A New Wiggle in the Wobble?

Uncovering Periodic Signals in Intensive Series

Christopher Dieck, Megan Johnson

Abstract Evaluating the residual series generated by differencing the values of UT1−UTC from an Intensive provides valuable information for use in assessing the quality of the Intensive series. Ideally, the residuals have a mean of zero, with some random noise. Applying a non-parametric Nadaraya-Watson kernel regression to the residuals of the MK-VLBA:PIETOWN VLBA Intensive series, with respect to multiple reference series, revealed that there is a statistically significant periodic deviation from the ideal. Additionally, a discontinuity in the series is seen and causally attributed to the 2018 Hawaiʻi earthquake through evaluation of the co-located GNSS receivers at both stations. Applying the same regression analysis to the KOKEE:WETTZELL IVS Intensive series suggests that the same periodic signal in the residuals may be present, just with a smaller amplitude. Analysis of the sensitivity of UT1−UTC to shifts in station position for both baselines likely explains the difference in amplitude; the value of UT1−UTC determined at KOKEE:WETTZELL is approximately four times less sensitive to station position shifts than that measured with MK-VLBA:PIETOWN. Though the MK-VLBA:PIETOWN UT1−UTC discontinuity is determined to be the result of a change in the MK-VLBA station position, there is no periodic change in the position of the co-located GNSS receivers that accounts for the periodicity noted in the UT1−UTC residual series. Therefore, either a heretofore unidentified mechanism is at play, a known mechanism is not being modeled in the estimation process, or there are errors in the applied models.

Keywords UT1, Intensive, VLBA

1 Introduction

Regular monitoring of the Earth's rotation phase is important to the maintenance of numerous systems at the foundation of modern society (e.g., GNSS). VLBI is unique among space geodetic techniques in its ability to directly measure this parameter, expressed as UT1−UTC. In any series of short duration, single-baseline VLBI sessions ("Intensives") must provide consistent and stable measurements of UT1−UTC as a function of time so that there is confidence in any one measurement from the series.

Both the relatively small number of observations in and the geometry of Intensives limit the parameters that can be estimated from these sessions. Thus, models must be used to construct the equations from which the estimates of UT1−UTC are made. There can be errors in those models, and investigations have shown that these errors propagate into errors in the measurement of UT1−UTC (e.g., Nothnagel and Schnell, 2008). One such model is the model of the position of the stations during the observation of the Intensive session.

In this work we explore the UT1−UTC values from the Intensive series observed on the baseline formed by the Maunakea (MK-VLBA; Mk) and Pie Town (PIETOWN; Pt) stations of the Very Long Baseline Array (VLBA). They exhibit a periodicity in their residuals to a reference series of Earth Orientation parameters (EOPs) and an isolated discontinuity in May, 2018. Section 2 describes the VLBI and GNSS data we use to investigate the hypothesis that station position shifts are the cause of both the discontinuity and the peri-

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odicity in the residuals. The analysis of the magnitude of the discontinuity and station displacement, as well as the calculation of the sensitivity of the measure of UT1−UTC on the Mk-Pt baseline to shifts in the participating stations, is performed in Section 3, with a discussion of the mixed results and necessary future work in Section 4.

2 Data

2.1 Maunakea-Pietown VLBA Intensives

From late 2011 through April 2021, the United States Naval Observatory (USNO) observed single-baseline Intensive sessions between the MK-VLBA and PIETOWN stations of the Very Long Baseline Array (Geiger et al, 2019). As a regular part of reviewing the data from the series, the values of UT1−UTC are differenced with one of three reference series: `latest_midnight.eop` from the NASA Jet Propulsion Lab, `eopc04_IAU2000.62-now` from the Paris Observatory, or `finals2000A.all` from the USNO, which is used in this work. While reviewing the resulting residual series in mid-2018, USNO staff identified a discontinuity which was preliminarily associated with the magnitude 6.9 Hawai‘i earthquake that occurred on May 4, 2018 (Dieck et al, 2019). The discontinuity could be corrected for in the USNO VLBI Analysis Center global solution after several 24-hour VLBI sessions that included the MK-VLBA station were observed following the earthquake. The last global solution that contained the discontinuity was `usn2019c`. This analysis of the Mk-Pt series thus utilizes the UT1−UTC values from that solution, and includes data from November 14, 2015 (when the Mk-Pt series resumed after major maintenance at MK-VLBA) to January 28, 2020 (the end of the `usn2019c` Intensive series).

2.2 Co-located GNSS Stations

To facilitate the testing of the hypothesis that a shift of the MK-VLBA station is responsible for the discontinuity of UT1−UTC residuals, we make use of the fact that both the MK-VLBA and PIETOWN stations have co-located GNSS receivers, labelled MKEA and PIE1, respectively. MKEA is 87.772 m from MK-VLBA, and PIE1 is 61.795 m from PIETOWN. Being so close (< 90 m) to each other at each site, we make the assumption that the VLBI and GNSS stations are subject to the same geologic processes and thus position changes recorded by the GNSS station apply directly to the VLBI station as well. Position information from both MKEA and PIE1 is processed by the International GNSS Service (IGS), and this work uses the station position history for each site from the third reprocessing campaign of the IGS, referred to as ‘repro3’.

Occasionally, the antenna or receiver of a GNSS station is repaired or replaced. According to the station logs, MKEA has a consistent setup from February 23, 2016 through September 23, 2018, and PIE1 has a consistent setup from June 30, 2017 through October 1, 2018. Thus, the time period when both stations have consistent setups that span the occurrence of the earthquake is June 30, 2017 through September 23, 2018.

3 Analysis

3.1 Application of the Nadaraya-Watson Estimator

Given the inherent scatter in the residual values, we employ the Nadaraya-Watson estimator (NWE; Nadaraya 1964; Watson 1964) to smooth the residuals. This facilitates the determination of the magnitude of the UT1−UTC discontinuity in the Mk-Pt residuals. The NWE returns an estimated value of a regression function m at a given point, x, calculated as the weighted average of a sample $\{(X_i, Y_i)\}_{i=1}^{N}$. The total weights are determined by the product of the inverse square of the sample values' formal errors, σ_{Y_i}, and the kernel, applied here as a Gaussian. The width of the Gaussian is set by the bandwidth parameter, the value of which is tuned by leave-one-out cross validation (see Feigelson & Babu, 2012).

By splitting the Mk-Pt UT1−UTC residuals at the moment of the earthquake (MJD = 58242.940) and applying the NWE to the two segments independently, we can calculate the difference in estimated UT1−UTC from before and after the earthquake. Prior to applying the NWE smoothing, the first order polynomial fit

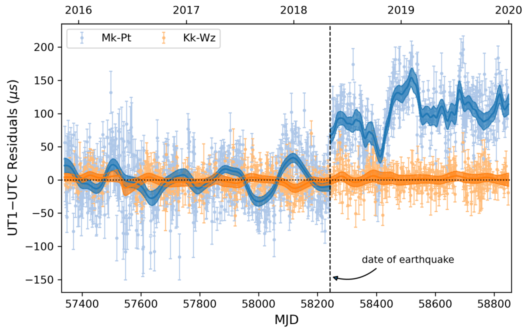

Fig. 1 The residuals of the Mk-Pt Intensives with respect to the USNO reference series, in light blue, and, for reference, the residuals of the Kk-Wz Intensives, in light orange. The date of the Hawaiʻi earthquake is denoted by the vertical dashed line. Both series of residuals have had large outliers removed and a first order polynomial fit and subtracted. For the Mk-Pt series, the polynomial was fit to the data prior to the earthquake and applied to the entire series. For each series, the regression functions calculated by the Nadaraya-Watson estimator are shown in the corresponding dark color with 3σ confidence bands in the shaded region. The Mk-Pt regression was applied in two parts, one before and one after the earthquake, to show the discontinuity and enable the magnitude of it to be calculated.

to the first segment is subtracted from both segments to remove any systematic offset from the series. The result of this process, shown in Figure 1, leads to the estimate of the magnitude of the UT1−UTC discontinuity of

$$\Delta(UT1-UTC)_{MK-VLBA} = 75.7 \pm 4.6\ \mu\text{s}. \tag{1}$$

As can be seen in the GNSS station position time series shown in Figure 2, there is no break at the time of the earthquake at the PIE1 station, but there is one at the MKEA station. The same method to determine the discontinuity in a time series at the time of the earthquake is applied to all three axes of the MKEA station, while each axis of the PIE1 data is smoothed as one segment. The resulting MKEA station displacement estimates are reported in Table 1.

Table 1 The estimated station displacements in each orthogonal axis of the MKEA GNSS station and the corresponding contribution to the expected shift in UT1−UTC based on the sensitivities reported in Table 2. The total magnitude of the station shift and the total expected shift in the VLBI measurement of UT1−UTC from the station displacement due to the earthquake are shown in the last row.

Axis	Displacement	Δ(UT1−UTC) Contribution
X	1.6 ± 1.2 mm	−0.8 ± 1.0 μs
Y	−7.4 ± 0.6 mm	24.4 ± 3.0 μs
Z	−9.9 ± 0.5 mm	43.6 ± 5.0 μs
Total	12.5 ± 1.4 mm	67.2 ± 5.9 μs

3.2 UT1−UTC Sensitivity to Station Position Change

To see if the observed station position shift at the MKEA site can explain the discontinuity seen in the Mk-Pt UT1−UTC residuals, we need to calculate how sensitive the UT1−UTC value is to changes in the a priori positions of the MK-VLBA and PIETOWN stations. By using real data but with altered a priori positions when estimating the value of UT1−UTC and comparing it to a control value where nothing was altered, we can directly calculate the sensitivity value for a given station of a particular baseline. Of course, this is the opposite of what is hypothesized to have occurred in the Mk-Pt series. There, the a priori MK-VLBA position did actually change, but the value used in the model did not. The consequence of this is that the simulated effect is equal in magnitude but opposite in sign from the real effect. The results of this calculation, performed on all Mk-Pt sessions from 2020, are shown in Table 2. Also shown in the table, by way of comparison, are the results of the same sensitivity analysis performed on the KOKEE:WETTZELL (Kk-Wz) Intensive sessions from 2020. The sensitivity value is the mean of the ∼200 individual measurements, and the uncertainty is the sample standard deviation of those measurements.

Table 2 The sensitivity of UT1−UTC to changes in station position for the stations of the MK-VLBA:PIETOWN Intensive baseline and for the stations of the KOKEE:WETTZELL Intensive baseline. Units are μs/mm. As expected, the sensitivities of the two stations of the same baseline are the same magnitude but of opposite sign. Note also the low magnitude and standard deviation of the sensitivities of the stations in the longer baseline compared to the stations in the shorter baseline.

Coord	Mk	Pt	Kk	Wz
X	−0.5 ± 0.47	0.5 ± 0.47	0.4 ± 0.06	−0.4 ± 0.06
Y	−3.3 ± 0.31	3.3 ± 0.31	−1.3 ± 0.09	1.3 ± 0.09
Z	−4.4 ± 0.45	4.4 ± 0.45	−0.1 ± 0.12	0.1 ± 0.12

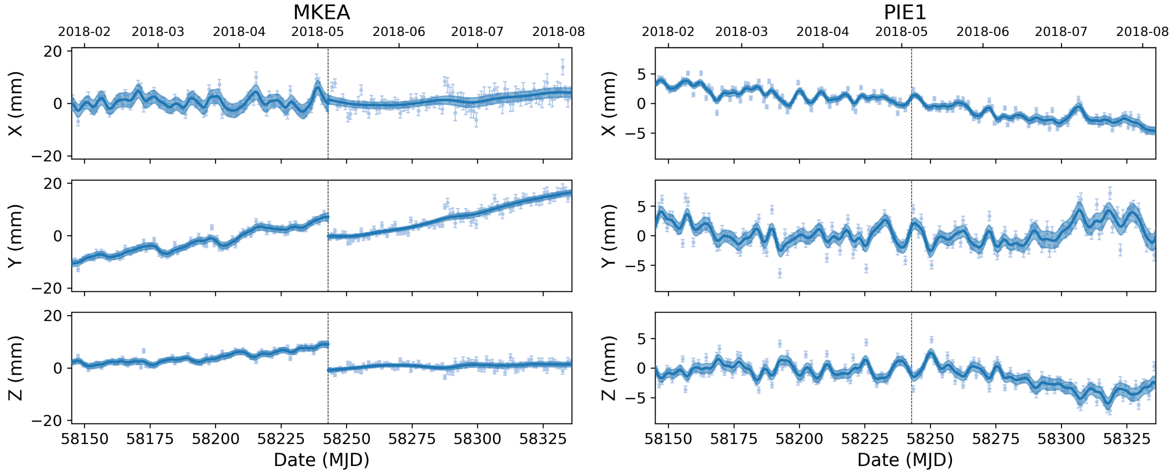

Fig. 2 The time series of the X, Y, and Z positions of the MKEA and PIE1 GNSS stations from the IGS repro3 data set. Values are from roughly three months before and after the Hawai'i earthquake marked by the vertical dashed line. Values relative to an arbitrary zero point are shown. The regression function calculated by the Nadaraya-Watson estimator is shown in the solid blue line, with the shaded blue regions denoting the 3σ confidence bands. No position shift is evident in the PIE1 data, so the regression is applied in one part over all the data, while there is a break evident at the time of the earthquake in the MKEA data. Thus, the regression for MKEA is applied in two parts. The vertical scales between the two stations are different, which enhances the apparent variability of the PIE1 series relative to the MKEA series.

With the MKEA station displacements reported in Table 1 and the sensitivities reported in Table 2, we calculate the expected shift in UT1−UTC due to the shift in the MKEA station as the total derivative of UT1−UTC with respect to the three coordinate axes

$$d(UT1-UTC) = \sum_{i=1}^{3} \frac{\partial UT1-UTC}{\partial x_i}\, dx_i. \qquad (2)$$

This can be restated as

$$\Delta(UT1-UTC)_{station} = S_X\Delta X + S_Y\Delta Y + S_Z\Delta Z \quad (3)$$

where the S_A are the UT1−UTC sensitivities and the ΔA are the station shifts in each orthogonal coordinate. Evaluating Equation 3 we find that

$$\Delta(UT1-UTC)_{MKEA} = 67.2 \pm 5.9\ \mu\text{s}. \qquad (4)$$

The error propagation calculation assumes uncorrelated Gaussian uncertainties because the sensitivities and the GNSS-measured station displacements are determined independently.

The difference between the estimated UT1−UTC discontinuity from Equation 1 and the expected shift in UT1−UTC from Equation 4 is 8.5 ± 7.5 μs, or 1.1 σ. The two values are statistically consistent. So, the change in position of the MKEA station, translated to a change in position of the MK-VLBA station, that happened at the same time as the UT1−UTC discontinuity explains why the jump occurred. Can the same effect account for the observed periodicity in the Mk-Pt UT1−UTC residuals?

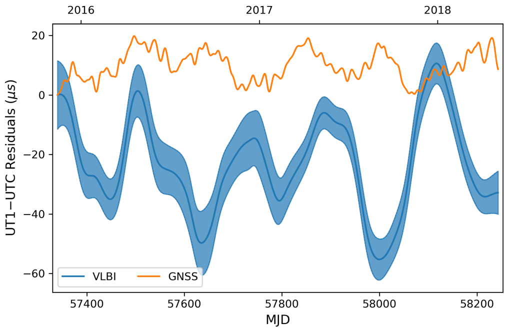

Fig. 3 Comparison of the observed UT1−UTC residuals from the Mk-Pt VLBI Intensive series (in blue) with the expected shift of the observed UT1−UTC value as calculated from the position shifts of the MKEA and PIE1 GNSS stations and the sensitivities of the co-located VLBA stations to those changes (in orange). Both curves are changed since a common starting date. This shows that the two are not closely related, and thus the changes in the station position alone are not sufficient to explain the periodicity in the Mk-Pt UT1−UTC residuals.

Using only data from before the earthquake, we extend the effective shift calculation to both MKEA and PIE1 and then add them together. Setting a common zero point for both the Mk-Pt UT1−UTC residuals and the expected effective shift calculation, we produce the two lines shown in Figure 3. No correlation statistics are necessary to see that the two curves do not correspond, either in amplitude or in phase. Thus, changes in the station positions are not sufficient to explain the periodicity in the UT1−UTC residuals, even with higher UT1−UTC sensitivities to such changes on the Mk-Pt baseline versus the Kk-Wz baseline.

4 Discussion and Conclusion

The analysis of Section 3.1 clearly shows that there is a periodic signal, with a period of roughly half of a year, in the Mk-Pt UT1−UTC residuals. It is present for residuals calculated from each of the three reference series (not shown here), and it is potentially present in the Kk-Wz residuals as well. This signal contributes to the systematic error of the measurement series and is not captured in the formal error. If subsequently used in combination, such a series would be too heavily weighted if only the formal errors were taken into account. It would also drive the predicted values of UT1−UTC away from the truth, most notably at the extrema of the periodic signal. There is no apparent reason why this effect would be limited to baselines of the VLBA, and there are indications the signal is present in other baselines. Therefore, it seems prudent to move forward under the assumption that this is affecting all Intensive baselines, though with varying severity seemingly dependent on the baseline length and geometry.

As the requirements on the precision and accuracy of UT1−UTC tighten moving into the future, the source of this signal needs to be better understood. From this work, it is not clear what causes the periodicity in the residuals. Though the station displacement due to the earthquake as recorded by the MKEA receiver is shown to be able to explain the UT1−UTC discontinuity in the Mk-Pt VLBA Intensive series, GNSS station position evolution does not explain the periodicity in the residuals. Therefore, one or more of the applied models used to establish the a prioris for the estimation of UT1−UTC with Intensives contains an error, a known contributor to variations in the output of the estimate is not being included in the estimation at all, or there is a mechanism that is not yet understood or identified that is causing this behavior. Further investigation to identify and correct this missing information must be undertaken.

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