Documentation of the Calibration Implementation for the Trigger Distribution in the Backplane-Network of the CTA-LST Camera

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Abstract

In order to get accurate camera results, an equalized time distribution of all triggers in the camera of the LST along the backplane network is necessary. An automated calibration procedure program was written and tested using different setups at CIEMAT.

Contents

1. Introduction

In the LST camera, the signal propagation is done in a daisy-chain style backplane to backplane. Ultimately, the time for an L1 signal from any given module to the center should be the same across the entire backplane network. The same goes for the camera signal coming from the center going to the backplanes. To implement this, an adjustment of the different delays on the backplanes is necessary.

2. Calibration Procedure

Every calibration cycle starts with a set of two neighbouring backplanes, out of which one is the backplane with the highest latency of the entire backplane network that is set up. Said backplane is the "reference" as well as the "pulser", meaning it is also responsible for distributing or pulsing the L0 signal, that will trigger the propagation of the L1 signal in both the reference and the "victim" module. Fig. 1 shows a simplified depiction of the setup.

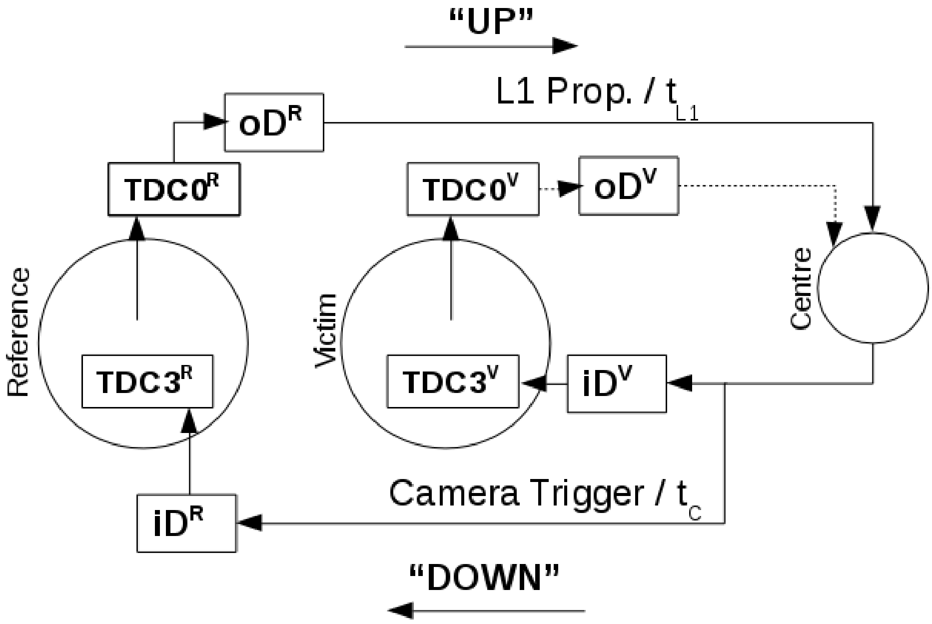

Figure 1: Theoretical Calibration Setup

Goal of the calibration is to set the outgoing delay (oD^V, Up-Calibration) as well as the incoming delay (iD^V, Down-Calibration) of the victim in a way that both t_{L1} and t_C are the same as for the reference. Determining the delay value can be done with the help of the TDC's, or more specifically the time difference between TDC3 and TDC0, so the time-difference between the L1 signal leaving the backplane and the camera signal returning to the backplane.

2.1. *Down calibration*

For the down calibration, the L1 signal distribution of the victim is deactivated. This way it is ensured, that the resulting camera signal is triggered by the L1 signal of the reference. Since both L1 signals (reference and victim) were triggered by the same L0 signal, we can assume that they reach $TDC0^R$ and $TDC0^V$ at the same time. Reading register 12 of both the reference and the victim gives us TDC3 - TDC0 = Δ for both modules. The value that has to be put on the incoming delay of the victim (ID^V) is thus equal to

$$t_{ID^V} = (TDC3 - TDC0)^R - (TDC3 - TDC0)^V = \Delta^R - \Delta^V \tag{1}$$

which is the time it takes the camera signal longer to reach the reference module in comparison to the victim module. Once the delay is set, it will take the same time for the signal to reach both. The value Δ^R is defined as the latency L.
In the actual calibration procedure, the delay is set in two steps: coarse delay (steps of $\approx$ 10 ns) and fine delay (steps of $\approx$ 36 ps) (See Chapter 3).

2.2. Up calibration or Latency

For the up calibration, the L1 signal distribution of the victim is activated and the L1 distribution of the reference deactivated. Δ^V now gives us the entire time the signal needs to go from the module to the center back to the module. The outgoing delay (oD^V) is set so that Δ^V is equal to the latency determined in the down calibration, so:

$$t_{OD^V} = L - (TDC3 - TDC0)^V \tag{2}$$

Again, this is done in two steps.
Now, both t_{L1} and t_C are identical for reference and victim. The victim becomes the new reference/pulser, a new neighbouring module is chosen as the victim and the process is repeated.

3. Computer/Program Implementation

The calibration procedure is implemented in a scripting language specifically programmed for the communication with the backplanes. The following roughly shows the structure of the program:

1. Set Reference, Pulser, Victim and Center Module IP as well as all their delays
2. Down Calibration
   - Enable L1 propagation for reference
   - Determine t_{ID^V} (1) and divide by coarse step size (10000 ns) $\rightarrow$ Apply that number (integer) of coarse steps. Repeat until difference smaller than 10000 ns.
   - Determine t_{ID^V} and divide by fine step size (36 ns) $\rightarrow$ Apply that number of fine steps. Repeat until difference smaller than 36 ns.
3. Up Calibration
   - Enable L1 propagation for victim
   - Determine t_{OD^V} and divide by coarse step size (10000 ns) $\rightarrow$ Apply that number of coarse steps. Repeat until difference smaller than 10000 ns.
   - Determine t_{OD^V} and divide by fine step size (36 ns) $\rightarrow$ Apply that number of fine steps. Repeat until difference smaller than 36 ns.
4. Set old victim as new reference/pulser and choose neighbouring module as new victim, repeat from 2.

The implementation can be found in its entirety in Appendix A.

4. Calibration Loop for CIEMAT Setup v1

At first, a chain of four modules was set up in order to test the calibration procedure:

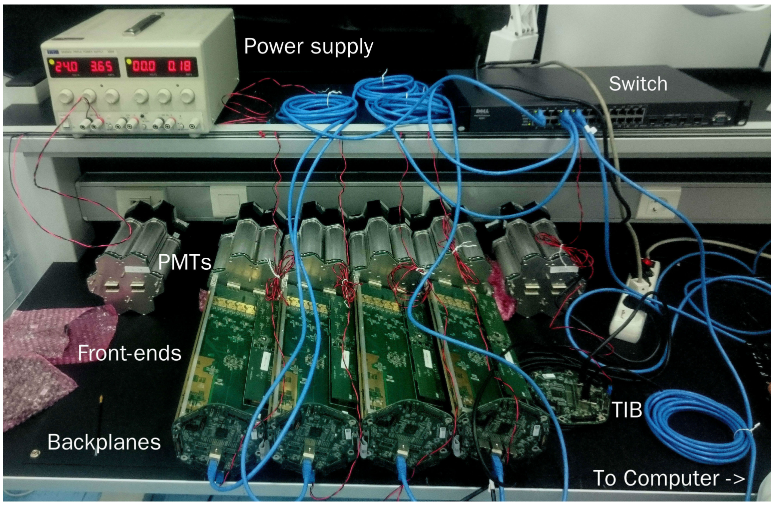

Figure 2: Setup v1 in the CIEMAT clean room

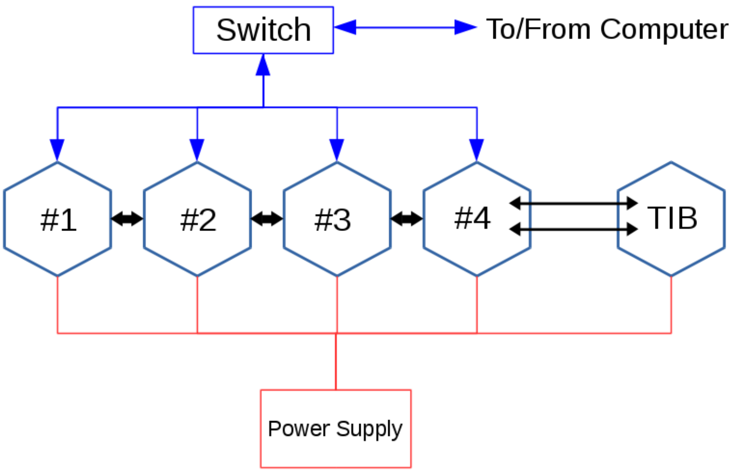

Figure 3: Block Diagram of the Setup

The initial delays were set to default values defined by the position of the module with respect to the centre module (in this case module #4, set with maximum possible coarse delay (0xB)) and all other backplanes set with decreasing values for increasing distance to the centre (0xA, 0x9 etc.)).
A chain of four modules allows three calibration procedure cycles, starting with the module furthest from the centre (#1) as the reference/pulser and moving inwards. This entire cycle is then repeated for different initial delays (cu: coarse-up, cd: coarse-down, fu: fine-up, fd: fine-down) of the first reference module to ensure the reliability of the procedure. The

commented source code can be found in Appendix B.
The following table shows an excerpt [1] of the results for the first run:

Initial Delays				TDC of bp no. x [ps]			
cu	cd	fu	fd	#1	#2	#3	#4
8	15	202	254	211619	211615	211085	211061
8	15	194	250	211361	211343	210733	210709
7	15	202	254	202125	202196	201684	201671
7	15	194	254	201848	201881	201326	201417

Table 1: TDC measurements made for different initial delays

In total, the calibration loop was performed 84 times in this test run. As expected, the TDC values go down for smaller initial delay values. One of the problems that occurred can be seen here, which is a drop of about 500 ps in the TDC value between the second and the third module. The source of that problem was an issue in the neighbour assignment of the centre module.
Apart from equalizing the TDC values of all the modules, the calibration procedure should also be as fast as possible. Given that the camera has to be calibrated a minimum of once per day, a time-consuming calibration procedure could waste valuable data-taking time. After optimizing the program and changing the pulser frequency, the time for one calibration run (four modules) was reduced by 50 % from $t \approx 2$min to $t \approx 1$min.

[1] Entire dataset in App.C

5. Setup v2

After a successful implementation of the calibration procedure for the initial setup, four more modules were added to the chain, requiring only small changes in the program implementation.

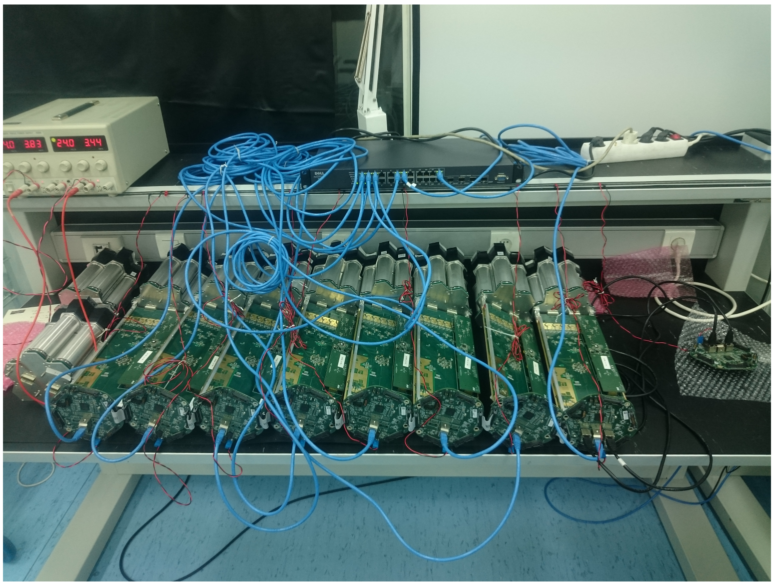

Figure 4: Setup v.2

The calibration procedure is repeated a number of times to check the stability of the TDC values and whether or not they lie within the allowed range of ≈ 300 ps when compared to the other backplanes. The following shows an excerpt of the data that was taken:

Module no.	TDC [ps] for six calibrations					
1	254723	254940	255040	254951	255047	254988
2	254771	254983	255047	254968	255136	255003
3	254846	254960	255082	255143	255117	255031
4	254804	255042	255103	255090	255132	255047
5	254739	255119	255039	255079	255110	254975
6	254741	254948	255052	255099	255110	254923
7	254779	254962	255112	255162	255177	254989
8	254794	254999	255202	255225	255234	254931
Average	254775	254973	255067	255095	255125	254984

Table 2: TDC measurements made for six different calibration runs

Calculating and plotting the time difference Δt of each TDC-measurement from the average of the calibration run (vertical direction in the table) as well as the difference between the maximum and minimum value of each run yields:

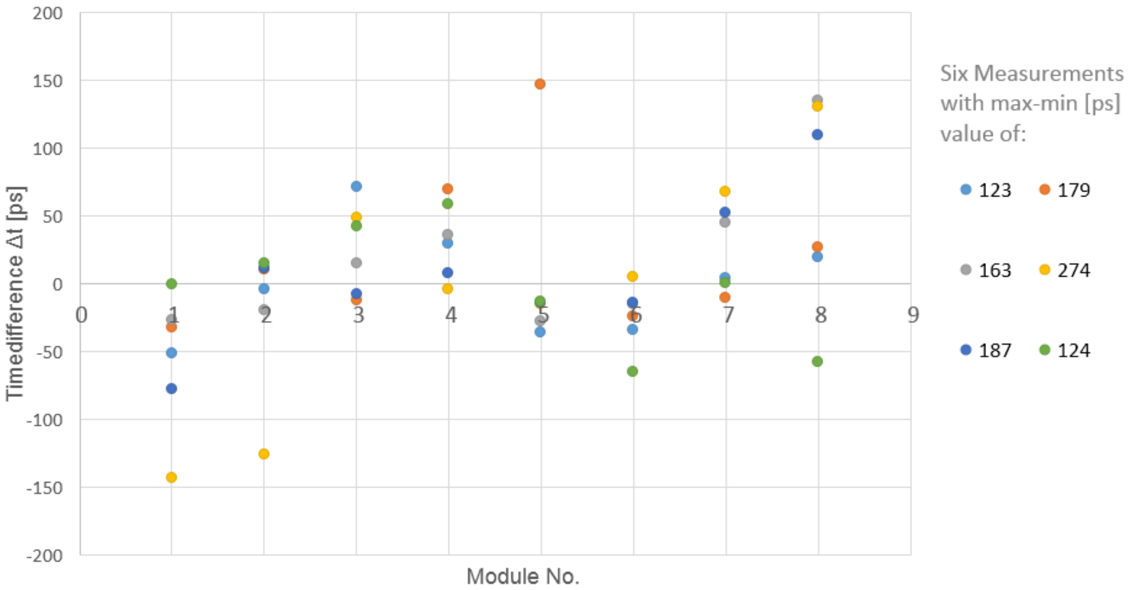

Figure 5: Deviation Δt of the measured TDC values of the different modules from the average across the same calibration measurement

The value of interest is the peak to peak time difference Δt_{pp}(max-min). For all of the taken data, this value lies within the allowed range of ≈ 300 ps. The calibration seems to work well.

Another interesting aspect is to compare the TDC values of the same module over the different calibration runs (horizontal direction in the table). Although this does not really play a role for the LST camera from a scientific point of view, it is interesting to see how much fluctuation is introduced. Again, both the time-difference from the average as well as the pp-value is calculated and plotted (Fig. 6).

The peak to peak values tend to be higher than among the different modules of the same calibration run, with values greater than 300 ps for all modules. This fluctuation stems from the wave shape of the clock.

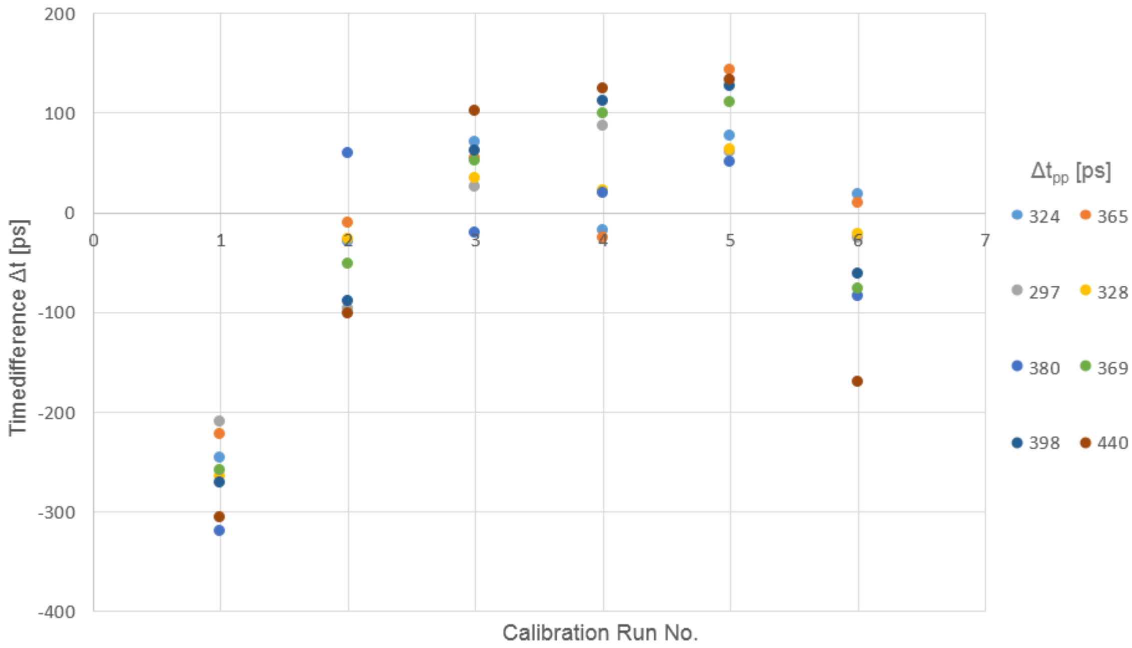

Figure 6: Deviation Δt of the measured TDC values of the same module from the average across all the calibration measurements

6. Calibration Loop for entire analog trigger backplane network

The next step will be to perform the calibration of the entire analog trigger backplane network, which is to go in pairs of two along the predefined paths for the signal distribution (See Fig. 7). For the calibration of a module that lies at the beginning of a path (so all modules on the edge) the initial reference is a neighbouring module on the edge that has already been calibrated. A program will be written that does the calibration for the entire analog trigger backplane network.

7. Conclusion

The Calibration of the trigger distribution in the backplane-network was successfully implemented and tested [...].

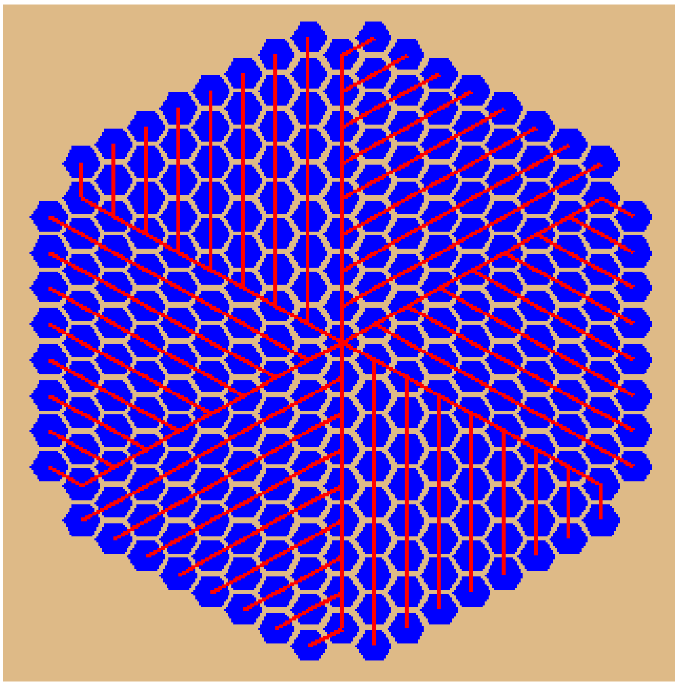

Figure 7: Paths for the signal distribution of the analog trigger backplane network

8. Appendix

A. Program Implementation

```

(---------- Predefined TOOLS & FUNCTIONS -----------)
( Manipulate registers in a way to read/write TDCs, set delays etc...)

{nop} :->
36 :step (fine step in ps)
9000 :coarse-step (coarse step in ps)
{2000000 usleep} :pulser-waiting-time
1024 :pulser-freq

{1000000 2 / usleep} :pulser-waiting-time
2048 2 * :pulser-freq

{11 0x2000 bp/write 100000 usleep 11 0 bp/write 100000 usleep } :reset-tdc
{11 0xffff bp/write 100000 usleep 11 0 bp/write 100000 usleep } :reset-all

{5 bp/read 0x3ff and 5 swap bp/write} :disable (disble l1 propagation)

{31 bp/read 32 bp/read 16 << +} :read-tdc


```

```
{
       reference -> reset-tdc
       victim   -> reset-tdc
       pulser -> fe/tp/enable
       pulser-waiting-time
       pulser -> fe/tp/disable
} :single-step


{.{CALLED SAVE/S!!!!!} nop} :save/s
{.{CALLED load/s} nop} :load/s

{
 15 and (get only the useful bits)
 4 <<  (shift)
 12 bp/read 15 and
 or  12 swap bp/write
} :set-coarse-down


{
 15 and
 12 bp/read 15 4 << and
 or 12 swap bp/write
} :set-coarse-up


{ 12 bp/read 4 >> 15 and} :get-coarse-down
{ 12 bp/read 15 and} :get-coarse-up


{0x0101 or} :adjust (force to have bit 1 of the two delay lines in cascade to 1)


{ (reset-delay-lines)
       11 0x0 bp/write
       11 0xc bp/write
       11 0x0 bp/write
       10000 usleep
       2 / dup 8 << or adjust
       2 swap bp/write
       7 0x0 bp/write
       7 0xc bp/write
       7 0x0 bp/write
} :set-fine-down
```

```
{ (reset-delay-lines)
       11 0 bp/write
       11 3 bp/write
       11 0 bp/write
       10000 usleep
       2 / dup 8 << or adjust
       1 swap bp/write
       7 0x0 bp/write
       7 0x3 bp/write
       7 0x0 bp/write
} :set-fine-up

{
  2 bp/read
       dup
       0xff and (lower part)
       swap 8 >> (upper part)
       +
} :get-fine-down


{ 1 bp/read
       dup
       0xff and (lower part)
       swap 8 >> (upper part)
       +
} :get-fine-up



{.{CALLING RESET-DEALY-LINES} nop} :reset-delay-lines

{ dup 0 > break-if -1 *} :abs


(-------------------------------ACTUAL CALIBRATION -----------------------------)

(---- Function that is called to start calibration ----)
{get-inputs time-calibration} :calibrate


(---get-inputs---: Get center, pulser, victim and reference IP from the stack and
    define these variables.)
```

```
{
       {space & ':fe/ip &} :create->
       create-> :victim
       create-> :reference
       create-> :pulser
       create-> :center

    ({space &} :createnumber->)
       (createnumber-> :referencenumber)
} :get-inputs


(---time-calibration---: Contains the four loops: coarse-down, fine-down, coarse-up, fine-up.)
{
init

.{----------------------- DOWN CALIBRATION -------------}

100000 :delta
.{LOOP FOR SETTING COARSE DOWN VALUES:}
{@delta 0 !=} (modified)
{
    coarse-step {read-tdc} {@delta 0x10 <} {get-coarse-down + set-coarse-down} loop-cycle
} while


cr cr . .      .{LOOP FOR SETTING FINE DOWN VALUES:}

10000 :delta
{@delta abs 10 >}
{
    step {read-tdc} {@diff abs 10000 <} {get-fine-down + set-fine-down} loop-cycle
} while

'goal-latency exist 1 != {@r :goal-latency} if (take only the first goal as the global one for the whole configuration)

(BYPASS THE DEFAULT GOAL LATENCY, TO CHECK THE ACCUMULATION OF ERROR)
@r :goal-latency

@report {_{        GOAL } @goal-latency .} if

```

```

cr  .

.{---------------------- UP CALIBRATION -----------------}

'configuration load
reference -> disable 97 0xffff l1/write 98 0xffff l1/write 99 0xffff l1/write 3 ' drop times

100000 :delta
.{LOOP FOR SETTING COARSE UP VALUES:}
{@delta 0 !=}
{
   coarse-step {@goal-latency} {@delta 0xc <} {get-coarse-up + set-coarse-up} loop-cycle
} while


cr cr . .      .{LOOP FOR SETTING FINE UP VALUES:}

10000 :delta
{@delta abs 10 >}
{
   step {@goal-latency} {@diff abs 10000 <} {get-fine-up + set-fine-up} loop-cycle
} while

cr .
@reference _ _{ } @victim _ _{ } @r _ _{ } @v .

} :time-calibration


(---init---: Called in time-calibration. Sets thresholds and initial delays.)
{
_{NEW SET: } .
cr .
_{REF: } @reference .
_{VICTIM: } @victim .

(Set the paths configuration)
    'configuration load

(Set a high freq in pulser)
    pulser -> fe/tp/disable @pulser-freq fe/tp/freq
```

```
(Set the l1 thresholds on victim and reference to count l1 triggers)
    reference ->  97 0x3030 l1/write 98 0x3030 l1/write 99 0x3030 l1/write 3 ' drop times
    victim    ->  97 0x3030 l1/write 98 0x3030 l1/write 99 0x3030 l1/write 3 ' drop times

center -> 6 bp/read (we want this: 0xbffe) 0xbfff and 6 swap bp/write
victim -> disable

(set some default value for course and fine delays)

    (reference -> 0x9 set-coarse-down)
    victim -> 0x1 set-coarse-down

    (reference -> 0x1 set-coarse-up)
    victim -> 0x1 set-coarse-up

    victim -> 138 set-fine-down
    (reference -> 140 set-fine-down)
    victim -> 138 set-fine-up
    (reference -> 1 set-fine-up)

} :init


(---loop-cycle---: Called in time-calibration. Gets TDCs and sets delay to equalize them)
{
:correction-action
:correction-criteria
:how-to-read-reference
:my-step

(TAKE PULSES)              single-step

(TAKE THE TDCS VALUES)   0 :flag
                                  {@flag 0 ==} {

                                 reference -> how-to-read-reference (read-tdc) :r
                                 victim -> read-tdc  :v
                             @r @v * :flag } while

(COMPUTE THE CORRECTION)  @r @v - :diff
```

```
                                     @diff my-step /  :delta     (modified)

(REPORT)          _{CURRENT VALUES reference: } @r _ _{ victim: } @v .
                                 _{DIFF } @diff _ _{ step set } @delta .

(SET THE VALUE IF NOT CRAZY)
       correction-criteria {
           victim -> delta (get-coarse-down + set-coarse-down) correction-action
                                    }   if

       single-step
              victim -> read-tdc :v
              reference -> how-to-read-reference :r
           (_{FINAL VALUES: reference:} @r _ _{ victim: } @v .)

} :loop-cycle
```

B. Setup Loop Program v2

```
'scripts/loadAll load

'scripts/time-cal-function load

{'vect literal->vector 'vect /{'192.168.1. swap &}} :fill

(Set initial delays according to distance from center)
{78 142 135 19 10 80 12 108} 'vect literal->vector

2 :val
'vect /{'192.168.1. swap & :fe/ip @val dup set-coarse-down set-coarse-up @val 1 +
    :val 150 150 set-fine-down set-fine-up}



.{#  Coarse Down  Coarse Up  Fine Down Fine Up }

2 :start-coarse-down


2 {


  @start-coarse-down 2 < break-if

2 :start-coarse-up
  2 {

```

```
      @start-coarse-up 1 < break-if
      150 :start-fine-down
      3 {

      @start-fine-down 1 < break-if
      150 :start-fine-up
        2 {

        @start-fine-up 1 < break-if

        192.168.1.78 :fe/ip
        @start-coarse-down set-coarse-down
        @start-coarse-up set-coarse-up
        @start-fine-down set-fine down
        @start-fine-up set-fine-up

@start-coarse-down _ _{ } @start-coarse-up _ _{ } @start-fine-down _ _{ } @start-fine-up .

@start-fine-up 4 - :start-fine-up


{108 78 78 142} fill calibrate (center pulser reference victim)
{108 142 142 135} fill calibrate
{108 135 135 19} fill calibrate
{108 19 19 10} fill calibrate
{108 10 10 80} fill calibrate
{108 80 80 12} fill calibrate
{108 12 12 108} fill calibrate


        } times
@start-fine-down 4 - :start-fine-down
      } times
@start-coarse-up 1 - :start-coarse-up
     } times
@start-coarse-down 1 - :start-coarse-down
    } times

_{SUCCESS} .
```

C. Results v1

```
#   Coarse Down  Coarse Up  Fine Down Fine Up
8  15  202  254
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211619 211615
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 211054 211085
```

```
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 211042 211061
8  15  202  250
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211618 211648
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 211088 211038
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 211060 211061
8  15  202  246
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211676 211629
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 211075 211110
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 211097 211077
8  15  198  254
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211471 211458
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 210867 210893
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 210870 210827
8  15  198  250
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211483 211508
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 210932 210998
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 210993 210910
8  15  198  246
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211477 211478
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 210899 210902
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 210855 210848
8  15  194  254
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211350 211335
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 210804 210684
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 210919 210953
8  15  194  250
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211361 211343
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 210782 210733
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 210763 210709
8  15  194  246
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211356 211338
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 210801 210763
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 210801 210834
8  14  202  254
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211699 211698
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 211126 211131
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 211113 211144
8  14  202  250
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211716 211695
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 211103 211071
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 211199 211192
8  14  202  246
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211697 211676
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 211161 211159
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 211141 211000
```

```
8  14  198  254
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211507 211543
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 210928 210927
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 210878 210918
8  14  198  250
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211539 211510
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 210968 210892
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 210930 210927
8  14  198  246
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211558 211549
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 210973 210929
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 210934 210935
8  14  194  254
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211424 211448
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 210829 210766
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 210724 210626
8  14  194  250
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211432 211349
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 210887 210989
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 210968 210904
8  14  194  246
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211420 211395
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 210858 210849
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 210873 210958
8  13  202  254
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211783 211842
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 211297 211139
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 211353 211346
8  13  202  250
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211790 211899
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 211346 211388
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 211356 211372
8  13  202  246
192.168.1.78 :fe/ip 192.168.1.142 :fe/ip 211770 211871
192.168.1.142 :fe/ip 192.168.1.135 :fe/ip 211406 211303
192.168.1.135 :fe/ip 192.168.1.19 :fe/ip 211358 211430
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References