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Enabling Accurate Differential Calibration of Modern GPS Receivers

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Abstract—The difference between the local time reference and a GPS receiver's internal time base is an essential contributor to the calibration of that receiver when used as a timing device. In the past, in the absence of a PPS (Pulse-Per-Second) output signal provided by the receiver, a one-time "tick-to-phase" measurement together with the reference PPS cable delay were used to represent the difference between the local time reference and the receiver's internal time base in the calibration process. The availability of a 1 PPS signal actually derived from the receiver's internal time base renders the "tick-to-phase" measurement obsolete, allowing for the measurement of the "tick-to-tick" time difference, which is a better representation of the relation between the receiver's time base and the local time reference. In the context of the synchronization between the MINOS (Main Injector Neutrino Oscillation Search) remote sites, NIST has developed an auxiliary electronic system to be associated with each receiver. Its core feature is the on-board time-interval counter (TIC) that continuously measures the receiver's "tick-to-tick" time difference, allowing for a dynamic and appropriate calibration of the receiver. The on-board TIC also measures the "tick-to-phase" time difference, albeit only for diagnostic purposes. Additional features of the auxiliary electronics, described in this paper, include RF power detection and conditioning, and pulse buffering and conditioning. Multiple calibration results for the MINOS synchronization setup will be presented and discussed.

I. INTRODUCTION

GPS receivers may be used as timing devices, with syntonization to a local frequency reference and/or synchronization to a local time reference. If the receiver's time base is not steered to the GPS timing information, the data in the file logged by it represents the difference between GPS time as represented by a specific satellite (referenced to the phase center of the local antenna) and the receiver's time base. The user of GPS receivers as timing devices is interested in knowing the relationship between the local time reference and GPS time, making it possible to relate the time at two separate locations.

In order to have meaningful comparisons of time in different places, a time reference plane is defined at each location of interest. A time reference plane, sometimes called a time reference point, is a specific physical place where a timing signal (pulse-per-second) is present: all the existing timing signals at that location are defined in terms of delay with respect to that place.

The discussion in this paper is limited to the use of GPS receivers as timing devices to relate local time at two different locations. Delays are inevitably part of any system implementation and, in the case of GPS receivers, have been grouped under three distinct contributions that have been part of the commonly accepted form by all GPS users. The difference between the GPS system time (as represented by PRN_n) and local time is:

$$\text{GPS time}_{PRNn} - \text{local time} = \text{GPS data} + REFDLY - CABDLY - INTDLY, \quad (1)$$

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where *GPS data* is the measured difference between the receiver's time base and GPS system time with only the propagation delay correction; *REFDLY* is the delay between the local time reference plane and the receiver's time base; *CABDLY* is the delay introduced by the cable connecting the antenna to the receiver; and *INTDLY* indicates the delay of the received GPS timing signal traveling through the antenna and receiver electronics, which is to be determined through a receiver calibration.

For a GPS receiver to work as a timing device, all delays specified in (1) must be determined. One of the difficulties of this proposition is the access to the receiver's time base, with respect to which *REFDLY* is defined.

Modern multi-channel, multi-frequency receivers often make available to the user a 1 PPS timing signal that is derived directly from the receiver's time base, thereby simplifying the estimation of *REFDLY*.

Figure 1 shows a simple schematic for a typical setup involving a GPS receiver used as a timing device, where all the quantities in (1) are indicated.

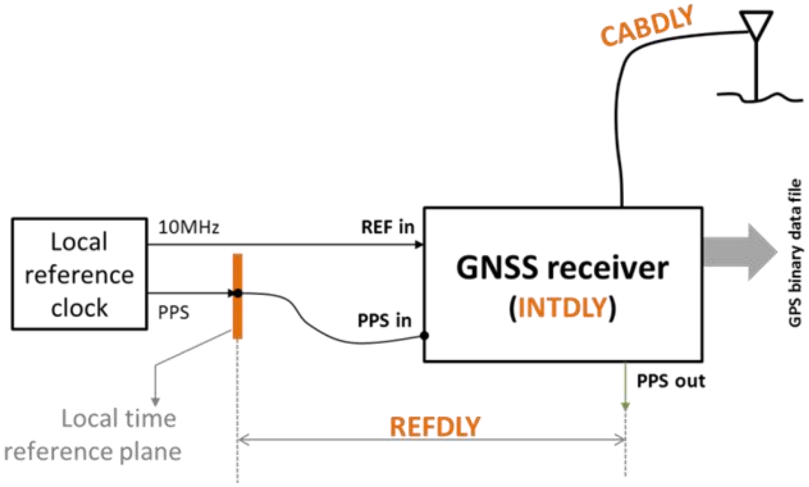

Figure 1. Simple schematic illustrating the definition of CABDLY, REFDLY, and INTDLY used throughout this paper.

In the generic case of Figure 1 a local clock provides a 10 MHz (or 5 MHz) signal to be used as a frequency reference for the receiver's internal oscillator (*REF in*), and a 1 PPS signal to be used to synchronize the receiver's time base to the local time reference plane (*PPS in*). The lack of a *PPS out* signal for older GPS receivers forced the user to define *REFDLY* as the delay between the local reference plane and the *PPS in* plus the delay between the *PPS in* and the closest zero-crossing of *REF in*, using *INTDLY* to contain any error in the REFDLY estimation, in addition to all delays inherent with the antenna and receiver's electronics. When the receiver, in turn, provides the user with a PPS signal that is a representation of the receiver's internal time base (*PPS out*), the *REFDLY* can then be defined as the time difference between *PPS out* and the local time reference plane.

II. WHY IS USING *PPS OUT* BETTER?

INTDLY is not directly measurable: it is possible to determine its absolute value only by using a full GPS simulator in an anechoic chamber, so it is generally determined differentially by comparison to a calibrated reference receiver in a common-clock, co-location setup. With the common-clock, co-location setup, we can also use a reference receiver (not necessarily calibrated) traveling between two remote locations to estimate the relative INTDLY difference of the two receivers for calculation of the time difference between the two locations. This method of determination of the relative *INTDLY* difference between two remote locations is referred to as a link calibration.

Such a link calibration is inherently not a continuous measurement, because the "reference receiver" has to travel between the two locations acting as a fly wheel. The lack of continuity renders the procedure vulnerable to unwanted changes that may happen inside any receiver, especially in the circuitry that locks the receiver's internal oscillator to the local time reference.

A good example of such an occurrence is shown in Figure 2, where different measures of REFDLY are compared for two GPS receivers. With reference to Figure 1, the delays called tick-to-phase and tick-to-tick are defined as:

$$\begin{aligned} \textit{tick-to-tick} &\equiv (\textit{PPS out} - \textit{PPS in})_{\textit{time difference}} \qquad (2) \\ \textit{tick-to-phase} &\equiv (\textit{PPS in} - \textit{REF in})_{\textit{time difference}} \end{aligned}$$

In the graphs shown in Figure 2, both quantities are measured (approximately every 100 s) for GPS2 and GPS8, which are both multi-frequency and multichannel units built at NIST and based on OEMV and OEM6 by Novatel,[2] co-located and referenced to the same time reference plane.

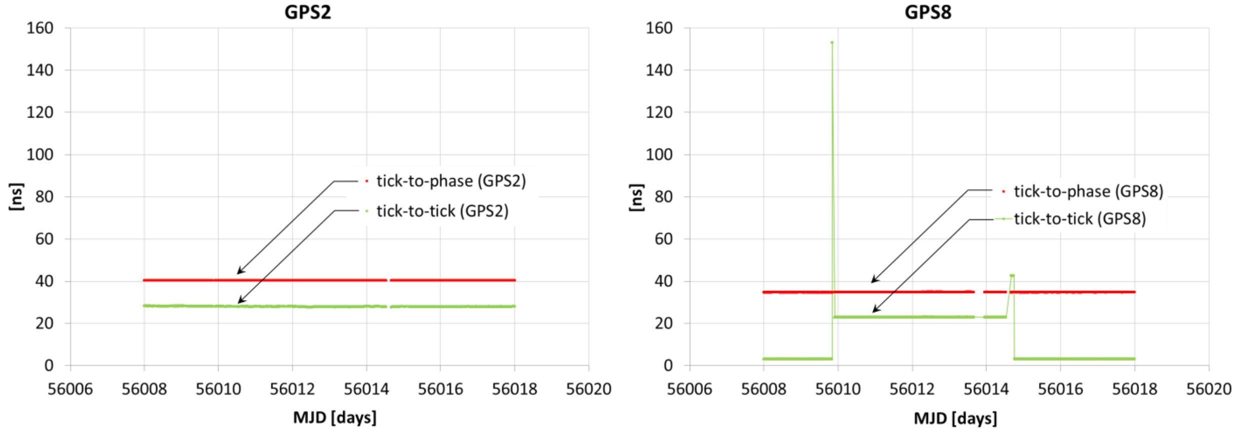

Figure 2. Example of the different kind of information conveyed by tick-to-tick (green) and tick-to-phase (red) measurements for two receivers (GPS2 and GPS8) co-located and referenced to the same time reference plane. The time steps occurring in GPS8's time base are detected by the tick-to-tick measurements only.

In the case of GPS2, the two measurements remain constant, but in the case of GPS8 the tick-to-tick measurement detected several time steps occurring in GPS8 internal time base. Specifically, all steps are an integer multiple of 10 ns, and given the frequency of GPS8's internal oscillator (100 MHz) they likely indicate cycle-slips of the internal PLL (phase-locked loop) in the receiver.

By using the tick-to-phase measurement to estimate *REFDLY*, the user would need to detect eventual time steps by performing repeated comparisons with a different receiver (that hopefully didn't experience the same kind of behavior simultaneously). The comparisons would produce different values for *INTDLY*, without informing as to which receiver in the differential comparison was actually experiencing the steps.

By using the tick-to-tick measurement to estimate *REFDLY*, in the presence of time steps like the ones shown in Figure 2, their provenance is clearly established and they can now be appropriately included in the comparison that allows the differential calibration of the receiver. In fact, in the case of the two co-located GPS2 and GPS8 receivers in common-clock configuration, we obtain from (1):

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[2] This information is provided for technical completeness. As a matter of policy, neither the authors nor NIST can endorse any commercial product. Other products may be found that work equally well or better.

$$(GPS8- GPS2)\ CVdiff + (REFDLY_8 - REFDLY_2) - (CABDLY_8 - CABDLY_2) = INTDLY_8 - INTDLY_2 \quad (3)$$

where *CVdiff* indicates the common-view difference for the GPS8,GPS2 pair. With the common-view difference, the measured *CABDLY* and the *REFDLY* estimated using both tick-to-tick and tick-to-phase measurements, the difference between $INTDLY_2$ and $INTDLY_8$ is calculated. The results are shown in Figure 3.

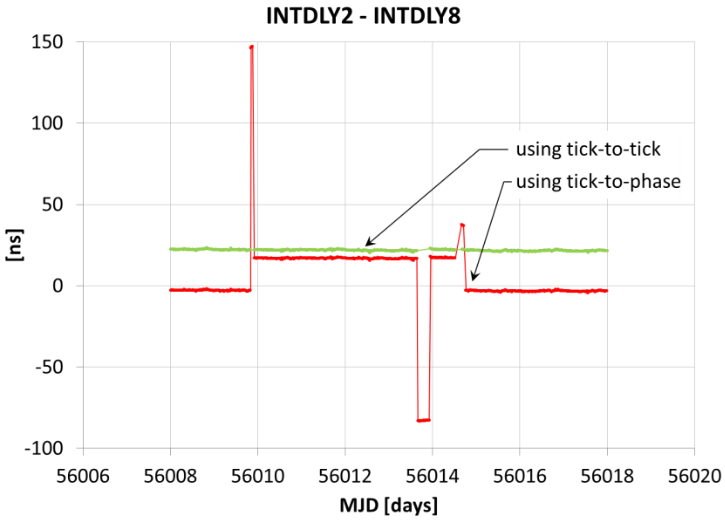

Figure 3. Difference between INTDLY for GPS2 and GPS8 calculated with REFDLY estimated from tick-to-tick (green) and tick-to-phase (red) measurements.

As discussed earlier, the case that used *REFDLY* as estimated using tick-to-tick measurements yields a constant *INTDLY* difference: the time steps are accounted for in $REFDLY_8$ and there is increased confidence in the comparison between the two receivers.

Finally, the tick-to-tick measurement truly measures the delay between the local time base and the receiver's time base: the PPS output signal is the best available representation of the receiver's time [1].

III. NIST-DESIGNED AUXILIARY ELECTRONICS

In the fall of 2011, members of the MINOS (Main Injector Neutrino Oscillation Search) collaboration at Fermilab in Batavia, IL, contacted NIST and USNO to discuss the timing setup for their facilities. The work described in this paper was stimulated by this collaboration, described in [2], and several receivers were equipped with the auxiliary electronics designed and implemented at NIST to be used for the synchronization of the remote sites for the MINOS experiment.

Figure 4 below shows a functional block diagram of the auxiliary electronics used for the synchronization of the MINOS experiment. The main capabilities of the auxiliary electronics are:

- PPS signal conditioning to allow 50-Ω load driving without degradation of the pulse shape;
- Reference signal (10 MHz in this case) conditioning and monitoring: a coarse frequency counter lets the user know the frequency to one digit and a power detector informs about its power level;
- Tick-to-phase and tick-to-tick measurements with programmable trigger voltage: the on-board TIC takes one start and two stops and utilizes the same reference signal that is provided to the receiver for its time base, ensuring coherent measurements. It is therefore possible to simultaneously measure tick-to-phase and tick-to-tick.

A microcontroller programs the TIC and communicates with the user via a RS-232 connection. The microcontroller also controls the insertion of a delay line of fixed length needed to avoid specific delays between the 10 MHz input and the PPS input that are unacceptable to the receiver [3], [4].

The receiver's manufacturer warns the user to avoid specific phase relations between the 5 or 10 MHz reference signal that may cause the internal PLL to skip cycles of the reference signal. The microcontroller is programmed to insert the delay line in the path of the RF signal if the tick-to-phase is measured to be unacceptable to the receiver.

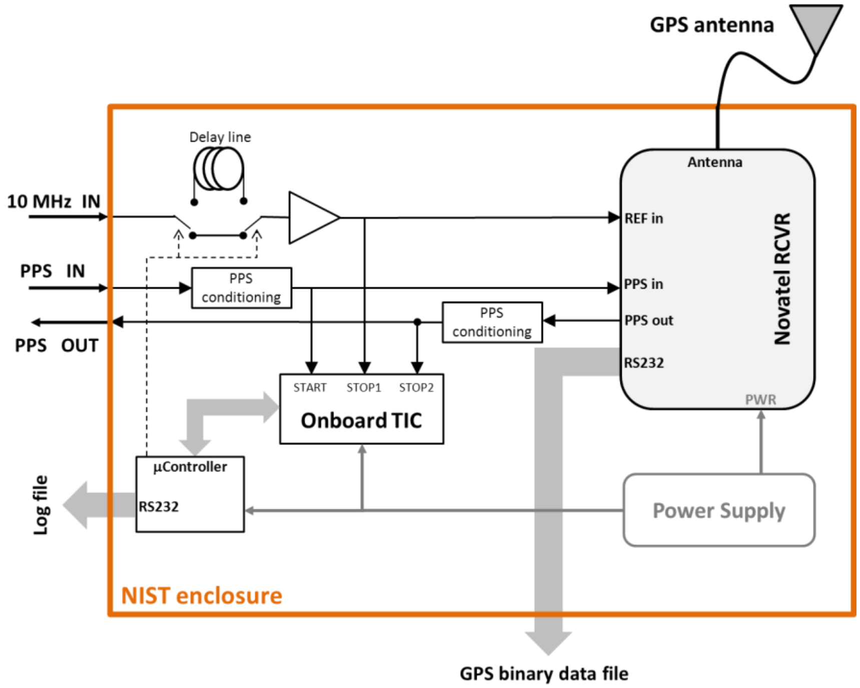

Figure 4. Functional block diagram for the GPS units equipped with the NIST-designed auxiliary electronics and used in the synchronization of the MINOS experiment.

A text file can be logged on a computer using the RS232 connection with the microcontroller with the following information:

- REF in frequency (5 or 10) [MHz]
- REF in power level [dB]
- Receiver's status (connection not shown)
- Tick-to-phase [ns]
- On-board TIC status for tick-to-phase measurement
- Tick-to-tick [ns]
- On-board TIC status for tick-to-tick measurement
- Delay line status (in or out)

Figure 5 displays some photographs of one of the GPS units deployed for the MINOS experiment, showing the front and rear panel of the enclosure, with a detail on the LCD screen in the front showing all the information that is contained in the text file output by the microcontroller via the RS-232 connection.

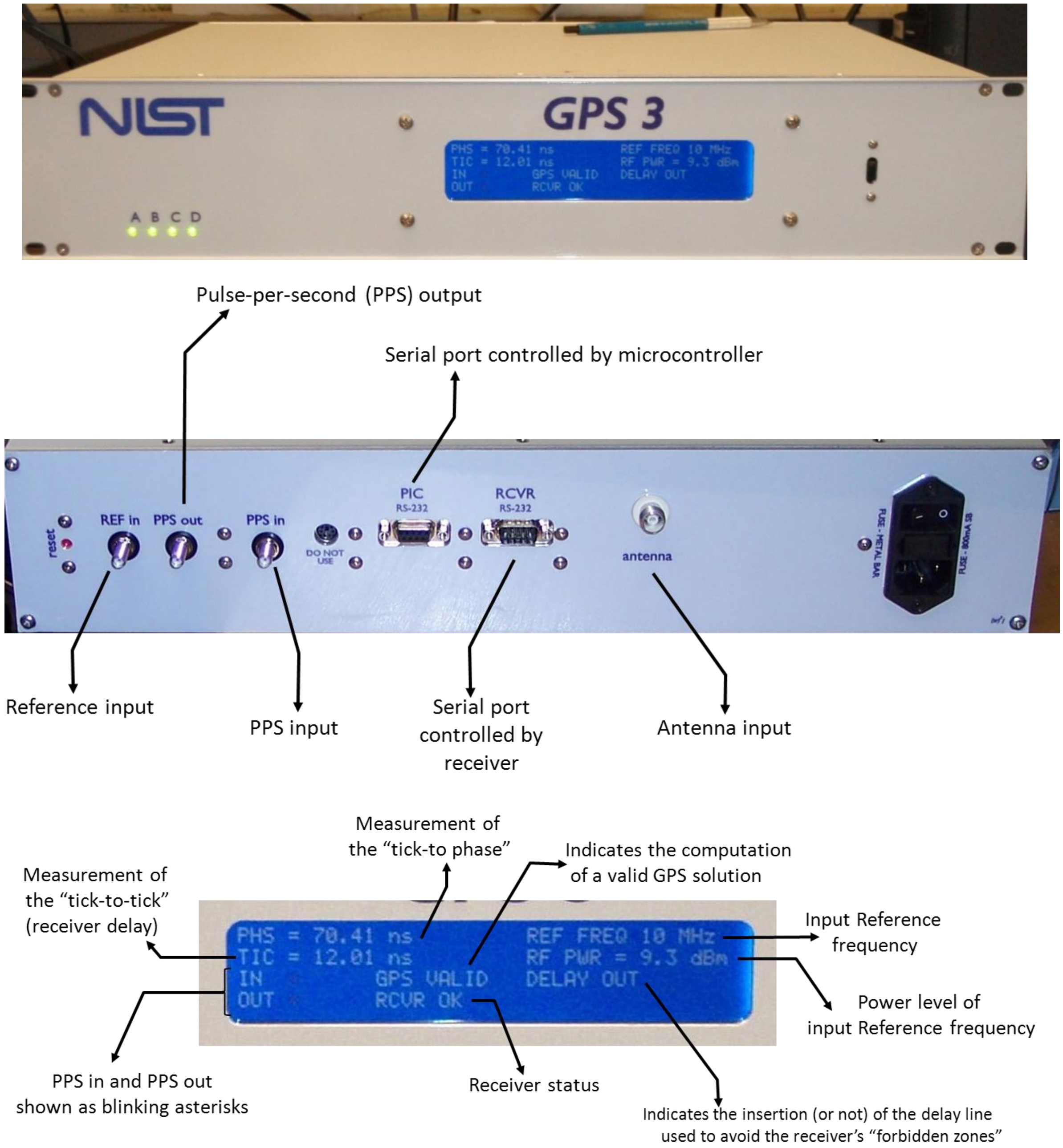

Figure 5. Photographs of one of the units deployed to synchronize the MINOS experiment. From the top, the front and rear panel and the LCD screen on the front of the enclosure are shown.

The auxiliary electronics introduces delays in both the RF and PPS paths towards the receivers that need to be measured and removed from the raw data provided by the time-interval counter. The addition of a test point on the circuit board that houses the TIC, as shown in the functional drawing in Figure 6, allows the determination of the four delays δ_1, δ_2, δ_3 and δ_4 by performing four independent measurements.

The first measurement determines the total delay $A = \delta_1 + \delta_2$ by injecting a PPS signal in place of PPS $\text{out}|_{\text{BOX}}$ and comparing it with PPS $\text{out}|_{\text{RCVR}}$ using an external time-interval counter. Similarly, $B = \delta_3 + \delta_4$ is also measured.

To measure $C = \delta_3$ a PPS signal is injected in the *test point* indicated in Figure 6 and compared with PPS $\text{in}|_{\text{BOX}}$ using an external time-interval counter.

Finally, to measure $D = \delta_1 - \delta_3$ two synchronized PPS signals are simultaneously injected in place of PPS $\text{out}|_{\text{RCVR}}$ and PPS $\text{in}|_{\text{BOX}}$ and are compared using the on-board TIC, whose result is shown on the front panel of the receiver's unit (see Figure 5).

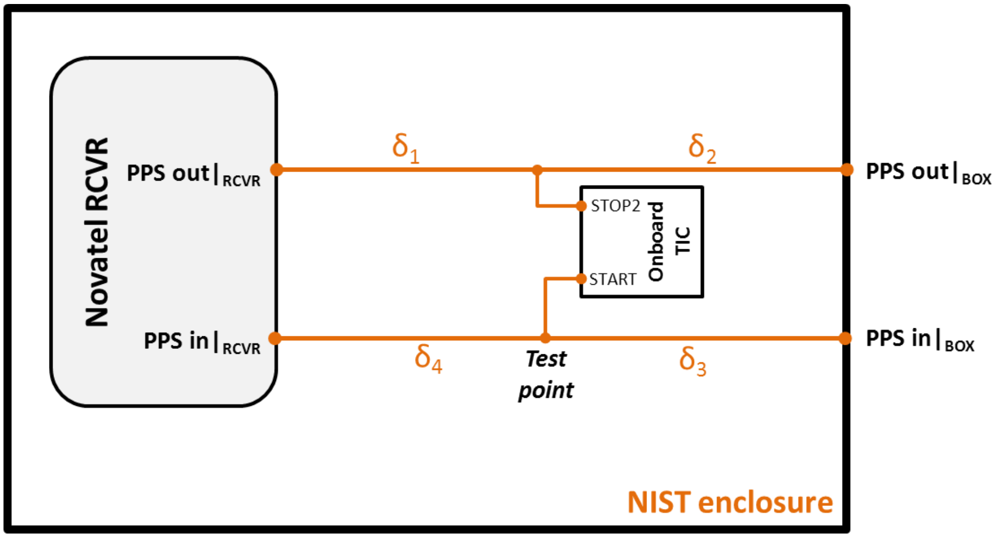

Figure 6. Functional diagram illustrating the delays introduced by the auxiliary electronics. By performing four independent measurements it is possible to determine δ_1, δ_2, δ_3 and δ_4.

The results of the four independent measurements are then used according to (4) to determine the 4 delays δ_1, δ_2, δ_3 and δ_4.

$$\begin{array}{ll} \text{1st meas.} & \delta_1 + \delta_2 = A \\ \text{2nd meas.} & \delta_3 + \delta_4 = B \\ \text{3rd meas.} & \delta_3 = C \\ \text{4th meas.} & \delta_1 - \delta_3 = D \end{array} \quad \rightarrow \quad \begin{array}{l} \delta_1 = C + D \\ \delta_2 = A + C + D \\ \delta_3 = C \\ \delta_4 = \mathrm{B} - \mathrm{C} \end{array} \tag{4}$$

These four quantities are then used by the microcontroller to provide the user with the best estimate of the tick-to-tick number, which is:

$$\text{tick-to-tick} \equiv (\text{PPS out}|_{\text{RCVR}} - \text{PPS in}|_{\text{BOX}})_{\text{time difference}}. \tag{5}$$

IV. SUMMARY

The GPS receiver units described in this paper were deployed to synchronize the MINOS experiment [2] both as fixed timing receivers at the various locations involved in the experiment, and as travelling units used for periodic and repeated differential calibrations. The NIST-designed auxiliary electronics enabled an increased level of confidence in the calibrations, yielding sub-nanosecond accuracies and nanosecond-level repeatability. An example of the repeatability and stability of repeated differential calibrations is shown in Figure 7, where the reference receiver used for the comparisons is GPS5. The other receivers are called GPS1, GPS2, GPS3, GPS4 GPS7, GPS8, and NIST. More details and additional data can be found in [2].

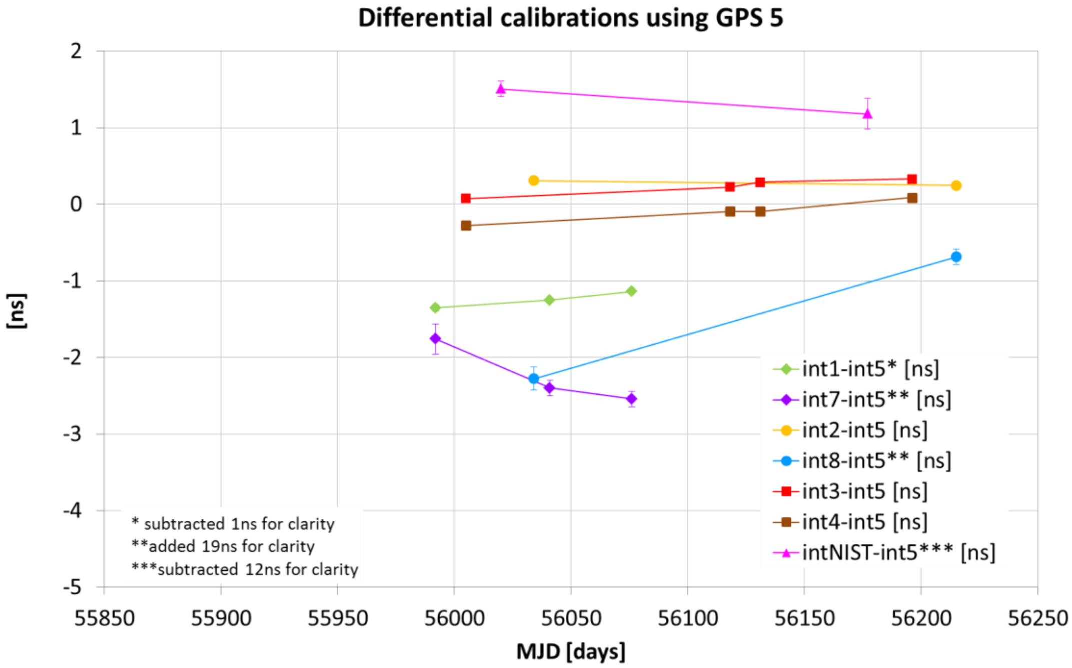

Figure 7. Example of repeated differenctial calibration of receivers GPS1, GPS2, GPS3, GPS4, GPS7, GPS8, and NIST using GPS5 as a reference receiver [2].

ACKNOWLEDGMENT

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