DELAY MEASUREMENTS OF PPS SIGNALS IN TIMING SYSTEMS

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***Abstract*—The uncertainty of measurements in timing systems is a function not only of the quality of the instruments and system components (time interval counters, pulse distribution amplifiers, Global Navigation Satellite System (GNSS) receivers, etc.) but also of the quality of the pulses carrying the timing information. This paper presents a study of the consequences of using pulse-per-second (PPS) signals in precise timing systems without properly considering their electrical characteristics. We discuss the effect of pulse shape, its distortion and instrument response on the measurement of time delay using PPS signals.**

I. Introduction

The "Guidelines for GNSS calibrations" [1] recently issued by the Bureau International des Poids et Mesures (BIPM) produced a renewed interest in timing calibrations with the intent of creating standard procedures to be adopted by all UTC-contributing laboratories. A crucial part of calibrations of time transfer links is the measurement of all of the various delays present in the time transfer systems. Many of these delays are related to the propagation of PPS signals into the system.

Every timing system component has its own time reference point: in many cases the rising edge of a pulse-per-second (PPS) signal. While PPS signals are chosen because they are unambiguous with respect to the fundamental unit of time, the second, they are very wide-bandwidth signals, whose characteristics may change dramatically depending on the source that produces them and upon the propagation characteristics of the systems that distributes them.

As an example, a GNSS receiver may create a PPS signal which differs significantly with respect to the one produced by a pulse distribution amplifier (PDA). As a general statement, each source produces a unique PPS signal, where the most obvious differences are rise time, voltage levels and nominal impedance. When the PPS has propagated through a pulse distribution amplifier and is detected by a time interval counter or a GNSS receiver, parameters like the threshold voltage, the bandwidth of the input port, and the impedance matching become important and are often partially unknown or difficult to determine. Finally, the transmission line for the PPS signals (likely a coaxial cable between 1 m and 20 m in length) must be carefully considered, because it will distort the pulse shape due to the dispersive characteristics of the cable.

In the paper, we discuss the effect of pulse shape, its distortion and instrument response on the measurement of time delay.

II. Pulse-Per-Second signals

A pulse is a rapid change in the amplitude of a signal from a baseline value to a higher (or lower) value (V_P), followed generally by a rapid return to the baseline value. A PPS consists of a pulse that repeats itself every second, ideally with a transition time equal to zero. A PPS signal can also be viewed as a digital signal that carries timing information at one (or both) of the transition edges. Since real PPS signals are band-limited, they use a finite time to transition between the baseline and a higher level and it becomes useful to associate the timing information of a pulse with the crossing of an agreed-upon voltage threshold. Using as a reference the simplified description of a pulse that is shown in Fig.1, the timing event identified by each pulse is defined by the crossing of the threshold voltage V_{TH}. While aware of the simple nature of this definition, we are deeming it suitable for the scope of this paper.

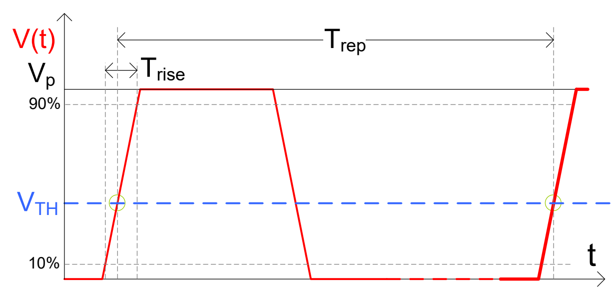

Fig. 1. Simplified depiction of a pulsed signal, with all the relevant quantities indicated.

A common PPS signal is a return-to-zero pulse (of duration between several hundreds nanoseconds and many microseconds) with $V_P = 2.5$ V delivered to a 50 Ω load, and with the time reference defined by a threshold level voltage V_{TH} of 1 V on the positive slope. Without excessive loss of generality, this work will be based on this type of pulse.

A. Pulse uncertainty

The uncertainty of the timing event identified by a pulse is a function of several parameters that, in turn, depend on the specifics of each timing system. A lack of knowledge, or a change, of the rise time of each pulse while propagating through the timing system clearly affects the determination of the timing event associated with it. An important consideration is that, besides dispersion in the transmission line used by the PPS signal, a significant distortion of the pulse shape (hence a change in its rise time) may be generated by impedance mismatch between components of the timing system as a consequence of the wide-band nature of pulsed signals. Also, while the value of the threshold voltage V_{TH} is mainly a parameter of the receiving end of the timing system it may have a significant impact on the timing uncertainty of a pulse: a slow pulse, with a larger rise time, is clearly more vulnerable to uncertainty due to trigger and amplitude noise.

B. PPS distribution system

Timing systems are often made by a time source (typically a PPS generator) and a distribution network, a combination of low-loss transmission lines and active distribution systems. The time reference is then delivered to several users (e.g. Time interval counters, GNSS receivers). In the system example in Fig. 2 we show simply a time interval counter, measuring the time difference between the local time scale and the primary clocks used for the computation of the steering of the offset generator, together with a link to the outside world represented by a TWSTFT (Two-Way Satellite Time and Frequency Transfer) modem. The time reference point for the system is defined at one of the outputs (for example 1) of the PDA. The arrows are generally coaxial cables.

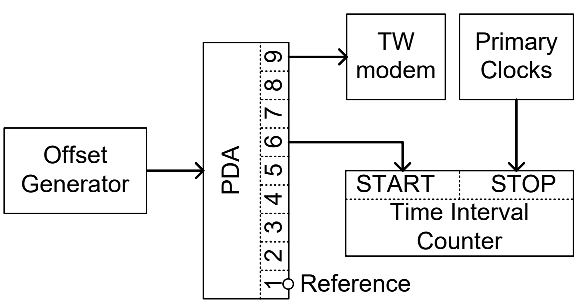

Fig. 2. Example of timing system in a laboratory. The time reference point in the system is defined at one of the outputs (for example 1) of the pulse distribution amplifier (PDA). The arrows are generally coaxial cables. For clarity only one time transfer device (TW modem) is shown here, although generally the PPS signal is distributed to several users. The time interval counter displayed here is a monitoring device that is part of the system.

1) Sources: The pulse source defines the initial rise time of the PPS. Uncertainty in the knowledge of its output impedance $Z_o(\omega)$ produces uncertainty in the rise time of the pulse as delivered to the rest of the system. With available technology, source rise times range from 10 ns to 50 ps, or even better.

2) Distribution network: The simplest PPS signal distribution network is a coaxial cable; more complex networks may include a cascade of PDAs interconnected by coaxial cables or may comprise also different transmission systems, including optical fibers. We limit our discussion to the case of coaxial cables. An other component of a distribution network is the PDA, which may acts simultaneously as a receiver and a source by generating the output PPS using a comparator (triggered by the input PPS) followed by a logic driver. We call this kind of PDA *active*. PDAs can dramatically change the characteristic of the PPS that flows through them: uncertainty in their input and output impedance generates uncertainty in the shape of the pulse, affecting the overall timing. In addition, active PDAs are also sensitive to any uncertainty in the trigger level of the internal comparator.

3) Receivers: A receiver detects each pulse in a PPS signal and generates a timing event. A receiver can be a time interval counter, or a device that uses the timing event to access other timing information, like a GNSS receiver, a TWSTFT modem or a similar time-transfer device. The voltage comparator within any receiver and the input stage leading to it are the main sources of uncertainty, in terms of V_{TH} and, through the input impedance and front end limitations, of time rise.

III. Delay of a coaxial cable

A correct measurement of the delay introduced by a cable is a fundamental building block in the accurate assessment of a distributed timing system. Coaxial cables are typically characterized in the frequency domain in terms of dispersion, attenuation and impedance. This approach is, in principle, useful from the viewpoint of PPS signals because of their inherent wide bandwidth, but it turns out to be limiting in practice because often the cable parameters are measured and specified for only few frequency values. It becomes then important to characterize the cable for a particular use, in this case with PPS signals.

A. Simulation

To understand the impact of a coaxial cable on the propagation of a pulse from a numerical point of view, we simulated it using a model for one of the most commonly used cables, a RG58 C/U. To validate the model, we compare the simulated attenuation and delay characteristics with the cable data sheet and a set of measurements performed with a network analyzer. Both the measurements and the simulation results are shown in Fig. 3 where the agreement is apparent.

Using this validated cable model, we now simulate the propagation of a pulse through a system consisting of an ideal PPS signal generator with parametrized pulse rise time and pulse shape, a coaxial cable whose transfer function is computed from 100 kHz to 100 GHz, and an ideal time interval counter. The simulation uses time increments of 5 ps, and works with $2\text{x}10^6$ points. Several cable lengths are simulated and for each one of them the source rise time is varied from 100 ps to 10 ns. The delay accumulated by each pulse through the cable is then recorded for each value of the rise time. The

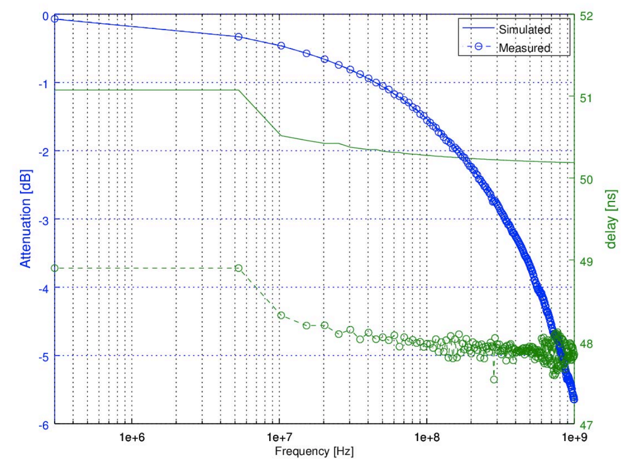

Fig. 3. Comparison between the simulation (-) and the measured (o) attenuation (blue) and delay (green) of a coaxial cable RG58 C/U as a function of frequency

results of the simulations are shown in Fig. 4, where each curve displays the excess delay introduced by the different lengths of cables when the rise time is larger than 100 ps. For example, a pulse with a rise time of 3 ns, when traveling through a 30 m long cable, will accumulate approximately 550 ps of additional delay with respect to a pulse with a 100 ps rise time traveling through the same cable. The simulation results agree with what we have experienced in timing measurements in our laboratories: when the rise time of the pulses increases, the delay of a cable as measured by the pulses themselves, increases too.

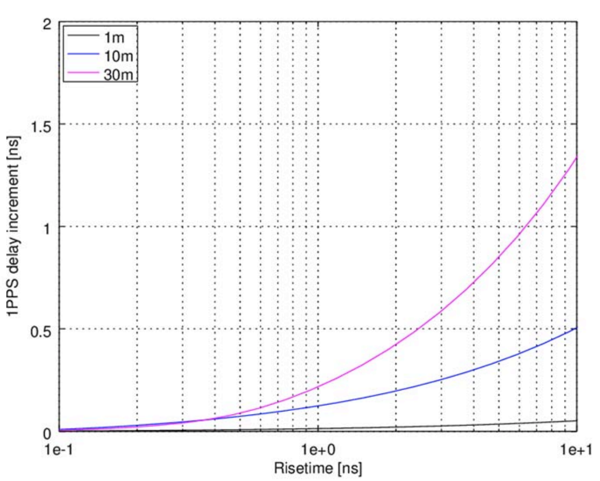

Fig. 4. Variation of PPS cable delay as a function of rise time for different cable lengths, computed using the model for RG58 C/U cables.

IV. The measurements

A. Test set

1) Cables Under Test: To validate experimentally the simulations described above we have measured several cables, among the most widely used in timing laboratories. The set of cables used throughout the paper are listed below:

- Test4 RG58 C/U, 0.5 m
- Test1 RG58 C/U, 1 m
- Test3 RG 58 C/U, 5 m
- Test2 RG 58 C/U, 10 m
- Test7 Heliax 1/4”, 4 m, FSJ1-50A
- Test6 Heliax 1/4”, 48 m, FSJ1-50A

The phase velocity for RG58 cables is approximately 66% of the speed of light, while for 1/4” Heliax is 84%.

2) Sources: In order to have different kinds of pulses available, two sources with significantly different rise time were used.

- SlowP it is the output of a HP3326A synthesizer set in two-pulse mode. The output pulses have an amplitude of 2.5 V, with a DC offset of 1.25 V delivered to a 50 Ω load. The rise time is approximately 8.6 ns.
- FastP it is the output of an active PDA, receiving the pulses from the same HP3326A through a very short cable (0.5m). The rise time of these pulses is approximately 460 ps.

3) Oscilloscope: Oscilloscopes are not a recommended instrument to measure time differences, but are used in this work to illustrate the effect of cable dispersion on the shape of PPS signals. For this purpose, we used a Keysight MSO6104A, a 4Gs/s, 1 GHz bandwidth oscilloscope, with input impedance set to 50 Ω and 1 V trigger voltage on the positive edge for the measuring channel.

4) Time Interval Counters: A time interval counter measures the elapsed time between two timing events at its inputs. One of the two inputs (START) is selected to identify the beginning of the elapsed time, while the STOP identifies its end. It is our recommended instrument for measuring time differences. In this paper, delays of cables and time differences between pulse sources were measured using two time interval counters with significantly dissimilar characteristics, as suggested by their very different stated RF bandwidths:

SR620, 300 MHz RF bandwidth [2].
GT688, 2.7 GHz RF bandwidth [3].

In reality, a specified RF bandwidth is perhaps not the best way to describe the measurement capabilities of a time interval counter as a function of the harmonic content (i.e. rise time) of the input pulses, but that discussion is beyond the scope of this paper and we will identify the two counter as ”slow front end” (SR620) and ”fast front end” (GT668).

B. Edge Measurements

The rising edge of the pulses generated by the two sources is measured before and after passing through the cables under test using the oscilloscope described in the previous section.

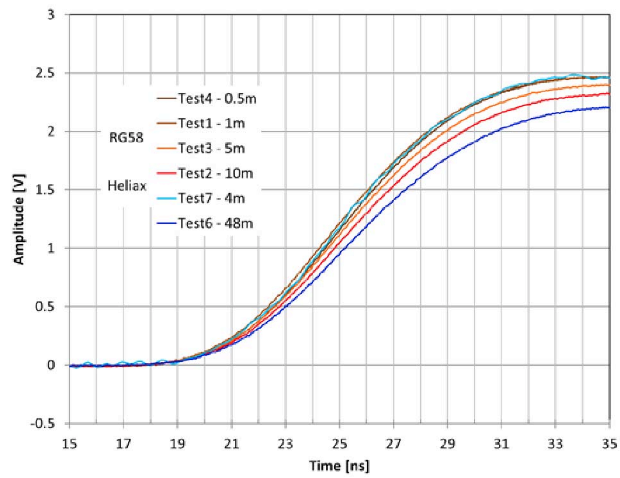

Fig. 5. Pulse rising edges generated for the SlowP case (8.6 ns) and measured at the end of the test cables.

No trace smoothing was used, while some trace averaging helped reducing the overall noise. The results for the SlowP case are shown in Fig. 5, while the ones for the FastP case are in Fig. 6.

While all traces have been acquired using a trigger voltage of 1 V, the curves have been re-aligned with respect to the beginning of each pulse to better illustrate the pulse distortion and its effect on delay measurements. The measurement of the source pulse directly (no cable) was possible only in the FastP case, while in the SlowP case the shorter cable used was 0.5 m (Test4). Also, the 1-GHz oscilloscope bandwidth may introduce a limitation in the displayed rise time for the FastP case, when measured at the source. We do not think either of these limitations significantly affects the discussion. These results show that the amount of measured delay introduced by a cable depends on the rise time of the propagating pulse itself. For example, after propagation through the cable named Test2(RG58, 10 m long) the 1-V trigger point is delayed by approximately 100 ps in the case of a 460-ps rise time pulse, while it is delayed by approximately 500 ps if the rise time of the pulse is 8.6 ns.

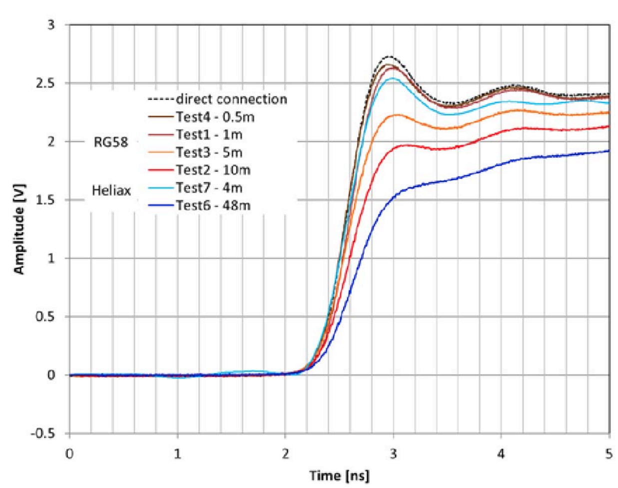

Fig. 6. Pulse rising edges generated for the FastP case (460 ps) and measured at the source and at the end of the test cables.

C. Cable delay measurements

The actual cable delay measurements were performed using the two time interval counters described in the previous section. We measure the delay of several cables of different lengths using the setup in Fig. 7. The difference between the measurements with each of the test cables (indicated by (1) in the figure) and the ones performed with the direct connection to the time interval counter (indicated by (2)) provide the delays of the test cables, shown in Table I.

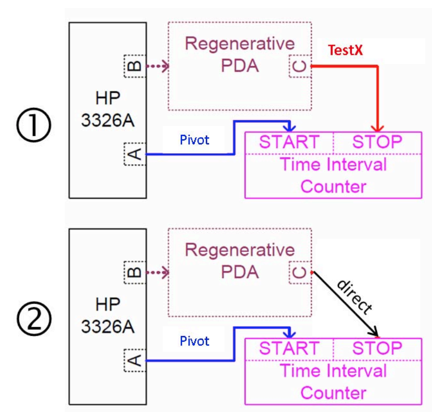

Fig. 7. Experimental setup for the cable delay measurements using the pivot method in the FastP case.

TABLE I
DELAY OF TEST CABLE USING BOTH COUNTERS. UNCERTAINTY 20 PS

	Cable Delay [ns]			
	RG58		Heliax	
	Test3 (5 m)	Test2 (10 m)	Test7 (4 m)	Test6 (48 m)
SR620	25.34	50.78	16.58	194.34
GT668	25.28	51.67	16.54	194.17

This first set of measurements simply tells us the delays of the test set of cables, and we can notice that the two different counters do not provide the same delay values for each cable: this is likely due to their very different front ends characteristics. We next use the setup shown in Fig. 8 to compare the cable delays when measured by the pulses with short rise time (FastP, 460 ps) and by the pulses with long rise time (SlowP, 8.6 ns). We call this difference (due to the different rise time of the pulses traveling through the cables) $\Delta delay$, computed by subtracting the measurements performed with the four configurations indicated in Fig. 8:

$$\Delta Delay = [(1) - (2)] - [(3) - (4)] \tag{1}$$

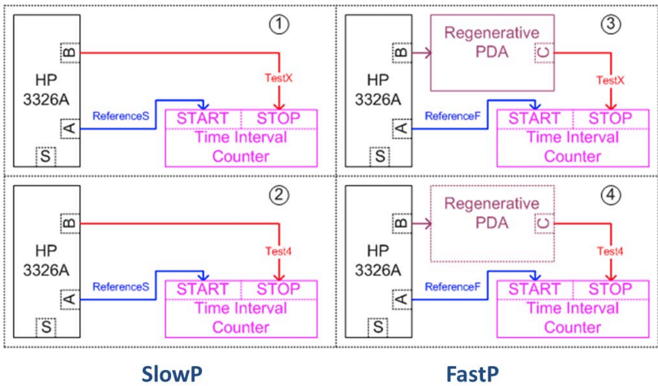

Fig. 8. Experimental setup for the cable delay measurements using the pivot method in the SlowP case.

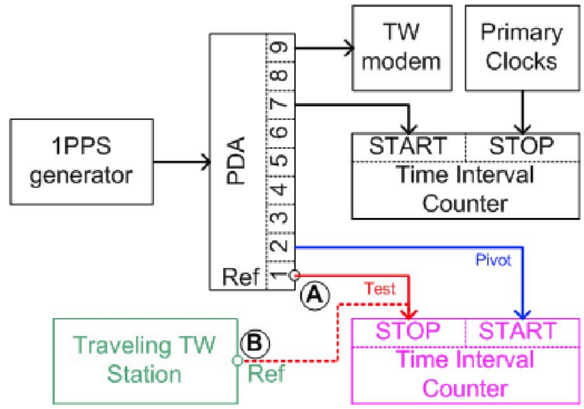

Fig. 9. Example of a timing laboratory setup where the measured quantity is the time difference between PPS signals at the location called (A) and (B). The blue cable is called the pivot, the red cable is called the probe and will move from (A) to (B)

The results are reported in Table II, for both time interval counters. Each measurements reported in Table I and Table II was taken with an averaging factor of 200 or more, and the overall statistical uncertainty of each measurement has been estimated to be approximately 20 ps.

TABLE II
DELTADELAY FOR ALL TEST CABLES IN PS USING BOTH COUNTERS. UNCERTAINTY 20 PS

	$\Delta delay$ [ps]			
	RG58		Heliax	
	Test3 (5 m)	Test2 (10 m)	Test7 (4 m)	Test6 (48 m)
SR620	252	443	56	789
GT668	232	431	58	713

The data shows consistent and statistically significant differences between the delay of each cable as measured using PPS signals with different rise times. These differences are observed by both time interval counters and are larger when the rise time of the pulse propagating through the cable is larger, confirming the same trend displayed in the simulation results of Fig. 4. We observe again that the cable delay measurements do not give the same results for both counters.

D. Time difference between different PPS signals

Another typical measurement occurring in timing laboratories is the time difference between PPS signals at different locations in a laboratory, indicated by (A) and (B) in the example block diagram shown in Fig: 9. This time difference is not directly measured by connecting the STOP and START ports of the time interval counter (shown in pink) directly to the (A) and (B) outputs, respectively. Instead, we use a method that we call ”pivot”, where the blue cable, called ”pivot”, remains connected to a PPS source (that is neither A nor B) for the entire duration of the measurement, while the red cable, called ”probe” is connected in turn to (A) and (B). The delay between (A) and (B) is then obtained subtracting the two measured quantities.

In principle, both cables (pivot and probe) and many of the time interval counter biases are common to all measurements and therefore should not affect the results. In reality, however, if the pulses at (A) and (B) have very different rise times, the length of the probe cable may introduce dissimilar amounts of distortion causing significant measurement errors.

To illustrate this, we measure the time difference between two PPS signals that, while originally coming from the same source, have very different rise times. The setup for these measurements is shown in Fig. 10, where the PPS at (A) has a rise time of 8.6 ns (SlowP) while the one at (B) has a rise time of 460 ps (FastP).

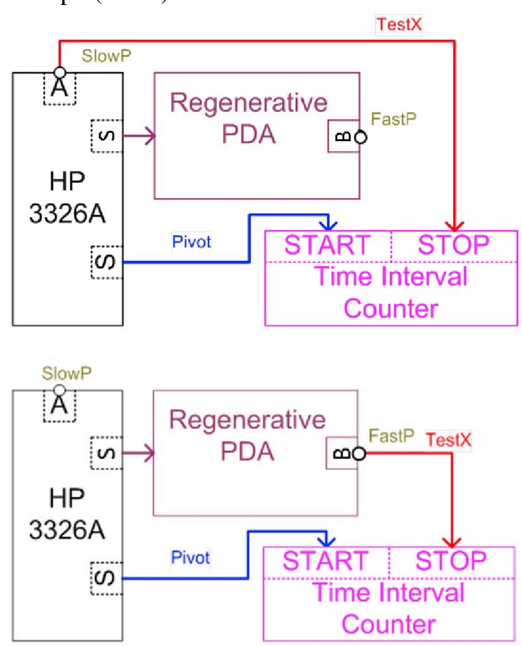

Fig. 10. Experimental setup for time difference measurements between dissimilar PPS sources, using the pivot method using both time interval counters (SR620 and GT668).

The results for the measurement of the time difference between locations (A) and (B), performed with both time interval counters are shown in Table III, where the result of using different counters and probe cables of different lengths is readily apparent: there is a discrepancy greater than 700 ps between the measurements performed by the two counters, and a discrepancy of approximately 400 ps between the use of a 1-m long probe cable and a 10-m long one. Both discrepancies between measurement of, in principle, the same quantity are statistically significant.

TABLE III
DISCREPANCY BETWEEN DELAY MEASUREMENTS WITH DIFFERENT COUNTERS AND DIFFERENT PROBE CABLES. UNCERTAINTY 20 PS

	delay(A)-delay(B) [ps]		Test1-Test2 discrepancy [ps]
	Test1 (1 m)	Test2 (10 m)	
SR620	632	238	396
GT668	1422	992	430
GT668-SR620 discrepancy [ps]	790	754	

V. CONCLUSIONS

We investigated the impact of cable attenuation and dispersion on the rising edge of propagating PPS signals and, consequently, on delay measurements when performed using pulses. Using a model, validated by measurements, we computed various cable delays as a function of the rising edge of the propagating pulses, for different cable lengths. Several sets of measurements were performed first with fast-rising pulses (FastP case, 460 ps rise time) on a number of test cables, using two time interval counters with substantially different front-end characteristics. These measurements showed a discrepancy between measurements of the same cable (with the same pulses) by the two counters, likely due to the different front-end characteristics of the two instruments: the counter with the slower front end (smaller stated RF bandwidth) measured consistently larger delay values.

The next set of measurements compared the results obtained using both kinds of pulses, slow-rising ones (SlowP case, 8.6 ns rise time) and fast-rising ones (FastP case, 460 ps rise time) yielding longer measured delays when the slow-rising pulses were used, well in agreement with the results of the simulations.

Finally, a last round of measurements was performed to measure the time difference between pulses in two different locations in the laboratory. The method used to perform these measurements, using a pivot cable and a probe cable, should be independent of cable lengths. In reality, because the two locations (indicated by (A) and (B) in Fig. 10 have very dissimilar pulses (one is sourcing slow-rising pulses the other fast-rising ones)the resulting measured time difference is larger when a shorter probe cable is used, indicating the dissimilar amount of distortion introduced by the probe cable on dissimilar pulses.

While we do not believe the discussion of sources of uncertainty in timing measurements using PPS signals has been exhausted in this work, it is clear from the results presented here that when building a pulse-based timing system, it is paramount to understand the shape of the pulses available, and that the smaller the rise time, the less significant the impact of cable distortion. It is also advisable to define the local time reference point at the output of a PDA rather than at the end of a coaxial cable, where the combination of poor source pulses (slow-rising), cable distortion and poor TIC trigger level quality can lead to significant uncertainty in its determination, especially if the cable is long.

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Certain commercial devices have been identified by name for technical completeness. This does not constitute an endorsement by NIST or SYRTE of these devices. The identified devices may or may not be the best available for the purpose described herein.

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