ACCURACY OF GPS TIME TRANSFER VERIFIED BY CLOSURE AROUND THE WORLD

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Abstract

The precision of time transfer over intercontinental distances by the GPS common-view method, using measurements of ionospheric delays, precise ephemerides provided by the DMA and a consistent set of antenna coordinates, reaches 3-4 ns for a single 13-min measurement, and decreases to 2 ns when averaging several measurements over a period of one day. It is thought that even this level of precision can be bettered by improving the ionospheric measurements, the ephemerides of the satellites and the antenna coordinates.

In the same conditions, an estimation of the accuracy is attained by using three intercontinental links encircling the Earth to establish a closure condition: The three independant time links should add to zero. We have computed such a closure condition over a period of thirteen months using data recorded at the Paris Observatory in Paris (France), at the Communications Research Laboratory in Tokyo (Japan) and at the National Institute for Standards and Technology in Boulder, Colorado (USA). The closure condition is verified to within a few nanoseconds but a bias, varying with time, can be detected.

1. INTRODUCTION

The excellence of worldwide time unification depends on the quality of the clocks kept by national timing centers and on the means of time comparison. Rapid development in the use of the Global Positioning System since 1983 has led to major improvements in the precision and accuracy of the metrology of time. Using commercially available GPS time receivers, time comparisons can easily be performed with an accuracy of 10 to 20 nanoseconds over intercontinental distances. However, it is possible to improve this performance by removal of systematic errors. In GPS time transfer, the three principal sources of error are the local antenna coordinates, the broadcast ionospheric model and the broadcast ephemerides. A thirteen-month experiment in which three long-distance time links are combined with simultaneous reduction of these error sources allows us to check the precision of the time transfer, and its accuracy through satisfaction of a closure condition.

2. THE EXPERIMENT

Three long-distance time transfer links between the Paris Observatory in Paris (OP), the Communication Research Laboratory in Tokyo (CRL), and the National Institute of Standards and

Technology in Boulder, Colorado (NIST) have been computed using the common-view method [1], for a 393-day period, from 1990 June 16 (MJD 48058) to 1991 July 13 (MJD 48450).

The GPS data taken at the three sites correspond to the international schedule issued by the Bureau International des Poids et Mesures for the establishment of TAI. Ionospheric delay measurements are performed by dedicated dual-frequency codeless GPS receivers, and precise ephemerides are provided by the US Defense Mapping Agency. Detailed characteristics of the three time links can be found in [2], with the description of the procedures used to obtain accurate antenna coordinates and to correct for ionospheric and ephemerides errors.

3. RESULTS AND DISCUSSION

The corrections to the antenna coordinates being already introduced, four different cases may be distinguished for each time link and for the closure, which is the sum of the three links:

* non-corrected values.
* values corrected for ephemerides only.
* values corrected for ionosphere only.
* values corrected for both ephemerides and ionosphere.

For each case, a Vondrak smoothing [3] is performed on the values UTC(Lab1) − UTC(Lab2). The smoothing used acts as a low-pass filter with a cut-off period of about 3 days. This period has been chosen as being approximately the limit between the short time intervals, where the measurement noise is dominant, and the longer intervals, where the clock noise prevails. For the closure, the smoothed values are interpolated at normal dates (0h UTC each day) and the interpolated values are simply added.

3.1. PRECISION OF TIME COMPARISONS

A first way to estimate the precision of the measurements is from the standard deviation of the residuals to the smoothed values. This is strictly correct if the smoothing has removed only the measurement noise. Over our whole data set, these residuals range from 10 to 15 ns for the uncorrected data, 8 to 10 ns for the data corrected for ephemerides only, 7 to 12 ns for the data corrected for ionosphere only, and 4 to 5 ns for the data with both corrections.

If the data points are regularly spaced, we can also use the time-domain stability measures $\sigma_y(\tau)$ and $\sigma_x(\tau)$ [4]. Applied to a time link $\sigma_x(\tau)$ allows one to characterize the types of noise that are present. In the case of white noise phase modulation (PM), the value of $\sigma_x(\tau)$ for the data spacing is the standard deviation of the white noise, which directly gives the measurement uncertainty. $\sigma_y(\tau)$ allows us to estimate the frequency stability with which clocks can be compared.

For the link OP−NIST which, being the shortest, has the largest number of data points, we can find two periods of 80 and 75 days respectively without any significant gap in the data. On average there are seven points per day and they are quite regularly spaced, the largest spacing being about 7 hours. Figure 1 presents the values of $\sigma_x(\tau)$ for the data over the period from MJD 48375 to

48450, without correction and with both corrections applied. It appears that white noise phase modulation can be identified for averaging times up to about 3 days without correction, but is not the dominant source for times of one day and over when the corrections are applied. The uncertainty of a single measurement is taken from figure 1 to be about 16 ns without correction, but this value is somewhat biased by the data recorded during the few days around MJD 48440 when Selective Availability was in effect. The measurement uncertainty is about 3 ns when the corrections have been applied.

It should be noted that such a measurement uncertainty makes it possible to access the true performance of the best clocks presently available: by averaging a few measurements over one day, a frequency stability of two or three parts in 10^{14} is realized for the link between two clocks. Thus in figure 2, which represents $\sigma_y(\tau)$ for the link OP−NIST over the same period as in figure 1, the values obtained with corrections applied represent the actual frequency stability of the two clocks for time intervals of one day and over.

For the other 80-day period, from MJD 48080 to 48160, the results are quite similar although the measurement noise is estimated to be at a slightly higher level, as discussed in section 3.3 below.

3.2. ACCURACY TEST: THE CLOSURE AROUND THE WORLD

A test of accuracy is performed by computing the closure around the world via OP, NIST and CRL. Daily values of UTC(OP) − UTC(NIST), UTC(NIST) − UTC(CRL) and UTC(CRL) − UTC(OP) are estimated from the smoothed data points. The resulting daily values of the deviation from closure, for the whole period under study, are shown in figure 3 for the non-corrected data and in figure 4 for the data with both corrections applied.

Figure 4 provides evidence of a gain in accuracy when the time links are computed with both corrections. To characterize and quantify the types of noise involved, figure 5 represents the values of $\sigma_x(\tau)$ for the closure, without correction and with both corrections applied. The gain is by a factor 2 to 3 for all averaging times. If we take into account the fact that the values for one and two days are aliased by the smoothing that has been performed on each link, the closure is relatively well characterized by white noise PM up to 16 days. This is not true for longer averaging times, as it is clear from figure 4 that significant biases exist, and that they vary with time. As an example, the mean value of the closure over consecutive 16-day intervals varies from −2 ns to +9 ns, whereas the standard deviation of the mean, assuming white noise, is 1 ns. The mean values over 16-day intervals have a global average of 4 ns and a standard deviation of 3 ns.

3.3 DISCUSSION OF THE ERROR SOURCES

The major three error sources, that are able to produce both long term biases and short term white noise PM, are those listed earlier in this paper: antenna coordinates, ionospheric delays, satellite ephemerides. While we have tried to minimize these errors, they are still present at some level so we try to estimate them here.

The error on the antenna coordinates has been estimated previously [**2**]. It could account for a few nanoseconds of residual error in the closure. However this error is roughly constant over the whole period, as the geometry of the common-view observations remains similar for each link. When more accurate coordinates become available from geodetic campaigns, it will be easy to account for them in the data. Accuracies of a few centimeters should then be obtained, and these will contribute negligibly to the error budget of the time transfer.

The accuracy of the measurements of the ionospheric delay by codeless GPS receivers has been reviewed recently [5]. It is estimated to be a few nanoseconds but it is not easy to characterize the residual effect. It is possible that P-code receivers will be used in the future, but it is not clear how this will improve the measurements. Also, although the global ionospheric activity is going to decrease from its recent maximum, it is not clear if it will be measured more accurately by the GPS receivers.

On the other hand, the ephemerides of the satellites are subject to constant improvement. The DMA processing scheme, for example, is regularly improved [6]. The fact that ephemerides are more accurate in 1991 than in 1990 may be visible in our data: figure 6 represents $\sigma_x(\tau)$ for the link OP–NIST for the two periods of about 80 days mentionned in section 3.1 above. The improvement of the spring-summer 91 period relative to that of summer 90 is quite clear for averaging times of up to one day, where the measurement noise dominates. In the future, ephemerides with sub-meter, or even decimeter, accuracy should become available, which will nearly eliminate this source from the error budget.

Finally it should be noted that the stability of the closure for averaging times of a few days is mainly affected by the many glitches that are apparent in figure 4. A careful review of the data indicates that for the second half of the data set, which corresponds to year 1991, all but one of the glitches are associated with a gap of more than one day in the data of one link. This aliasing effect is less clear for the first half of the data set. This fact also favors an improvement in the quality of the ephemerides with time, although chance cannot be ruled out as an explanation.

4. CONCLUSIONS

Results of a 13-month time transfer experiment indicate that, after corrections for ionosphere and ephemerides have been applied, the precision of a single intercontinental GPS time transfer measurement is about 3-4 nanoseconds, and can be reduced by averaging. The accuracy is estimated also to be 3-4 nanoseconds, but significant biases, which vary with time, are still present. It is thought that the accuracy, as estimated by the closure condition, is improving with time, and will eventually reach 1 ns if the ionospheric contribution can be reduced to below this level.

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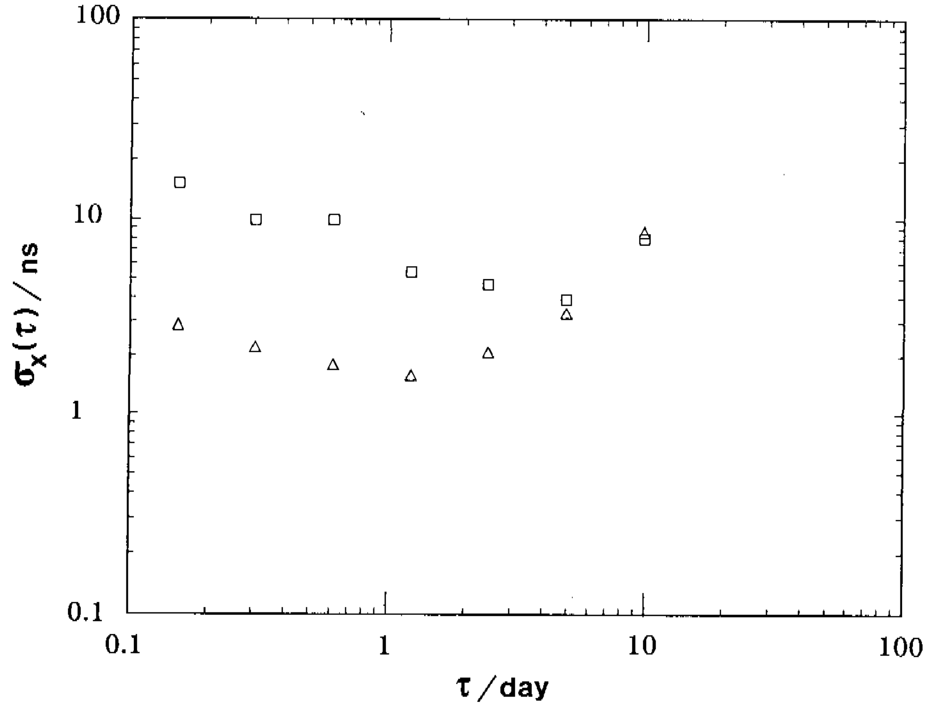

FIGURE 1: Square root of the time variance $\sigma_x(\tau)$ of the link OP-NIST over the period MJD 48375 to 48450, for data without corrections (squares) and for data corrected using precise ephemerides and measured ionospheric delay (triangles).

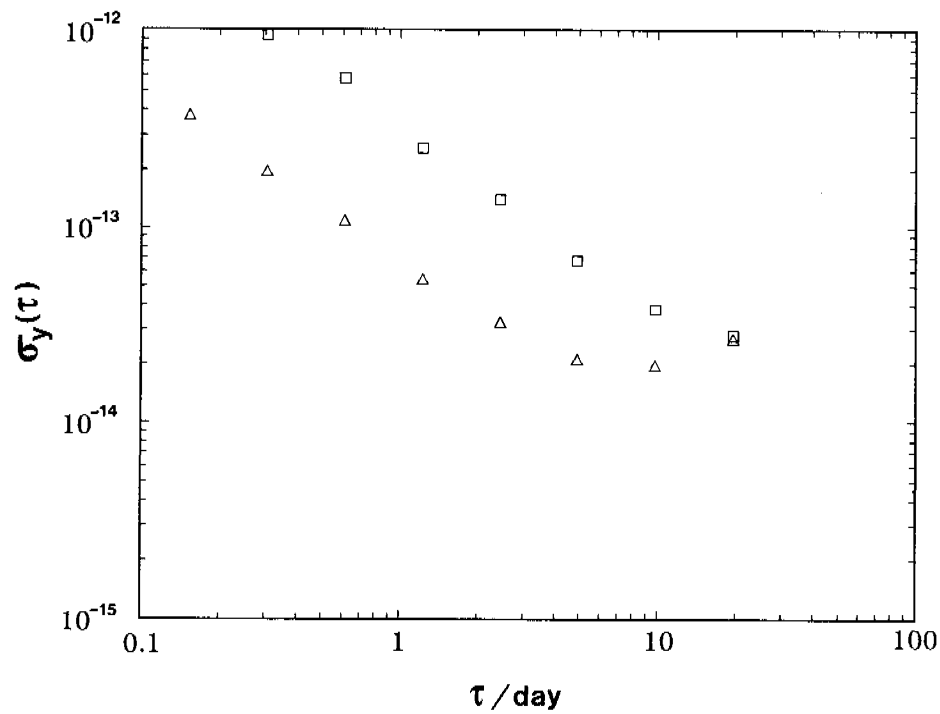

FIGURE 2: Square root of the two-sample Allan variance $\sigma_y(\tau)$ of the link OP-NIST over the period MJD 48375 to 48450, for data without corrections (squares) and for data corrected using precise ephemerides and measured ionospheric delay (triangles).

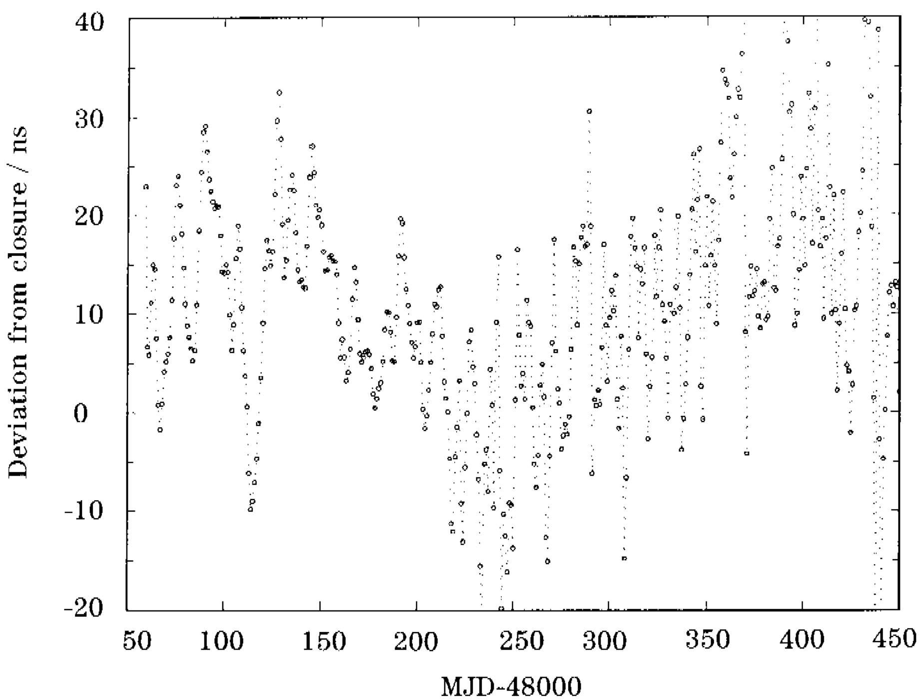

FIGURE 3: *Deviation from closure around the world via OP, NIST and CRL with non-corrected data.*

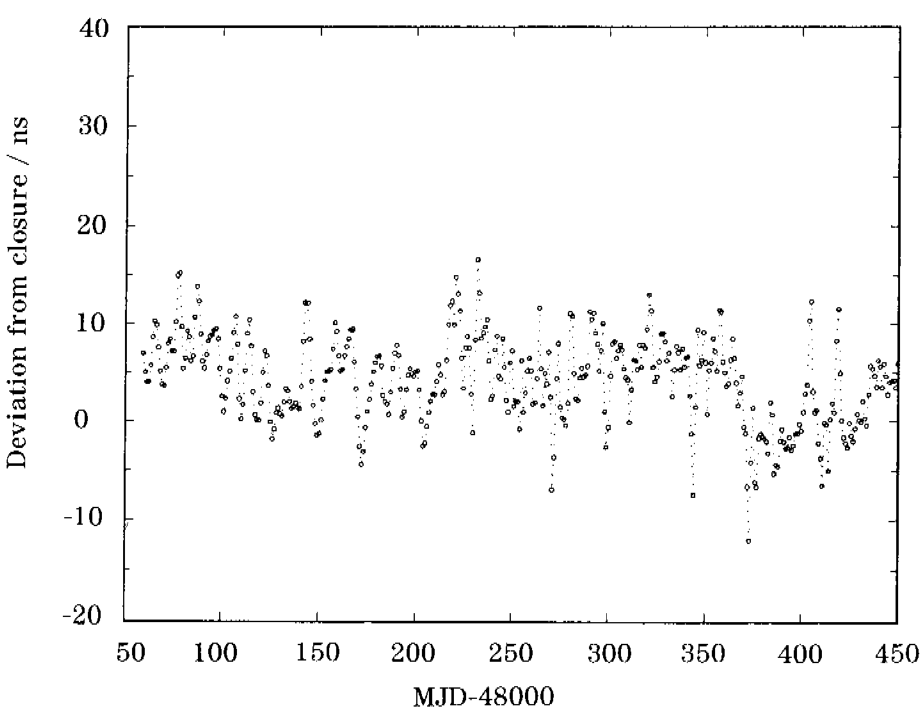

FIGURE 4: *Deviation from closure around the world via OP, NIST and CRL with data corrected for precise ephemerides and measured ionospheric delay.*

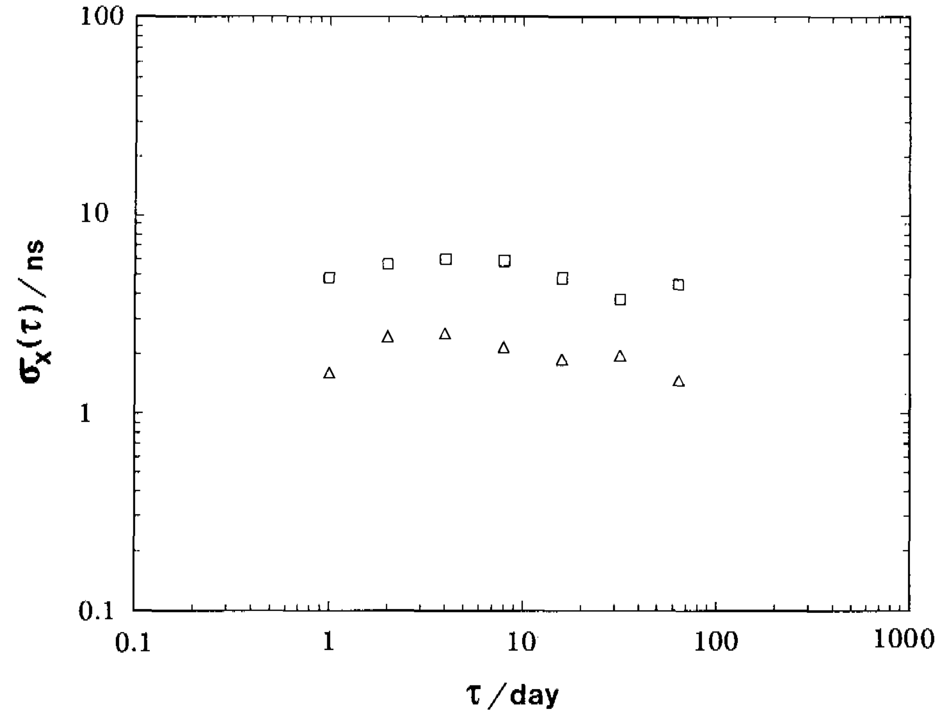

FIGURE 5: *Square root of the time variance $\sigma_X(\tau)$ of the deviation from closure over the period MJD 48058 to 48450, for data without corrections (squares) and for data corrected using precise ephemerides and measured ionospheric delay (triangles).*

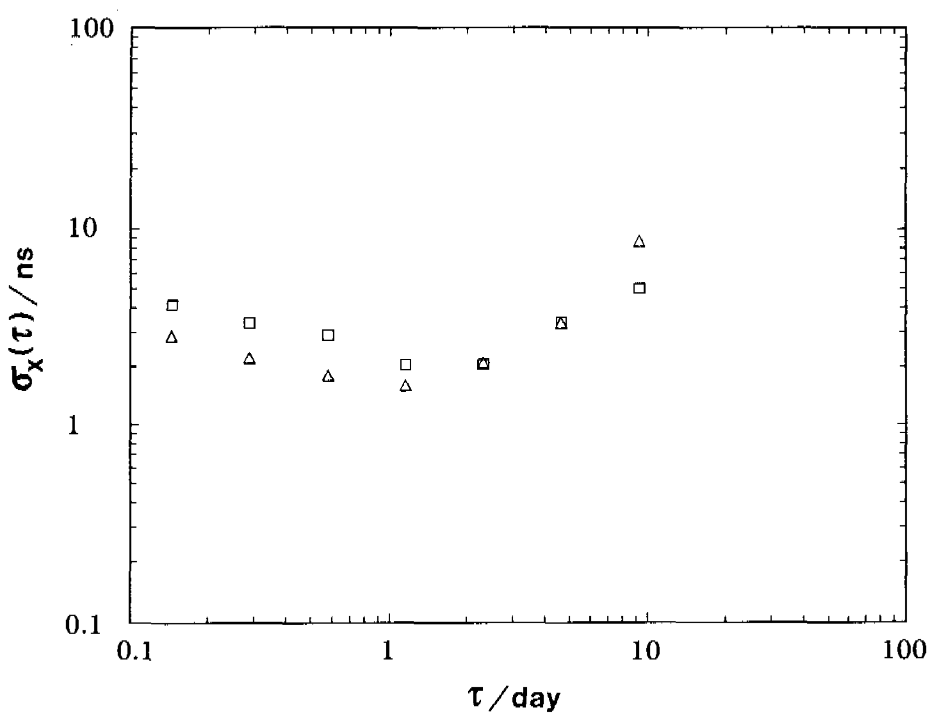

FIGURE 6: *Square root of the time variance $\sigma_X(\tau)$ of the link OP-NIST for data corrected using precise ephemerides and measured ionospheric delay over the periods MJD 48080 to 48160 (squares) and MJD 48375 to 48450 (triangles).*

QUESTIONS AND ANSWERS

David Allan, NIST: Would it not have been better to measure the frequency stability using Mod $\sigma_y(\tau)$? Since you have white PM, you can see the frequency more quickly and actually optimally.

Mr. Petit: We generally use $\sigma_y(\tau)$.

Mr. Allan: But Mod $\sigma_y(\tau)$ gives a better measure of what the clock is doing with white PM.

Dr. Gernot Winkler, USNO: In other words, you are not interested in frequency, but in time interval? Would you like to comment on the possibility of keeping the data at the stations, as with time, it is possible that by using all of the data, to improve your position with respect to the GPS reference system.

Mr. Petit: Yes, of course, that is a way of improving the station coordinates. That has actually been used, but clearly it is not the best way to get good coordinates. I would prefer to get very close to a VLBI or satellite laser ranging station and use precise surveying to obtain the station coordinates. That should give centimeter accuracy and will be done in the very near future.

Dr. Winkler: I agree, but my comment was addressed to the general time user, who cannot easily connect to a such a primary reference point as defined by laser or VLBI. He may well be better served by keeping all the records.

Mr. Petit: That is what we have done. Last June we introduced for all station clocks, a list of coordinates to be used that were derived from the time data themselves. This was because before this time, the station coordinates were uncertain by several meters. This was clearly visible in the time data. We now think that all the time stations are accurate to a level below one meter.

Dr. Martin Levine, SAO: Can you tell me the meaning, on the slide, of "raw data"? Is that the data as output by the receiver? Does it include the built in broadcast ionospheric and tropospheric corrections?

Mr. Petit: Yes, that is the data as it comes. It is the regular output of the receiver, with the built in broadcast corrections, but has not been processed to include our corrections.