various processing methods for computing calibrations, with trade-offs for convenience, complexity, and accuracy.

A. *OP-NIST*

Table I and Figure 2 give the values for differential calibrations between OP and NIST since 1983 [1]. The values denoted d are differential time corrections to be added to [UTC(NIST)-UTC(OP)], and u(d) are estimated uncertainties for the periods of comparisons. All calibrations are of NBS10 at NIST compared to NBS51 at OP except for the November 2009 calibration. The NBS10 vs. OP NBS51 calibrations were all C/A code only comparisons. The November 2009 calibration compared the new primary receiver at NIST, NISTn1, with TTR01 and OPMT at OP. NISTn1 is a Novatel OEM4-G2[*] used at NIST for providing both CGGTTS and RINEX format data to the BIPM and IGS. This provides the backup link to the NIST TWSTFT link. OPMT, an Ashtech Z12-T[*], provides the RINEX files to the BIPM that are used for the NRCan PPP computation or for the CGGTTS TAIP3 files. There is no endorsement or critique either implied or intended. This is the source for the backup link to TWSTFT for the link OP-PTB in the TAI network. The NISTn1 vs. OPMT comparison included codes on L1 and L2, yielding a P3 comparison. The best stabilities seem to be on the order of a few ns or better over a year. There are some larger variations that are unexplained, and an apparent walk of almost 10 nanoseconds over 20 years.

IV. CALIBRATION HISTORY

A. *OP-PTB*

We present first, in Table II and Figure 3, the calibrations from the BIPM website [7] for C/A receiver calibrations between OP and PTB.

TABLE I. SOME PAST CALIBRATIONS BETWEEN NIST AND OP

OP Receiver	NBS51-NBS10		TTR01-NISTn1		OPMT-NISTn1	
Date	d/ns	u(d)/ns	d/ns	u(d)/ns	d/ns	u(d)/ns
July 1983	0.0	2.0				
September 1986	0.7	2.0				
October 1986	-1.4	2.0				
January 1988	-3.8	3.0				
April 1988	0.6	3.0				
March 1995	-3.7	1.0				
May 1996	-3.0	1.5				
May 2002	-5.0	3.0				
July 2003	-5.6	1.9				
December 2003	-4.6	3.0				
December 2005	-8.7	3.0				
November 2009			-9.4	0.8	-7.3	0.8

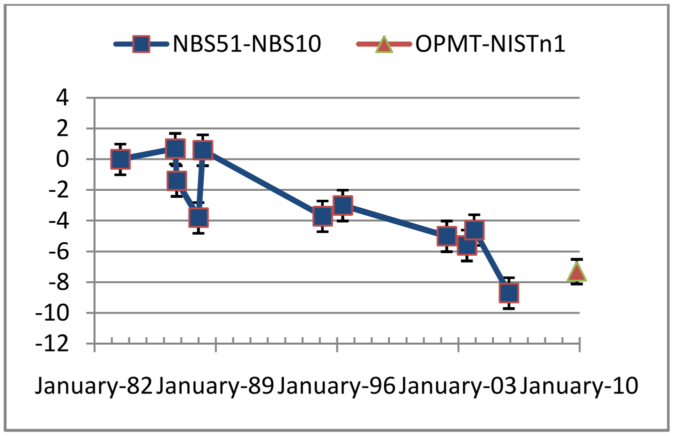

Figure 2. NIST-OP calibration values from Table 1.

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[*] Note that we include product names and model numbers only for reference. No endorsement or critique is implied.

TABLE II. DIFFERENTIAL TIME CORRECTIONS D TO BE ADDED TO [UTC(PTB) – UTC(OP)], AND U(D) ARE ESTIMATED UNCERTAINTIES FOR THE PERIODS OF COMPARISONS.

Date	d / ns	u(d) / ns	
October 1986	9.4	2.0	
October 1994	4.0	2.0	
July 1997	2.0	3.0	
November 1997	4.0	2.0	
March 1998	–6.0	2.0	
June 1998	5.0	3.0	
March 2002	–1.0	3.0	
June 2003	–4.7	3.0	
August 2003	0.1	3.0	
June 2004	0.1	3.0	
July 2004	0.6	3.0	TTR5 – TTS2
September 2006	–4.2	3.0	TTR5,TTR6 – TTS3
November 2009	10.3	3.0	
November 2009	4.8	3.0	

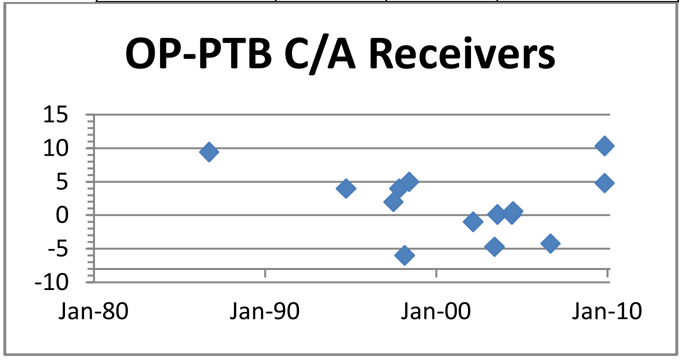

Figure 3. Plot of the data in Table II for the link OP-PTB. The receivers at OP were an NBS TTR5, then an AOA TTR6. At PTB the Code receivers were an NBS TTR5, then an AOS TTS2, followed by an AOS TTS3.

Apparent variations in calibration repeatabilities may be due to using different receivers. The best stabilities seem to be on the order of a few ns or better over a year. Next, we consider the OP-PTB GPS TAIP3 calibration link. Table III, and Figure 4 provide the P3 OP-PTB link calibration results for a direct comparison with other GPS C/A calibration results. All calibration data were computed by the BIPM during calibration campaigns, except the last line, which was released in the frame of the Galileo Fidelity activities from OP and CNES calibration campaigns [8]. Since receiver calibration values are implemented in respective receivers here, contrary to the previous C/A receiver calibrations, it is appropriate to only compare the change in values between these results and other tables. For some periods we see very little change between calibrations. For others there are 5-6 ns over a year or less, though the uncertainties are comparable in magnitude.

Finally in this section, we study the uncertainty budget consistency between GPS and TWSTFT on the OP-PTB link. Here we present an assessment of the uncertainty budget consistency between GPS and TWSTFT on the OP – PTB link. We have built daily averaged differences between UTC(OP) – UTC(PTB) as obtained from TAIP3 GPS CV and by TWSTFT. Figure 5 shows the results over two years, from February 2009 to February 2011, some outliers having been averaged out. The vertical lines materialize some events having potentially affected the measurements, like reference clock changes or a satellite transponder change. The horizontal lines are the plus or minus one sigma limits around 0, obtained from the quadratic sum of the uncertainties claimed for both techniques on the OP-PTB link. Over the whole period, the GPS TAIP3 combined uncertainty was estimated at 3.3 ns (1 σ). The TWSTFT combined uncertainty at 1 σ was estimated to be 1.1 ns until April 2009, 1.2 ns from May to November 2010, and 1.3 ns afterwards. The resulting uncertainty on the difference between both techniques is about 3.5 ns (1 σ). Over the last two years, the results obtained on the OP-PTB link are consistent with the statistics of the respective uncertainty budgets, despite major events like either reference clock changes for both techniques or a satellite change for TWSTFT, which require each time local measurements of new delays. There remains an average bias of about 2.0 ns over the period, which is probably due to some delays not properly taken into account. This calls for a better understanding and new measurements of both equipment chains.

TABLE III. . DIFFERENTIAL TIME CORRECTION D TO BE ADDED TO [UTC(PTB) – UTC(OP)] WHEN MEASURED BY GPS TAIP3 COMMON-VIEWS, U(D) BEING THE ESTIMATED TOAL UNCERTAINTIES

Date	d / ns	u(d) / ns
2002-07	10.8	5.0
2003-05	10.8	5.0
2004-08	15.0	5.0
2006-04	13.3	5.0
2008-04	13.7	5.0
2008-11	7.7	3.2

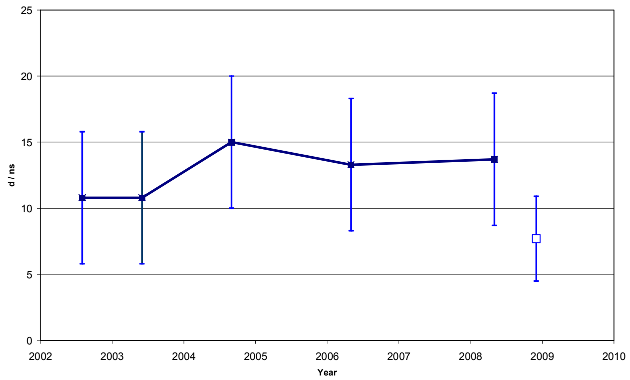

Figure 4. Plot of the data in Table III for the link UTC(PTB) – UTC(OP) by GPS TAIP3. The OP GPS receiver is OPMT. The PTB receiver is PTBB. The last point is kept separated from the others as it is the only one not measured by the BIPM.

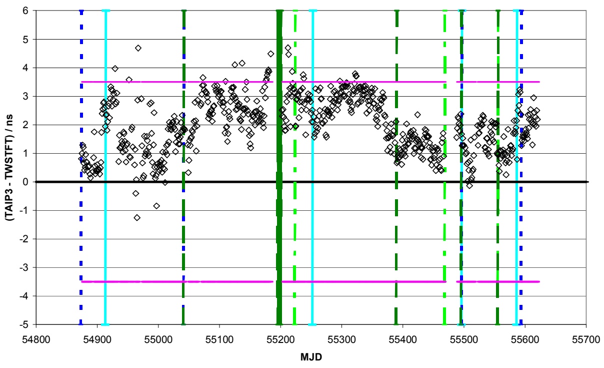

Figure 5. Daily averaged differences between UTC(PTB) - UTC(OP) by GPS TAIP3 CV and UTC(PTB) - UTC(OP) by TWSTFT.

TABLE IV. USNO – NIST CALIBRATIONS

Date	d/ns USNO C/A receivers - NBS10	u(d)/ns	d/ns USNO P3 receiver - NISTn1	u(d)/ns
Sep-86	25.3	2		
Sep-94	-9	3		
Dec-94	-7.6	1		
May-07	-7.5	2		
Aug-10			-6.2	2
Apr-11			-0.5	1

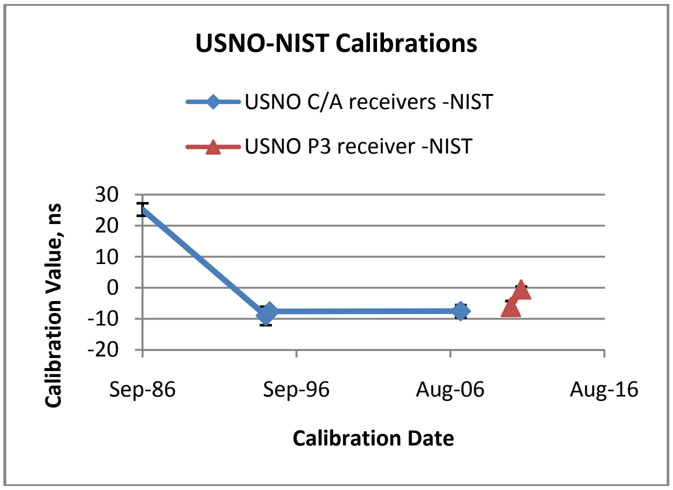

Figure 6. USNO-NIST calibration values from Table III.

B. *USNO-NIST*

Calibrations between USNO and NIST are presented in Table IV and Figure 6. These data come from the BIPM website files [7], except for the most recent calibrations of August 2010 and April 2011. These latter two use the two-frequency receivers at both labs, and are not yet finalized.

C. *USNO-OP*

Data for calibrations between USNO and OP from the BIPM website are presented in Table V and Figure 7. Given that a 14 ns step was introduced in 1997, the data are separated into calibration results before and after this event. The most recent results, from 2003 to 2007, show variations at about 2 ns per year, except for the large variation from 9 ns in 2002 to 2.4 ns in 2003. Given the good values over several years, this suggests the possibility of missing information regarding the large change over the earlier periods.

TABLE V. USNO-OP CALIBRATION VALUES FROM THE BIPM WEBSITE. A 14 NS STEP WAS INTRODUCED IN FEBRUARY OF 1997.

Date	d/ns before +14 ns	u(d)/ns	d/ns after +14 ns	u(d)/ns
Dec-84	32	10		
Oct-86	25.3	2		
Apr-87	15.6	5		
Jun-91	-14			
Jun-94	-13	2		
Sep-94	-9	1		
Dec-94	-7.6	1		
Mar-95	-20	2		
Jan-96	-14	2		
Apr-02			9	3
Dec-03			2.4	3
Jan-06			-4.5	3
Mar-07			-2.3	3

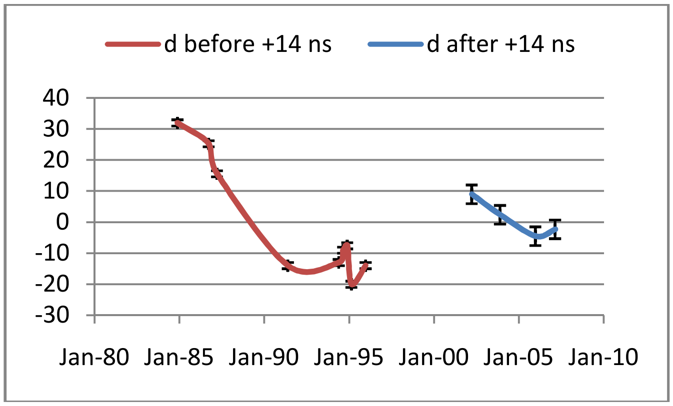

Figure 7. USNO-OP calibration data from Table V.

V. CLOSURE CALCULATIONS

We take some of the most recent calibrations and compute the total around closed loops. Clearly, the results should be 0. Note that the symbol +/- or σ in the Table VI indicates the total uncertainty for the given calibration.

C/A code, L1 frequency receivers:
OP-NIST (TTR6-OEM4)= 9.4 +/- 0.8, 2009/11
PTB-OP (TTR5,6-TTS3)= -4.8 +/- 3.0, 2009/11
USNO MOT1-PT05= 2.3 +/- 1.2, 2010/06
NIST-USNO MOT3= -7.5 +/- 2.0, 2007/05
Sum= -0.6 +/- 3.9 ns

C/A code, L1 frequency receivers:
OP-NIST (TTR6-OEM4)= 9.4 +/- 0.8, 2009/11
USNO-OP= -2.3 +/- 3.0, 2007/03
NIST-USNO MOT3= -7.5 +/- 2.0, 2007/05
Sum= +0.4 +/- 3.7ns

TABLE VI. CLOSURE FOR 2-FREQUENCY RECEIVERS

Labs	C1/P1 mean	C1/P1 σ	P2 mean	P2 σ	P3 mean	P3 σ	Year/ month
OPMT-NIST	-7.3	0.8	-7.2	0.9	-7.5	2.5	2009/11
PTBB-OPMT	3.3	1.0	0.4	1.4	7.7	3.3	2008/11
USN3-PTBB	…	…	…	…	-0.4	0.7	2010/06
NIST-USN3	13.1	2.0	17.6	2.0	6.2	6.0	2010/08
closure					6.0	7.3	

We see that each of the closures agree with a sum of 0 within the uncertainty. However, there is a large variation in the uncertainties for the calibrations.

VI. ABSOLUTE CALIBRATIONS

For supporting TAI, only differential calibrations are required; absolute calibrations are not necessary. Nevertheless, without any absolute calibrations, the entire TAI network could walk off. Also, it is convenient to have absolute calibrations, as this can be accomplished at a single lab without reference to any other [9]. However, absolute calibrations are generally less accurate than differential. We include a history of some absolute calibrations at NIST, as they give a measure of both the accuracy and difficulties of absolute calibration as well as the stability of receiver delays over time.

The first primary GPS receiver at NIST was NBS10.

NBS10

June 1986	53 ns	NRL
April 1987	57 +/−5 ns	
Sep 1998	54.4 +/−2 ns	

A new receiver named NIST has been primary since 2006. The 2006 Differential calibration of L1 against NBS10set the delays as L1, L2=-44.7, -44.7.

2007 NRL calibration receiver+antenna required change (not implemented) of

L1 +9.4 +/−0.4, L2 +2.3 +/−3.3.

2011-April USNO calibration of only the receiver required

L1 -25.2 +/−0.3, L2 -42.9 +/−0.3.

Comparing to the receiver only values from 2007 NRL

L1 -28.5 +/−0.4, L2 -45.4 +/−3.3 ns.

There appears to be a change of +3.3 +/−0.5 ns in the L1 channel, from 2007 to 2011.

VII. CONCLUSIONS

The historical GPS receiver calibration data appear mixed in quality. Some periods indicate potential for good repeatability, perhaps a few ns/year; But other periods show calibrations vary 10's of ns over a year or less. The closures are in line with the combined uncertainties, but these uncertainties can be as large as 7.3 ns for k = 1.

These results show that standard methods for calibrations are needed. Three aspects need standardization: 1) measurement methods, 2) processing methods, and 3) methods for computing uncertainties. This seems mandatory to reach the ns uncertainty level or below.

In any cases, regular calibrations are needed, either relative calibration campaigns or absolute calibration of separate elements of a GPS receiver chain. Coordinating GPS calibrations should be the goal to better support the generation of UTC. Receivers appear capable of supporting 1-2 ns stabilities over a year. Calibration uncertainties may be achievable at the 1 ns level. Hence differential calibrations should be accomplished approximately annually. Achieving this will take collaboration on the part of many laboratories and the BIPM.

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