TDC-V4
Application notes

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TDC-V4
Range Extension

Presentation

TDC-V4 delivers 26bits Time Encoding words with 120ps steps ; so, the Range is 7.8ms.

The two following methods could be implemented into TDC-V4 in order to extend the range beyond 7.8ms while keeping 120ps steps and respecting the data format. These two methods are previewed in the mapping of the 6bits Label Field of the 32bits data format (see User Manual chap 6 : Data Format).

- ***REX-1 method*** : development of double-words Time to Digital Channels delivering two 32bits words per hit, so spreading the Range without limit.

  REX-1 method presents 3 disadvantages :
  - ✓ the maximum rate without data losses is divided by 2
  - ✓ the surface of silicon used in the FPGA is increased
  - ✓ General logics is made more complex in order to permit configuration Range Extension ON or OFF for each Channel.

  REX-1 method presents 1 advantage :
  - ✓ there is no possibility of time de-synchronization because of loss of data when the global data rate is too high.

- ***REX-2 method*** : no development of special Time to Digital Channel and development of a unique "period flagging generator REXT" ; the Service words delivered by REXT and continuously mixed along the Time Encoding words onto the data flow permit the Host computer to calculate the Range Extension without limit with a very simple algorithm.

  REX-2 method presents 1 disadvantage :
  - ✓ there is possibility of time de-synchronization because of loss of data if the global data rate is too high. This disadvantage can be overcome by using the period count written onto the data field of the REXT Service word (see User Manual chap 6 : Data Format)

  REX-2 method presents 3 important advantages :
  - ✓ no decrease of the maximum rate without data losses
  - ✓ small extra silicon surface used
  - ✓ general logics is kept unchanged

Because of the advantages of the REX-2 method, REX-1 method is not implemented nowadays.

Whatever the used method, INTERNAL-GATE Analysis is unusable as the Analysis Duration is then limited to 7.8ms. We have to operate in EXTERNAL_GATE Mode with finite or infinite Analysis Duration (see User Manual chap 3d : Modes of Function).

Implementation

With the REXT-2 method, the REXT Service Channel delivers continuously Service Words, which are mixed into the Coding Words and recognized by their Labels.

- ✓ in about the middle of the first half 7.8 ms range, a Service Word is delivered with the following Label

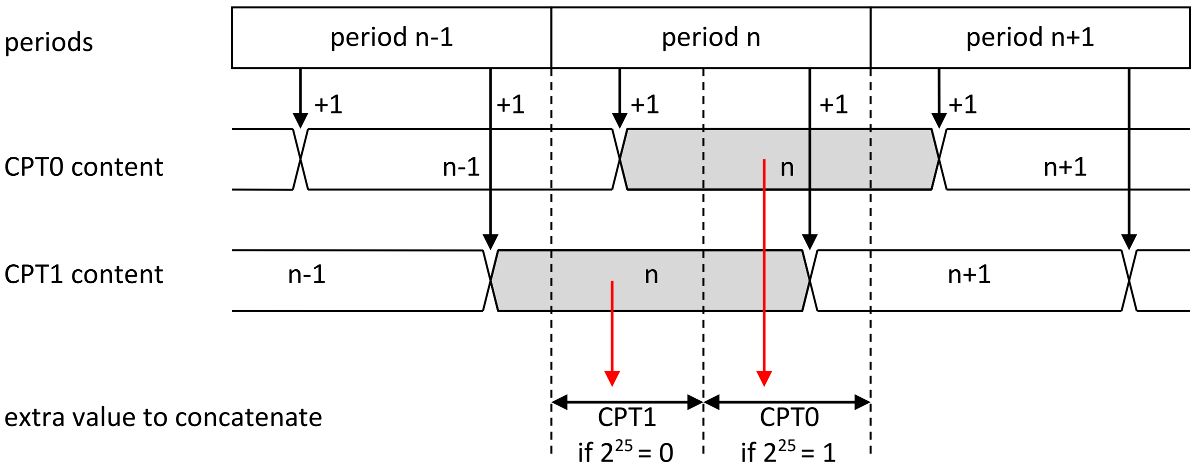
2^{31}	2^{30}	2^{29}	2^{28}	2^{27}	2^{26}
1	1	1	0	0	0

- ✓ in about the middle of the second half 7.8 ms range, a Service Word is delivered with the following Label

2^{31}	2^{30}	2^{29}	2^{28}	2^{27}	2^{26}
1	1	1	0	0	1

Extending the TDC-V4 range implies to develop an algorithm in order to calculate, for each time encoding received from the TDC, the pattern of bits to be concatenated beyond 2^{25}. In his application, the user has to install 2 counters (CPT0 and CPT1). At each time is received a Start Word corresponding to an Event Triggering, CPT0 must be initialized to -1 and CPT1 must be initialized to 0.

The algorithm follows simply the chronogram below :



The program can be written as below :

```
Processing of CPT0 :
    CPT0 = -1       if the Triggering Start Word (Label = 10000X)
    CPT0 = CPT1     if the Service Word with Label = 111000

Processing of CPT1 :
    CPT1 = 0            if the Triggering Start Word (Label = 10000X)
    CPT1 = CPT0 + 1     if the Service Word with Label = 111001

Processing of any Coding Word :
    extra value to concatenate =   CPT0   if 2^25 = 0
                               =   CPT1   if 2^25 = 1
```

TDC-V4 + ISIBox
encoding the SLOW_START or EXT_END TTL inputs

ISIBox carries out an interface for the following signals to be time encoded by TDC-V4 :

- ✓ NIM standard : 16 "Stop channel" inputs (CH0 … CH15)
- ✓ NIM standard : 1 "Trigger channel" input (FAST_START)
- ✓ Differential ECL standard : 16 "Stop channel" inputs (CH0 … CH15).

2 signals in TTL standard are also carried out by ISIBox and may be time encoded :

- ✓ TTL standard : SLOW_START input
- ✓ TTL standard : EXT_END input.

Using SLOW_START

1. In the NEXT_START Mode, whatever the signal or command used to trigger an Event, the Start Channel may be used to time encode multi-hits signals present on the SLOW_START input after the triggering and during the Analysis Duration (see User Manual chap 3-e).
   In the Event data list received by the Host computer, the time encoding of the SLOW_START signals laid between the Start Word and the EOE Word (see User Manual chap 7 : Data encapsulation).

2. If the Additional Channel is implemented in TDC-V4, this Channel may time encode multi-hits signals present on SLOW_START input (see User Manual chap 3-e).

Using EXT_END

1. In the INTERNAL_GATE Mode and if the EXT_END signal is not used to stop analysis, the Start Channel may be used to time encode multi-hits signals present on the EXT_END input after the triggering and during the Analysis Duration.

2. If the Additional Channel is implemented in TDC-V4, this Channel may time encode multi-hits signals present on the EXT_END input (see User Manual chap 3-e).

3. In the EXTERNAL_GATE Mode, the Analysis can be ended by the EXT_END input signal. In this Mode, the mono-hit EXT_END signal may be encoded in NEXT_START Mode by setting FORWARD_GATE (see User Manual chap 3-d). This mechanism enables time encoding of the actual Analysis Duration of the Event.

TDC-V4
Using OVERFLOW information

Any Stop encoding Channel comprises a 512 words deep FIFO memory. Whatever the TDC-V4 Mode of Function, this memory is empty at the triggering of the Event. If an Event comprises more than 509 hits on a specific Channel and if the rate of the data acquisition system is smaller than the hits rate, the FIFO memory may be full and some encodings may be lost.

Although this occurrence may be rather unlikely, it is useful to be alerted. So, the Data Format table (see User Manual chap 6 : Data Format) shows the bit 2^{26}, named OF, in the Label field of the words delivered by any Stop encoding Channel.

The presence of (OF = 1) in the Label of the n^{th} word delivered by on particular Channel into the data list collected by the Host computer indicates that an unknown number of hits could not be encoded after the $(n + 509)^{th}$ word delivered by this Channel.

- ✓ Presence of OF = 1 is an alert rather than a tool for data processing
- ✓ <u>If an Event comprises less than 509 hits onto each Channel, never (OF = 1) does occur</u>
- ✓ An Overflow occurrence on some channel does not disturb the encoding on the other Channels
- ✓ The Start encoding Channel does not deliver OF information if NEXT_START Mode is selected.

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NdA-04

TDC-V4
NARVAL compatibility

IPNO Laboratory developed data acquisition software NARVAL with a specific driver controlling TDC-V4. So, standard TDC-V4 version has been modified in order to comply with NARVAL driver.

Standard TDC-V4 version and Narval compatible TDC-V4 version show up some slight differences concerning data collection through the PCI Bus (see User Manual chap 8 : PCI Bus Data Collection) according to the following table :

	Standard	**NARVAL**
@SEMAPHORE	2AFC04h	2AFC04h
@SIZE	2AFC08h	2AFC08h
@DATA	2AFC18h	2AF7FCh
Max Buffer Size	509	256

Identification of *ISITime01 TDC*, *Standard TDC-V4 version* and *Narval TDC-V4 version* is carried out according to the following table :

	ISITime01	**Standard TDC-V4**	**NARVAL TDC-V4**
Subsystem Vendor ID	9054h	C400h	C400h

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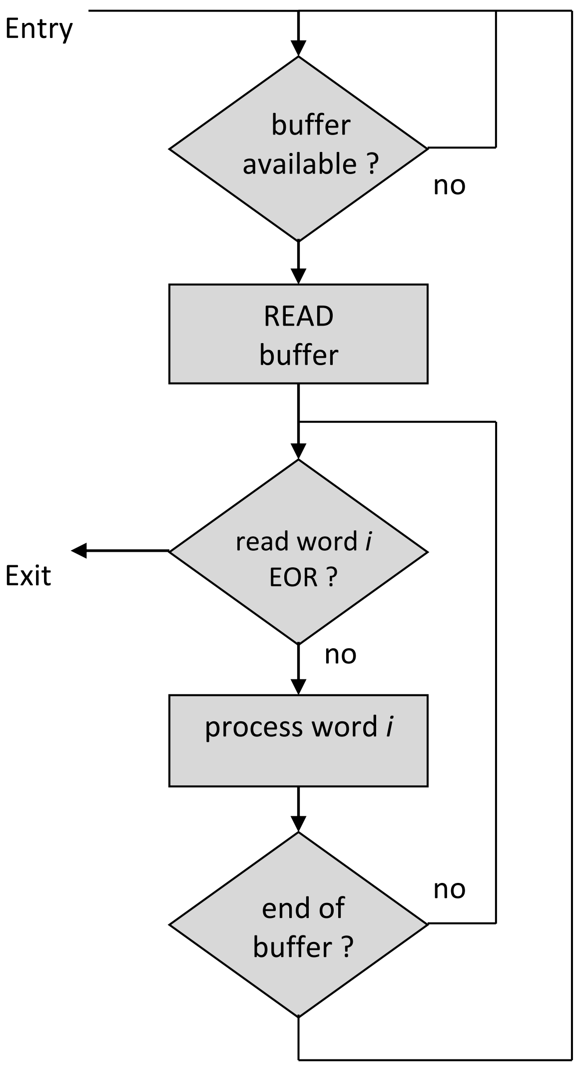
TDC-V4
Using the EOR (End of Run) Service Word

The EOR (End of Run) Service Word is the last word of the data list delivered by TDC-V4 following the reception of the command RUN = OFF (see User Manual chap 4-b : the RUN Command). The data field of the EOR Service Word could be filled with some useful information (as Run Number). With the TDC-V4 2013-06 version, the data field is filled with 0.

Detecting this Service Word in the data list asserts that all the data laying in the TDC are fully collected ; then, EOR should be preceded by an EOE (End of Event) Service Word and cannot be followed by any data. That permits to quit properly the data processing task.

Using the DLL (see User Manual chap 12 and 13) implemented in a Host computer with a mono-core architecture, the principle of data collecting and processing software could be as it follows :



TDC-V4
Backward Mode

1- This Mode of Analysis can be used to encode Stop signals occurrence before the Triggering signal. It can be associated with the INTERNAL_GATE Mode or the finite duration EXTERNAL_GATE Mode.

This Mode is useful when the triggering signal is very selective but occurs after the Stops which are to be encoded. Otherwise, all the Stops must be delayed with delay lines or electronic devices, that may be heavy and, sometimes, impossible due to the weak resolution of long duration analog delays.

If this Mode is used, calculation of Stop durations relative to the triggering signal Start may give negative numbers. In order to get only positive numbers, we have to do

$$D = (T_{Stop} – T_{Start}) + OFFSET$$

OFFSET being given by the following table :

	BACKWARD_DURATION	**OFFSET (decimal)**
0	0 ns	1024
1	0 ns	1024
2	120 ns	2048
3	240 ns	3072
4	360 ns	4096
5	610 ns	6144
6	860 ns	8192
7	1,3 µs	12 288
8	1,8 µs	16 384
9	2,8 µs	24 576
10	3,8 µs	32 768
11	5,7 µs	49 152
12	7,7 µs	65 536
13	11,6 µs	98 304

2- In other respects, using Backward Mode permits to overcome the Latency Time of some nanoseconds separating triggering instant from the ability to encode the Stop signals.
In particular, setting BACKWARD_DURATION = 0 ns allows all the Stop signals around the triggering instant to be encoded.

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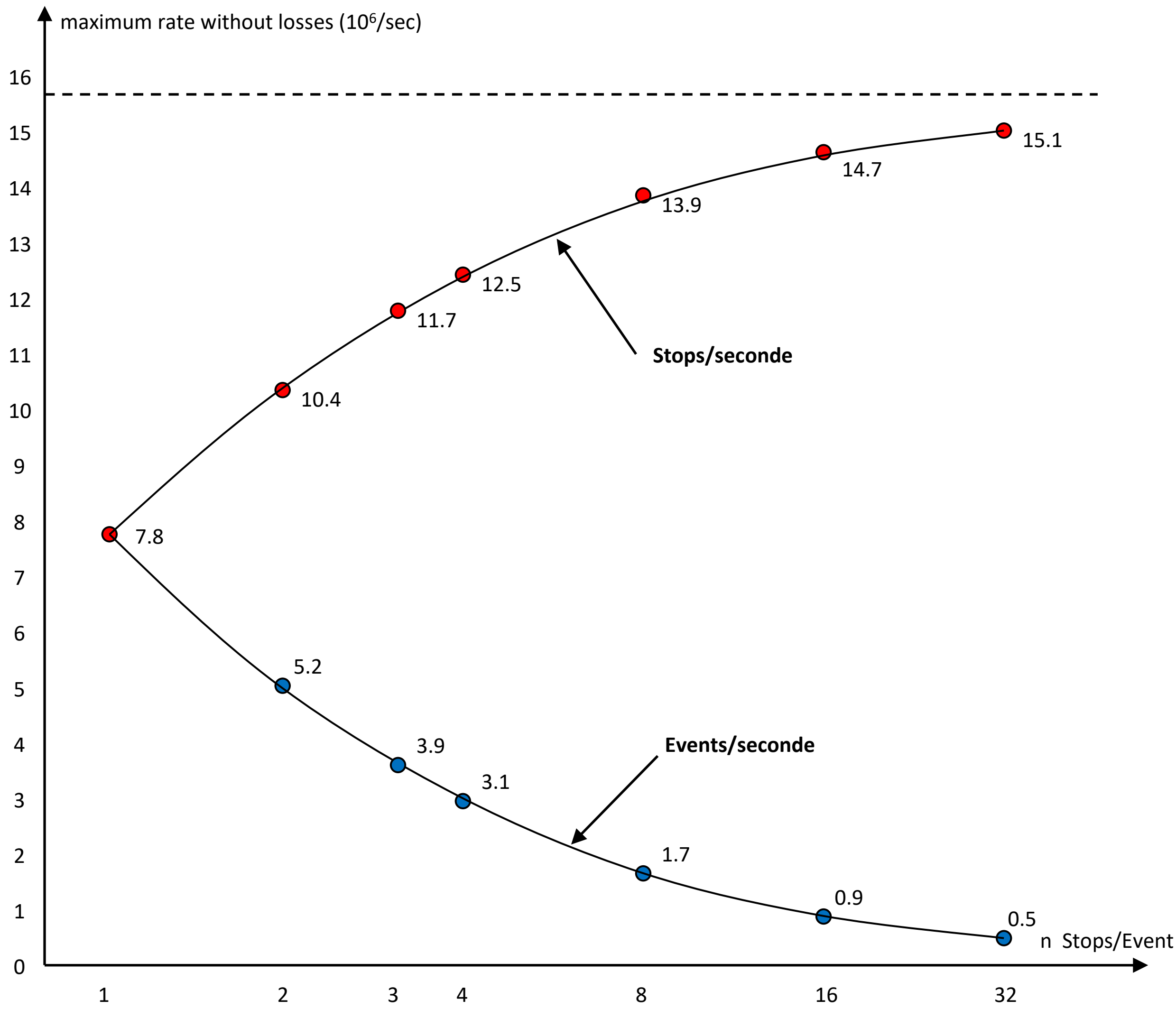
TDC-V4
Data rates without losses

If we are dealing with very high physical rates, two ways can be considered :

1- *software filtering*

With this approach, all signals are encoded by the TDC-V4 : no Triggering, no Analysis Duration, no Data Encapsulation (only remains the ability to inhibit some encodings by the way of the START_GATE and STOP_GATE input signals). "Event Building", that is to gather the only data likely relative to a same physical event, must be made by software. Large mass memories and the ability of fast data collecting and processing of recent computers allow to deal with large throughputs. So, if noises are not too large relating to useful signals, the best performances are got with the *Continuing Analysis Mode* (see User Manual chap 10) : 15.6 MegaWords/second. Rate is presented on the following figure***,** function of the Event composition = 1 Start + n Stops :

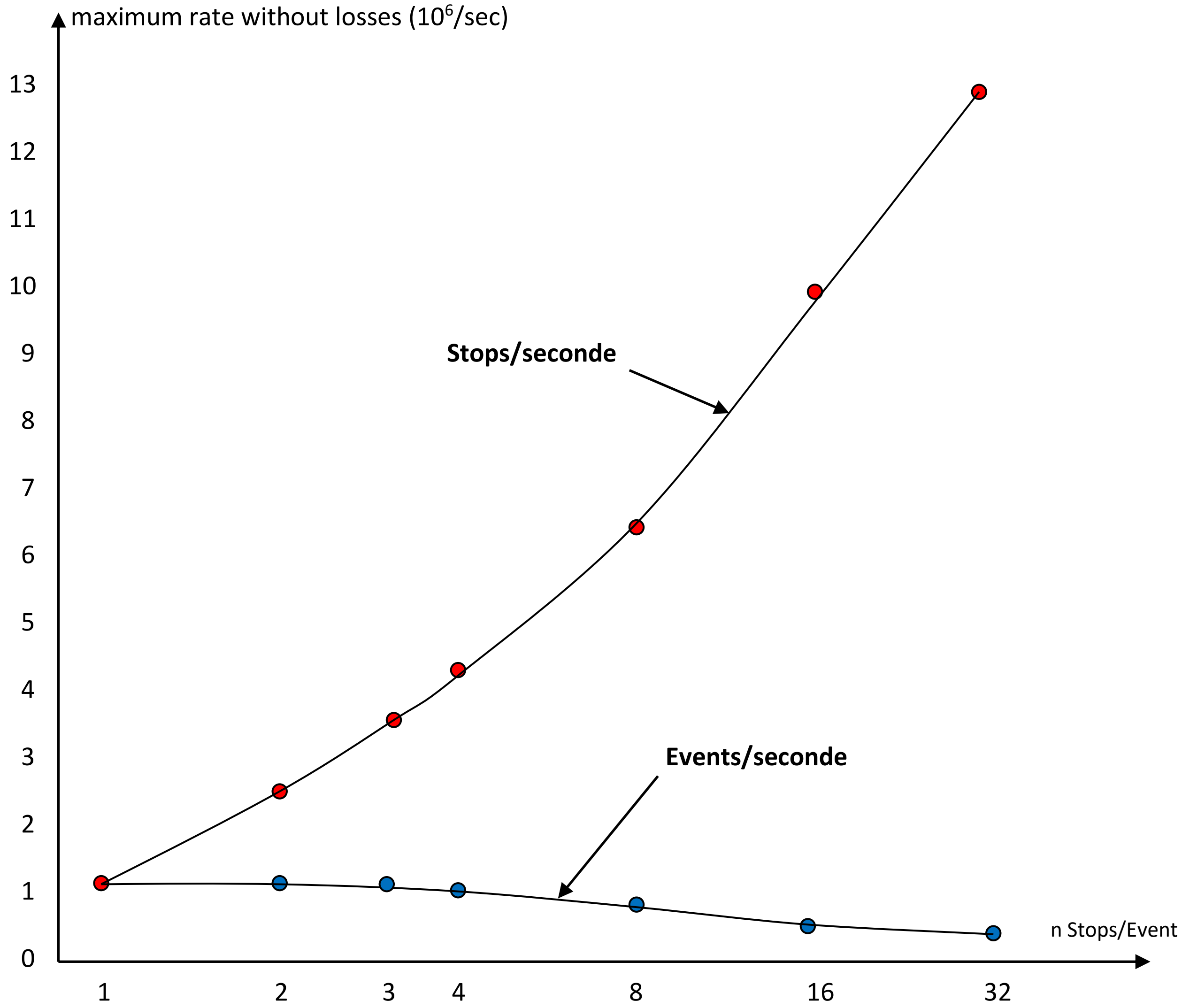


2- hardware filtering

With this approach, TDC-V4 encodes only the signals selected by a Triggering followed by an Analysis Duration ; data relative to an Event are encapsulated into a table.

So, noise signals present out of the Analysis Duration are eliminated and the Host computer has less data to process but hardware filtering decreases the throughput performances compared to the Continuing Analysis Mode throughput described above.

Rate in *Accumulation Mode* (see User Manual chap 10) is presented on the following figure***,** function of Event composition = 1 Start + n Stops and INTERNAL_GATE = 180ns :



These maximum rates without losses are limited neither by the PCI Bus nor by the bridge to access it but by some compromises done in the FPGA of TDC-V4. Some amelioration is possible if necessary.

* Data reported on the two figures above are deduced from measurements carried out by Gustavo Garcia (Synchrotron SOLEIL) with a multi-core computer under Windows XP.

TDC-V4
Sliding Duration Mode and Statistical Correction

Differential Non Linearity (DNL, see NdA-09) measures the discrepancy between the actual width of the steps of a converter. These distortions corrupt the exactness of measurements or during spectrum shape decomposition.

Generally, a DNL is regarded as good if it is better than about 4 %.

These characteristics is the most difficult to control concerning a TDC, particularly with the FPGA technology, because of technological dispersions from a chip to another one and inside each chip.

Overcome these dispersions can be operated off line from measured DNL figure.

TDC-V4 carries out 2 methods in order to overcome these dispersions on line :

- Sliding Duration *
- Statistical Correction **.

Only the Sliding Duration method is implemented into the present version of TDC-V4 by setting OPTIMIZATION = DNL (see User Manual chap 3-e). Valuation of the Statistical Correction method is in progress.

Whatever the DNL improvement method, the Resolution is then slightly decreased and the TDC user has to estimate what is the most important parameter for his application : Resolution or DNL ?

* *The principle of Sliding Duration*

A known analog duration is added on line to the encoded Triggering instant and the corresponding numerical value is subtracted from the encoding results ; a residual DNL remains but the Resolution is not strongly decreased.

Take care : this method is unusable with the Continuing Analysis Mode.

** *The principle of Statistical Correction*

At each TDC Channel is associated a table of statistical corrections is calculated from the DNL histogram of the channel ; the corrected DNL is perfect but the Resolution is rather decreased.

This method is usable with Continuing Analysis Mode.

TDC-V4
Integral Non Linearity (Exactness)

Non Linearity quantifies the error between a duration T to be measured and the actual measure of T. That characterizes the converter exactness. One distinguishes :

- *Integral Non Linearity* (INL) which quantifies the error relative to the ideal response over the whole range of the converter
- *Differential Non Linearity* (DNL) which quantifies the local dispersion of the width of the contiguous steps defined by the converter.

INL is a continue function of T. In order to exclude the stochastic noises, non-correlated with T, INL is evaluated in mean value.

DNL is a discrete function of the step number.

Generally, if the converter is deterministic, INL at duration T is roughly given by the integration of the DNL function from 0 to T.

Because of the Sliding Scale* mode of operation of TDC-V4, the converter is not deterministic and the general rule is false : INL, then Exactness, tends towards zero with statistics, independently of the DNL function

On the following page, the figure shows the INL function of a TDC-V4 after having intentionally and strongly disturbed the DNL distribution of the converter :

- ✓ green : 5 points resulting of the integration of a bad DNL distribution ; the worst offset relative to ideal DNL is about 0.5 bin
- ✓ red : the real INL measured by the mean of a coaxial line with a continuously variable length line (see photo on the following page) ; 2 points were rejected, because mechanical instabilities.
- ✓ black : linear fit of the measures.

The figure shows that the actual INL curve (red) is very linear and presents any correlation with the function resulting from integration of the bad DNL (green). No Exactness default if statistics is sufficient.

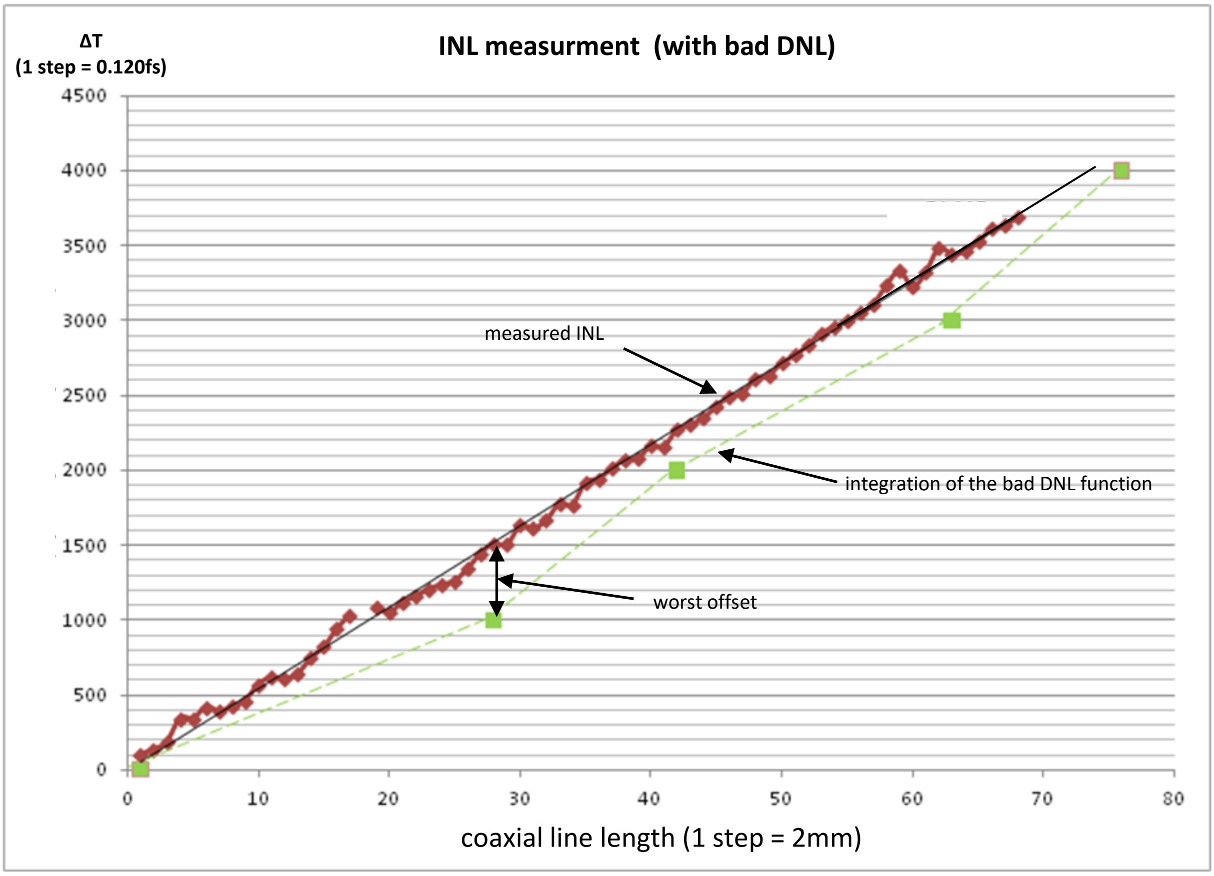
The slope (306.10^9m/s) is not exactly the light speed in air because of the materials constituting the variable line.

* *Sliding Scale Mode*

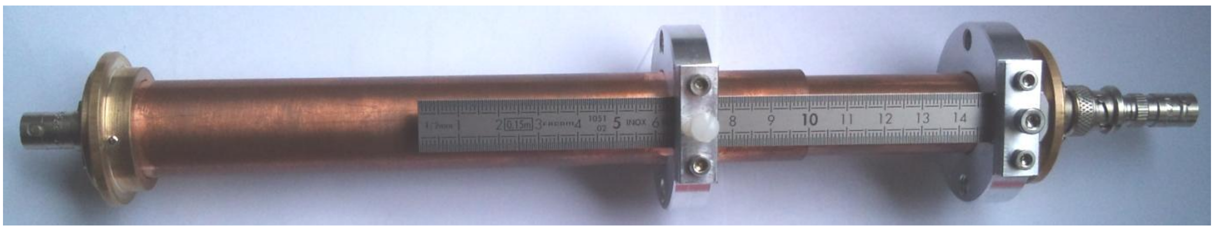
For each new measurement, at the instant of the Start of the duration, the origin of the time scale of the TDC is randomly changed. So, a same duration ΔT is never encoded by the same portion of the time scale of the TDC.

Thanks this mode of operation,

- ✓ the DNL figure is largely improved (but non zeroed)
- ✓ the exactness default tends towards zero with statistics.



0 < coaxial line length L < 140mm
coaxial line step = 2mm
TDC-V4 step = 0.120ns
slope = 306.10^9 m/sec



continuously variable length coaxial line

TDC-V4
Enhanced Resolution

TDC-V4 is upgradable in an Enhanced Resolution version on request. All the functionalities of the normal version remain in the enhanced one. Notably, the version is fully compatible with the IsiBox Interface and software.

Adjustment to get Enhanced Resolution is a little laborious to develop for all the channels. In this version, the enhanced resolution channels characteristics are the following :

- Time step : 60ps.
- Exactness : Exactness default trends towards zero with statistics
- Resolution = 30ps RMS
- DNL = 4% RMS