ESTIMATING UTC – UTC (APL) AT THE
JHU APPLIED PHYSICS LABORATORY

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Abstract

Our master clock accuracy goal at the Time and Frequency Laboratory of the Johns Hopkins University Applied Physics Laboratory (JHU/APL) is to maintain UTC (APL) within ±20 nanoseconds of UTC. This is a challenging goal, because it requires the estimation of the future character of UTC – UTC (APL) up to 6 weeks beyond the latest issue of Circular T from the BIPM. Furthermore, the accuracy of our timescale-based estimation is challenged by the environmental influence on our ensemble of six clocks and the statistical limits to the dynamic characterization of these sources. This paper will describe the estimation algorithm used to determine the steering of UTC (APL). We will describe how the residual drift within the JHU/APL timescale affects our ability to estimate UTC – UTC (APL) and how we have modified the algorithm to remove this drift from the timescale prior to computing the estimation.

I. INTRODUCTION

The JHU/APL Time and Frequency Laboratory (T&F Lab) is one of many timing laboratories which contribute clock data to the BIPM for the computation of International Atomic Time (TAI). The JHU/APL clock data are referenced to UTC (APL). JHU/APL also sends GPS data to the BIPM to compare UTC (APL) to UTC via All-In-View GPS time transfer. The monthly Circular T publication from the BIPM reports the difference between UTC and the master clock (UTC (k)) of each contributing laboratory at 5-day intervals for a given month. However, the data arrive about 2 weeks into the following month, which means that UTC – UTC (k) must be estimated for that period and extended until the next issue of Circular T, a total of up to 6 weeks. Therefore, laboratories that steer their master clock to UTC must have a reliable and accurate estimation algorithm on which to base their steers.

The Time and Frequency Laboratory at JHU/APL has such an estimation algorithm, which has been in use for the last 5 years. During that period, the algorithm has been modified to improve accuracy so that we have been able to achieve our goal of maintaining UTC (APL) to within ± 20 nanoseconds of UTC 95% of the time over the last 2 years. A standardized estimation algorithm does not yet exist for widespread use, so timing laboratories typically have their own version of an estimation algorithm which has been customized for their use. Ours is a fairly simple algorithm which could also be used by laboratories with a small number of clocks like JHU/APL and is presented here.

II. UTC (APL)

UTC (APL) is the reference for all measurements made in the Time and Frequency Laboratory. It is the output of a microphase-stepper which is driven by a high-performance cesium. Microphase-stepper adjustments are based on our estimations of UTC – UTC (APL) and are made once or twice a month, usually soon after the latest Circular T is received and once more if necessary to maintain our accuracy goal of ± 20 nanoseconds of UTC. Fig. 1 shows a page from a recent issue of Circular T reporting that UTC (APL) is well within our goal.

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CIRCULAR T 249                                               ISSN 1143-1393
2008 OCTOBER 10, 12h UTC
                     BUREAU INTERNATIONAL DES POIDS ET MESURES
              ORGANISATION INTERGOUVERNEMENTALE DE LA CONVENTION DU METRE
    PAVILLON DE BRETEUIL F-92312 SEVRES CEDEX  TEL. +33 1 45 07 70 70  FAX. +33 1 45 34 20 21  tai@bipm.org

1 - Coordinated Universal Time UTC and its local realizations UTC(k). Computed values of [UTC-UTC(k)]
    and uncertainties valid for the period of this Circular.
    From 2006 January 1, 0h UTC, TAI-UTC = 33 s. From 2009 January 1, 0h UTC, TAI-UTC = 34 s.

Date 2008    0h UTC      AUG 31   SEP  5   SEP 10   SEP 15   SEP 20   SEP 25   SEP 30   Uncertainty/ns
        MJD               54709    54714    54719    54724    54729    54734    54739    uA    uB    u
Laboratory k                                        [UTC-UTC(k)]/ns

AOS  (Borowiec)           -0.6      3.4      5.4      8.8     11.1     14.5     15.6    0.6   5.1   5.2
APL  (Laurel)             -2.5      7.3      4.2      3.8      7.4      8.0      8.0    1.5   5.1   5.3
AUS  (Sydney)            322.4    342.1    353.3    364.5    387.6    408.9    429.2    1.5   5.1   5.3
BEV  (Wien)               6.9     -2.5     -5.4    -14.7    -16.9    -24.5    -28.2    1.5   3.2   3.6
BIM  (Sofiya)          -6689.3  -6697.8       -        -   -6673.5  -6707.7  -6718.1    2.0   7.1   7.4
BIRM (Beijing)         -5999.2  -6030.5  -6063.4  -6100.5  -6130.7  -6163.8  -6210.1    2.0  20.0  20.1
BY   (Minsk)            240.5    -16.7    -11.8      3.8     12.0     24.5     37.1    7.0  20.0  21.2
CAO  (Cagliari)       -2206.5  -2202.0  -2212.9  -2219.3  -2240.1  -2268.1  -2298.4    1.5   7.1   7.3
CH   (Bern)              -3.6      2.3      7.1      7.5      6.3      4.4      3.3    0.6   1.5   1.6
CNM  (Queretaro)         -7.3     -0.7     -1.9     -2.8     -3.5     -8.5     -2.9    2.5   5.1   5.7
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Fig. 1. Excerpt from BIPM Circular T with UTC – UTC (APL).

The Circular T reports typically arrive 10 to 14 days after the first of each month and report values for the previous month. Consequently, we must estimate UTC – UTC (APL) for up to 6 weeks in advance until the next report arrives. After the next report arrives, we are still estimating because we are already up to 2 weeks into the next month. Therefore, it is a never-ending cycle of estimating and updating our estimation parameters. Consequently, we must use an estimator which is reliable up to 6 weeks beyond the latest issue of Circular T. The estimator must be able to discriminate frequency variations in UTC (APL) and be based on a reliable reference.

III. DISCRIMINATING VARIATIONS IN UTC (APL)

The JHU/APL Timescale is the ensemble of six atomic frequency references, three high-performance cesium-beam references, and three hydrogen masers. We use the JHU/APL Timescale as our discriminator, because it has slightly better stability performance than any of its individual components, when referenced to UTC (APL), as shown in Fig. 2, and is less subject to frequency changes. The JHU/APL timescale algorithm is designed for autonomous operation with minimal intervention. However, one of our masers has a large mostly constant drift which results in a small residual drift that appears at about 500 hours in the timescale. For the timescale to work as a discriminator, this drift must be removed. Deweighting the offending maser was found to remove this residual drift, but it also effectively removed the contribution of an otherwise good clock.   Instead, we took the approach of

removing the drift from the segment of the timescale that is used as the discriminator before it is incorporated into the estimation process. This would also minimize the affects of any other irregularities caused by the other clocks in the timescale.
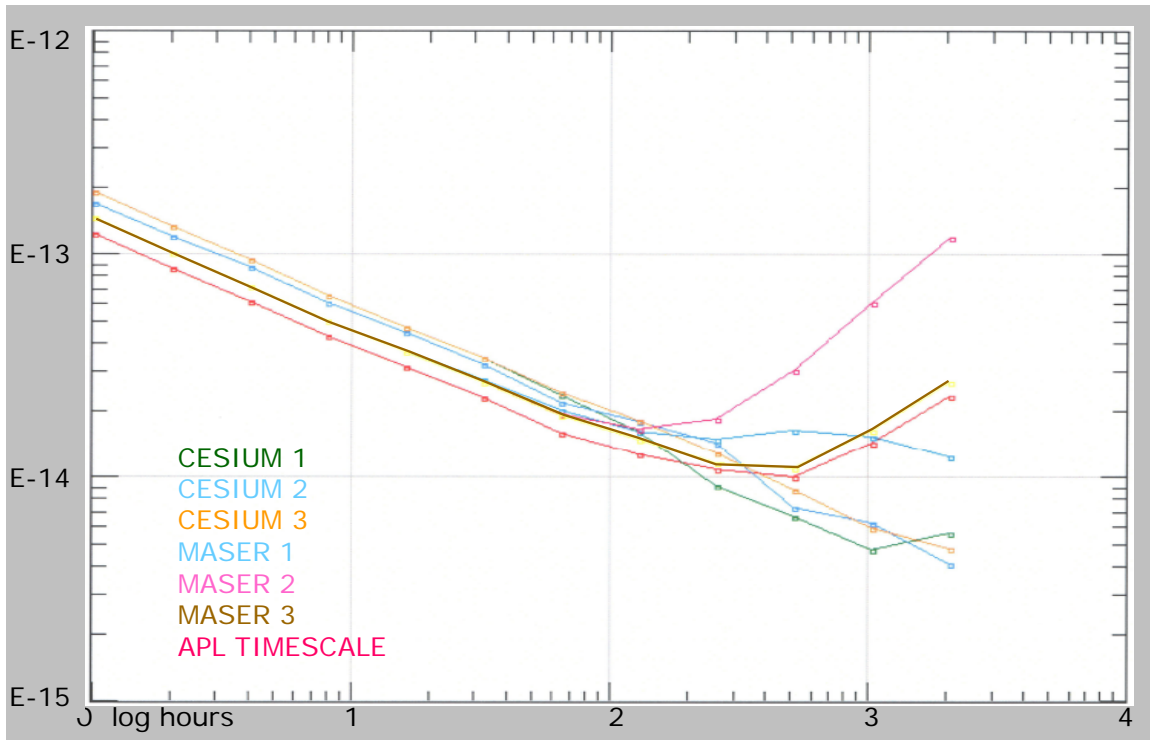

Fig. 2. Stability of six atomic clocks of JHU/APL ensemble and the Timescale against UTC (APL).

Removing the drift leaves a timescale segment which should reflect only the variations of UTC (APL) and whatever noise exists in the timescale, as shown in Fig. 3. But how well does it discriminate the UTC (APL) variations? A simple correlation was computed between UTC (APL) – UTC (APL unsteered) and UTC (APL) – (Drift Removed APL Timescale), both of which should reflect the steers in UTC (APL). As represented in Fig. 4, this resulted in a correlation coefficient of 0.906, which was very encouraging.

But could the timescale reliably discriminate the intrinsic variations of UTC (APL) for the purpose of estimating UTC – UTC (APL)? To test the timescale's reliability, 2 years of UTC – UTC (APL) from Circular T data were correlated with corresponding Timescale (APL) – UTC (APL) data. This produced a correlation coefficient of 0.939 (Figure 5), which strengthened our confidence in the timescale as a discriminator to base our estimations of UTC – UTC (APL).
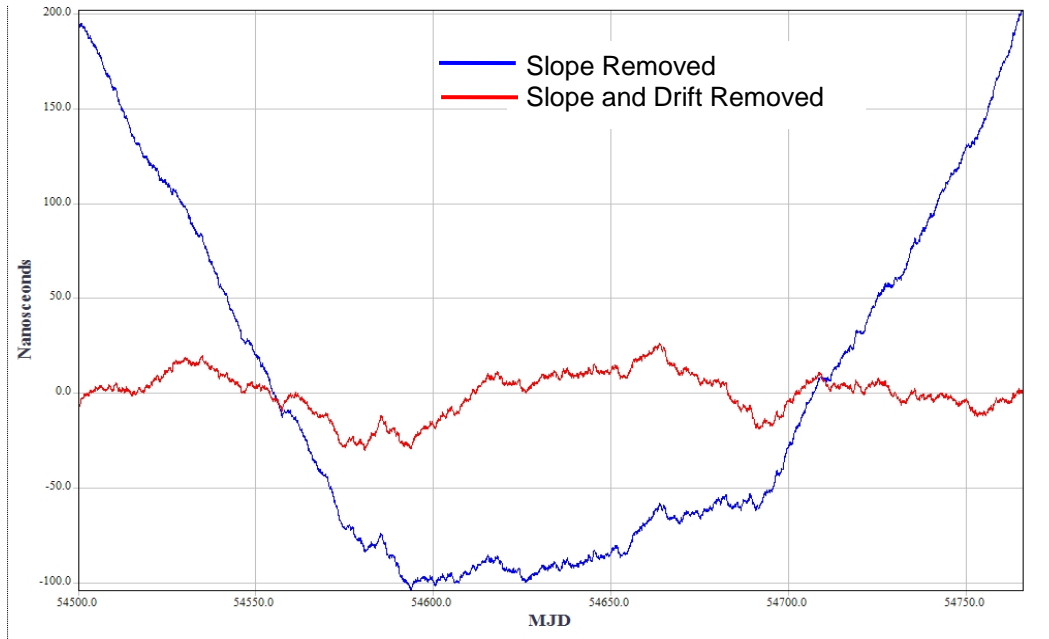
Fig. 3.   Comparison of JHU/APL Timescale with slope removed and slope with drift removed.
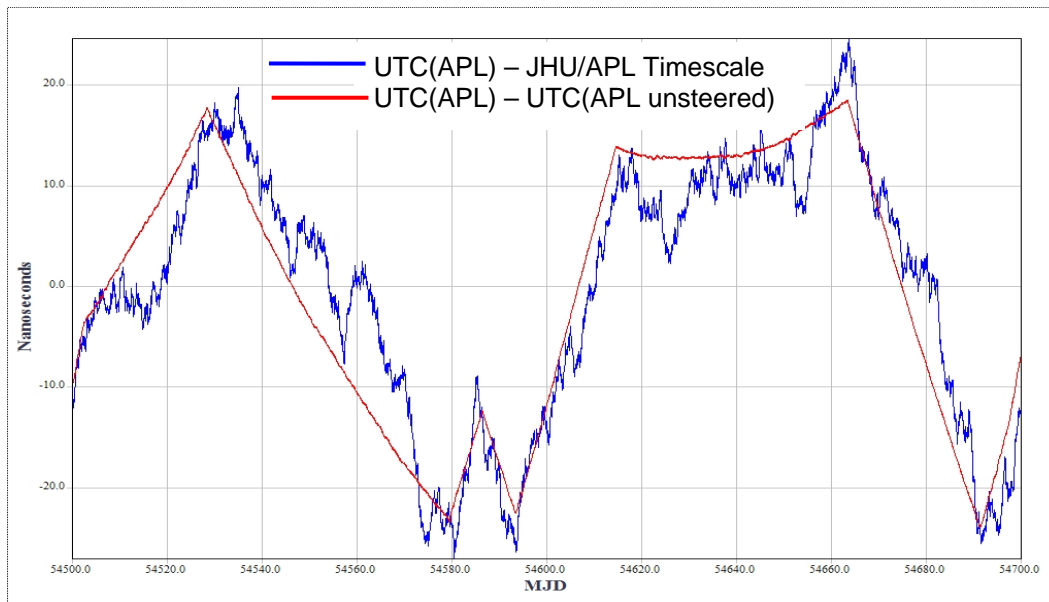

Fig. 4. Comparison of UTC (APL) – JHU/APL Timescale and UTC (APL) – UTC (APL unsteered), showing high correlation of 0.906, slope and drift removed from both plots.
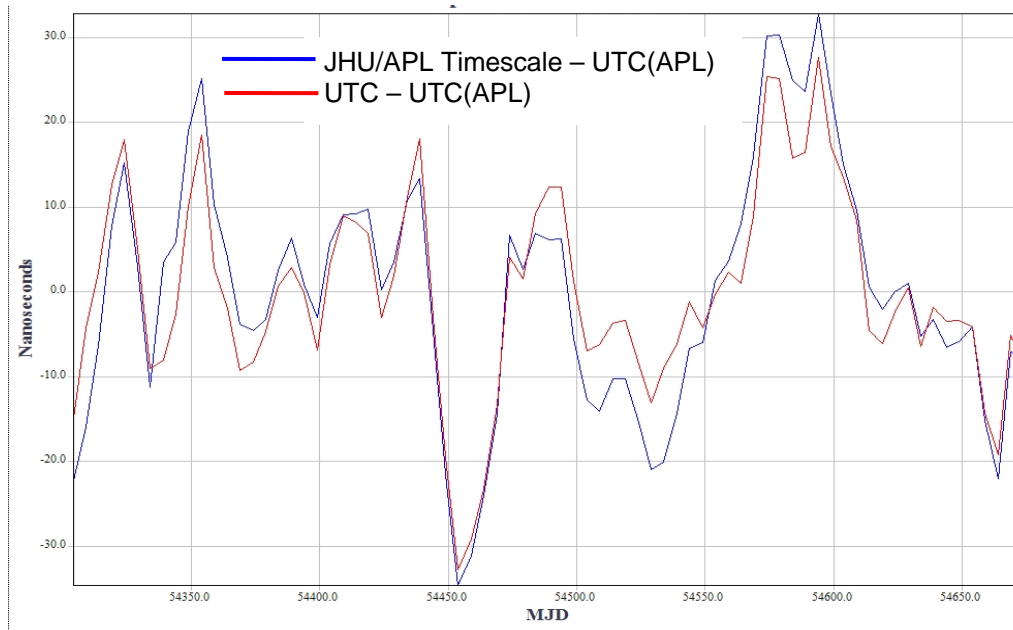
Fig. 5. Comparison of JHU/APL Timescale – UTC (APL) and UTC – UTC (APL), showing high correlation of 0.939, slope and drift removed from both plots.

IV. THE ESTIMATION PROCESS

Circular T reports UTC – UTC (APL) values at 5-day intervals. A question then emerges as to what set of the latest 5-day values will produce the best estimates of UTC – UTC (APL)? To find the best set, 35 repetitive computations are made using the latest 15 to 50 5-day value sets. The computation procedure is as follows:

1. Remove the drift from the corresponding UTC (APL) – Timescale (APL) data set

2. Compute UTC – Timescale (APL with drift removed)

3. Compute a quadratic fit of UTC – Timescale (APL with drift removed)

4. Use the coefficients of the quadratic fit to compute estimated values of UTC – Timescale (APL with drift removed)

5. Compute estimated values of UTC – UTC (APL).

Our experience has shown that the data set which best matches the latest reported values from Circular T and produces an RMS value which is less than or equal to 2.5 nanoseconds for the entire data set, also produces the best estimates of UTC – UTC(APL). Finding the best data set need only be done once a month, after the arrival of Circular T. Once it has been found, it is used until the next issue of Circular T. The variations in UTC (APL) will appear as the difference between the estimated UTC – Timescale (APL) and UTC (APL) – Timescale (APL). The estimation is projected to the current day and UTC (APL) is steered if necessary (Figure 6). When the next issue of Circular T arrives, the actual values can be compared to the estimated values (Figure 7) and the estimation process can be evaluated for accuracy.
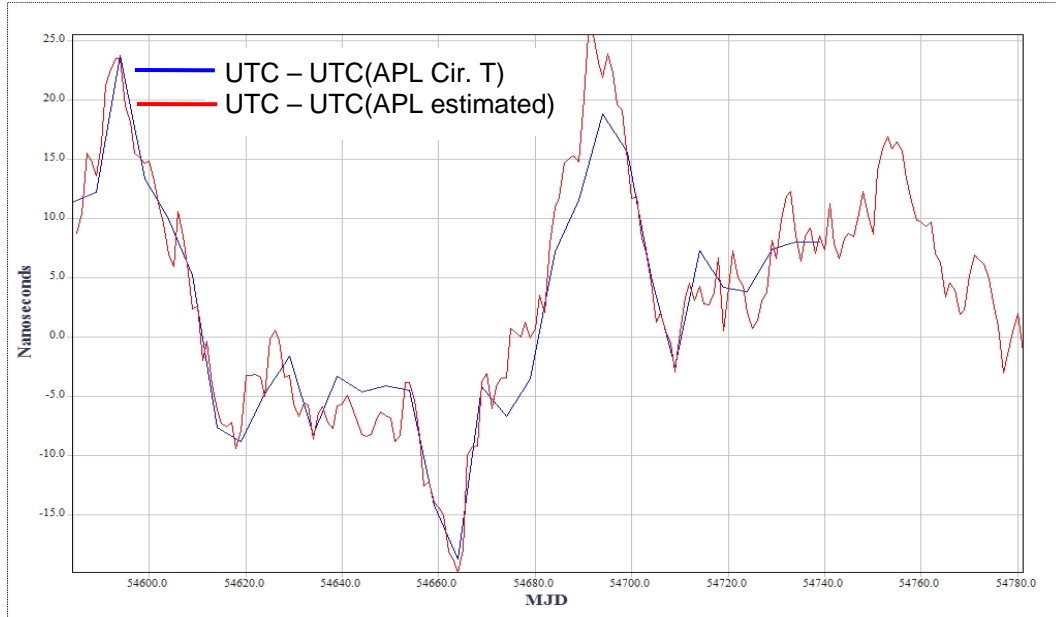
Fig. 6. Comparison of UTC – UTC (APL estimated) and UTC – UTC (APL) as reported in the Circular T. Note continuing estimation of UTC (APL) over 40 days following last Circular T reported data.
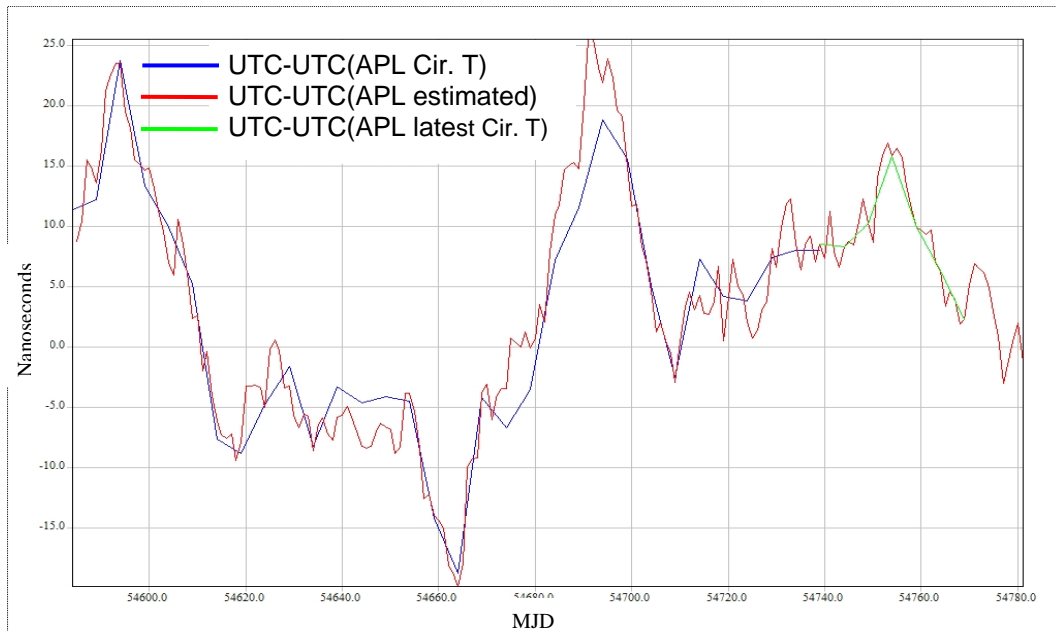

Fig. 7. Comparison of UTC – UTC (APL estimated) and UTC – UTC (APL) as reported in the Circular T. Note the agreement of the latest 30-day innovation of Circular T data with previous estimation of UTC (APL).

Tables Circular T #248, Circular T #249, and Circular T #250 compare the reported and estimated values of UTC – UTC (APL) from three consecutive issues of Circular T. Table Circular T #250 is reporting the latest 30-day interval described in Fig. 7.

Circular T #248

MJD	Rep.	Est.	Diff.
54674	-6.7	-4.6	-2.1
79	-3.5	-1.9	-1.6
84	7.2	8.4	-1.2
89	11.5	11.4	0.1
94	18.8	17.7	1.1
99	15.6	9.7	5.9
54704	5.1	-1.6	6.7
09	-2.5	-4.1	1.6

Circular T #249

MJD	Rep.	Est.	Diff.
54709	-2.0	-2.3	-0.2
14	7.3	5.3	2.0
19	4.2	2.0	2.2
24	3.8	4.2	-0.1
29	7.4	10.9	-3.5
34	8.0	12.0	-4.0
39	8.0	12.6	-4.6

Circular T #250

MJD	Rep.	Est.	Diff.
54739	8.0	8.5	-0.5
44	3.0	8.3	-5.3
49	5.7	10.2	-4.5
54	10.4	15.8	-5.4
59	4.9	9.9	-5.0
64	1.6	6.3	-4.7
69	0.9	2.3	-1.4

The estimation errors listed in Tables Circular T #248, Circular T #249, and Circular T #250 range from 0.1 to 6.7 nanoseconds during the 3 consecutive months reported and illustrate the accuracy of the estimation process. Furthermore, the process provides the accuracy required to meet our twice a month steering goals. During the past 2 years, we have been able to maintain UTC (APL) to within ± 20 nanoseconds of UTC 95% of the time, as shown in Fig. 9.
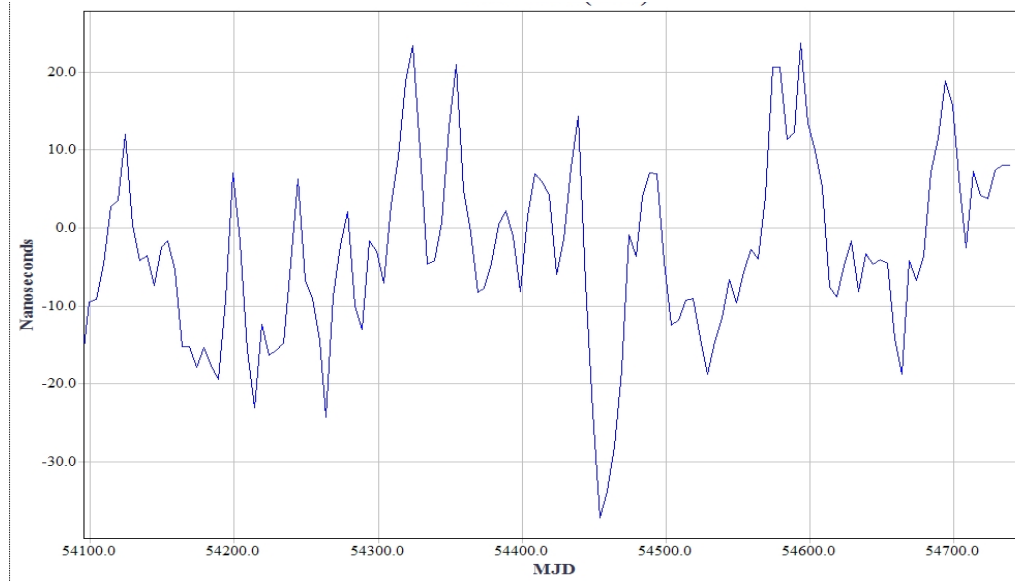
Fig. 9. Past 2 years of UTC – UTC (APL) accuracy.

V. CONCLUSION

The JHU/APL Time and Frequency Laboratory is using an algorithm developed at JHU/APL to estimate UTC – UTC (APL) for the purpose of steering the Master Clock UTC (APL) to UTC. We have shown that a drift-free, frequency-based timescale works as a reliable discriminator to reflect the intrinsic variations of UTC (APL) and that a quadratic fit that best matches the latest Circular T values of UTC – UTC (APL) produces the best estimates. We do not claim perfection, but we have a system and it works. The estimates are reliable up to 6 weeks beyond the latest issue of Circular T to allow us to keep UTC (APL) within our goal. In the future, with the acquisition of synthesizers to replace our aging microphase-steppers and combined with more frequent adjustments, we hope to improve our steering capability and narrow our stability goal.