Cookbook

An introduction to an innovative technology

The TDC Cookbook

RELEASE 2.0

AS OF OCTOBER, 2002

acam - solutions in time

Precision Time Interval Measurement

acam
mess·electronic

Preface

Since its founding in 1996, **acam messelectronic** gmbh has been developing and producing solutions and concepts for measuring time intervals with resolution in the picosecond range. The aim of the company is to establish ultra-precise short time interval measurement with all its specific advantages, as an alternative to traditional analog measuring procedures in the area of sensor technology, and to exploit the great potential for applications in the industrial field. To this end, **acam** offers a complete infrastructure for ultra-precision time interval measurement using integrated circuits, and the products developed and provided by **acam messelectronic** gmbh are TDC (Time-to-Digital Converter) based. These integrated circuits, which employ purely digital-based processes (CMOS as a rule), provide the optimum basis for innovative 'solutions in time'.

acam is dedicated not only to continuous enhancement of the existing product range, but also to respond to customer demands and suggestions with a high degree of flexibility and openness. This ensures that the resulting solutions are custom tailored and represent the state-of-the-art in ultra-precise time differential measurement.

Time is one of the most basic physical units. This is precisely what distinguishes it as a 'vehicle' for further calculation of other physical parameters such as distance, position, velocity, etc. At high clock speeds, traditional procedures such as fast counters quickly become expensive, complicated, current consuming, … or are hard pressed to reach sub-nanosecond resolutions.

The ever-increasing pace of semiconductor technology now permits even smaller time intervals to be determined to high precision, and the TDC can now be used. A TDC converts time intervals into digital values at high resolution. In this way TDC bridge the gap between the analog world of physical quantities and the digital world of today's electronics. TDC represent the core of the **acam messelectronic** product range, and exploit full digital semiconductor processes. They are used wherever physical quantities need to be digitised for purposes of data processing, with applications including

- ☐ Ultrasonic-based flow and density measurements
- ☐ Nuclear and high-energy physics
- ☐ Laser distance measurement
- ☐ Ultrasonic position feedback devices
- ☐ Capacitance and resistance measurement
- ☐ Frequency and phase measurement.

It is especially in these sectors where TDC represent a technological leap for the further enhancement of already existing components and systems and make possible the development of new, innovative concepts which would simply not be feasible using traditional technology.

acam-messelectronic gmbh
Am Hasenbiel 27
D - 76297 Stutensee-Blankenloch
Tel +49-7244-7419-0
Fax +49-7244-7419-29
email support@acam.de

Index

1 - General information

This first section describes operating principle, possibilities and features of TDCs, classifies the functional operating modes and describes the different behaviours of calibration mode and resolution adjustment mode.

1.1 - Measuring principles

1.1.1 - Analog time interval measurement

Analog time-to-digital converters use two working phases. In the first phase the measured time difference is converted into an analog voltage (Time-to-Amplitude Conversion, or 'TAC'), in a second step this analog voltage is digitized with usual methods (Analog-to-Digital Conversion, or 'ADC'). This TAC-ADC combination is the classical way to do high precision time interval measurement. Although very high resolutions can be achieved, down to a few picoseconds, this technique is subject to many restrictions. The following figure 1 shows the correlation and the sequence of the measurement.

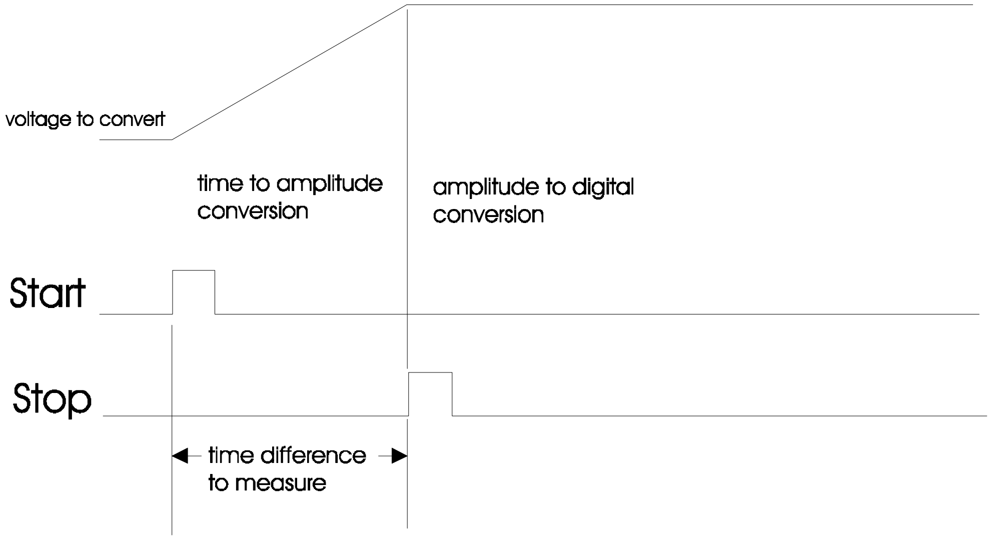


Figure 1 – How an analog TDC works.

Digital delay time TDCs on the other hand work without any analog components. They are part of those innovations that have been made possible by the major technical progress in semiconductor technology over the years. They use the delay of simple logical gates (i.e. inverters) for fine quantisation of time intervals. Due to the enormous achievements in signal speed, especially in the CMOS sector, it has become possible to implement such TDCs in standard CMOS processes with resolutions in the picosecond range. As a result, solutions can be integrated into a single system-on-chip that are efficient, power saving, space saving and none the less inexpensive.

Digital TDCs can be split into two groups

- ☐ Absolute delay time TDCs
- ☐ Relative delay time TDCs

All digital TDC variants can be traced back to one of these two groups.

1.1.2 - Absolute delay time TDCs

This type of TDC uses the absolute propagation time of signals through simple logical elements for fine quantisation of time intervals.

In other words, it determines how many inverter cycles the measured time difference consists of. Figure 2 shows the principle of operation. Clever circuit set-ups, redundant elements and special layout methods on the chip enable the exact reconstruction of the number of basic delay times. The resulting resolution is strictly dependent upon the basic delay time in the chip. Resolutions in the area of 40-100 ps can be reached by a simple set-up of the measuring core and the use of a state-of-the art CMOS process.

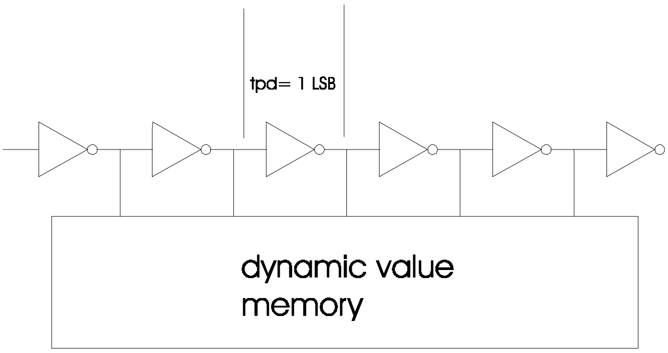


Figure 2 – Absolute delay TDC, principle of operation.

Absolute delay time TDCs have the following additional advantages:

- ☐ The delay time of the inverter can be precisely adjusted and stabilised at a specific temperature by using a phase controlled loop (PLL)
- ☐ The resolution can be improved up to values of ± 20-30 ps via calculations; all sensitive factors are detailed in § 2.4.

This chip typology belongs to the group of universal TDCs, which can be adapted to (almost) any type of task.

1.1.3 - Relative delay time TDCs

While the absolute delay approach only permits the available resolution to be bound to the speed of the semiconductor process, we can skip this limit by using the relative delay time solution. As the name explains, this type of TDC measures a relative delay time difference between two delay chain elements to get fine quantisation, as evidenced in figure 3.

With the help of a specific circuit set-up, the resolution becomes identical to the difference between the two running times t_{pd1} and t_{pd2}, and is possible to reach delay values far under the gate delay time.

Fundamentally, any resolutions can be obtained, but limits exist regarding precision due to quantisation errors and some other error sources. This leads to a practical resolution of approximately 1/5 of the delay time. Given the use of modern CMOS process, this is in the 10-15 ps range.

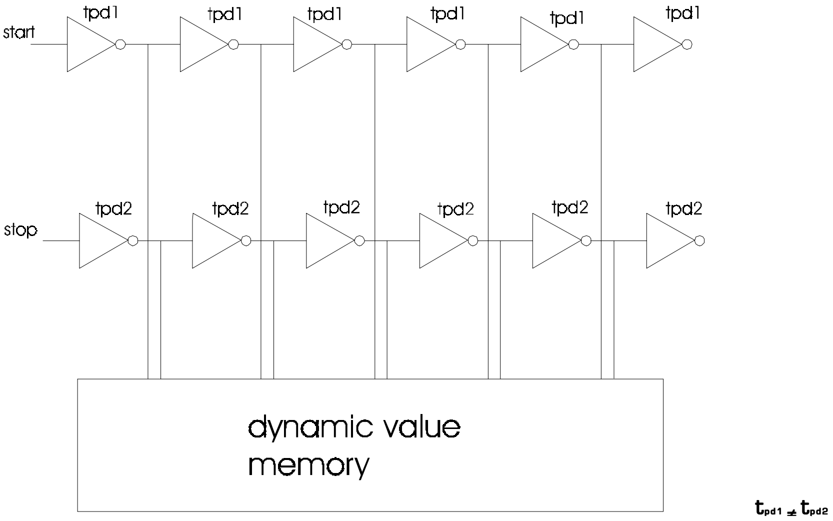


Figure 3 - Relative delay TDC principle of operation

An excellent differential non-linearity addresses this solution to specific measurement tasks, and wherever this parameter plays a major role, this type of TDC should be the first choice.

In some cases the use of an absolute delay time TDC is questionable or almost impossible, like the implementation of a quartz-exact adjustment of the resolution with simple on-chip elements, or when a multi-hit is required (absolute delay TDCs have limited double pulse resolution since this measuring mode requires a conversion time, resulting in a relatively long lag time). In conclusion, the relative delay time TDCs belong to a special solutions group that can be applied wherever their advantages are useful.

1.2 - Measuring range

The measuring range necessary for the realisation of various applications can spread out from several nanoseconds for some applications in fundamental research (i.e. high energy physics), to a few milliseconds for industrial applications (e.g. linear position controllers).

Even for larger time differences, a resolution in the picosecond range may be needed, leading to a measure dynamic range in excess of 30 bit ! Today's TDCs can fulfil these requirements "comfortably". Concerning measuring range, they can work on two principles which are basically very different.

1.2.1 - Basic measuring range

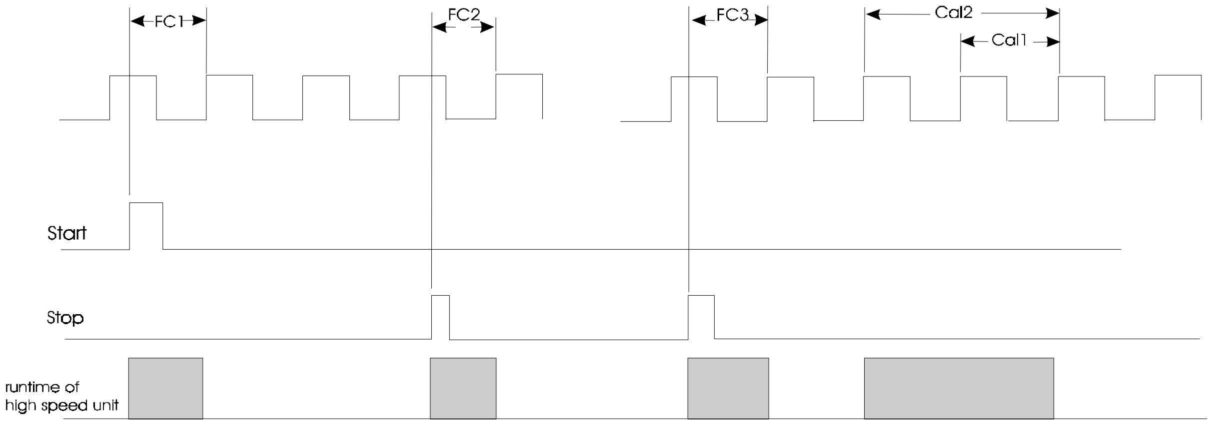
In the basic measuring range the entire time difference is measured with the high speed measuring core of the TDCs. The start signal sets the quantisation going, while the stop signal saves the momentary internal state, from which the measured time difference can be reconstructed.

Time differences of up to approximately 10-15µs can conveniably be measured with this basic method, but noise effects and other analog effects become more and more noticeable. As long as time difference is below 5 µs, standard deviation ranges from 0.5 LSB to 0.7 LSBs. Above, it tends to increase. When respecting certain rules, it can be kept below 1 LSB.

Depending on the chips and the measuring mode used, a minimum measuring difference exists below which measurement does not work. The TDC-GP1, however, offers measuring modes that allow a zero time difference to be measured, and that without a specific definition of Start and Stop signals, so that Stop may arrive before Start and thus the time interval, possibly negative-valued, is still measured correctly (see TDC-GP1 manual).

1.2.2 - Extended measuring range

There are several TDC applications that need a larger measuring range than the one covered by the basic technique; to fulfil this need, a course counter (sometimes called "pre-devider") has been introduced. It permits the extension of the measuring range without affecting the standard deviation. The principle is evidenced in figure 4.



$$\text{time} = \text{period}*(CC + \frac{FC1-FC2}{Cal2-Cal1})$$

CC = value of the precounter

Figure 4 – Extended measuring range, basic operation.

The basic principle is the following: Time lag "fine count 1" (FC1) is measured from start to the rising edge of the calibration clock signal. Symmetrically, time lag FC2 is measured from stop to the rising edge coming next. The course counter holds the number of clock oscillations between start and stop. At an appropriate moment, not too far away from the measurement itself, a calibration fine count is performed. It concerns one ("Cal1") and two ("Cal2") oscillation periods respectively. The long time lag measuring result is then calculated via the above formula.

Thus, the measuring range depends on the depth of the coarse counter, only. Virtually any value is possible. The fine counter is in operation only part of the time (see grey squares in fig.4), which may lead to a very low energy consumption.

An example to clarify the matter (do not take it seriously, it is just an example)

In order to measure a time difference of a thousand years (!) with the full TDCs resolution, a calibration clock frequency of 1 MHz is used, and a coarse counter depth of 55 Bit is needed.

This is a counter that can be comfortably integrated on a chip.

The measuring result will have 100 ps resolution and will be 70 Bit wide. Please prevent from power shut-down, though…

1.3 - Calibration and adjustment methods

The delay time of logic gates operating on a chip is a very imprecise matter. The resulting delay time value can vary greatly and depends upon fabrication process, temperature and voltage variations. Temperature and voltage variations can cause delay time changes larger than 50 %, but can be compensated by using two methods established:

- ☐ Software calibration (like above)
- ☐ Direct adjustment of the delay time via hardware methods

The hardware methods can be further divided into two methods:

- ☐ Resolution Lock
- ☐ Resolution Adjust

1.3.1 - Software calibration

The time difference is measured with an unknown resolution. Calibration values are then generated relative to the measuring event. This is best done directly after a measurement and is necessary to normalise the measured value. The calibration values are generated by measuring well-defined time differences of known values against the unknown resolution. These known time differences can easily be derived from a quartz clock, that offers an excellent absolute precision and low jitter.

With reference to figure 5, the unknown measuring value V_{meas} can be found directly on the measuring line, just like the two calibration values V_{cal1} and V_{cal2}. This line is characterised by a gradient which corresponds to the resolution, and a zero offset. With the help of two reference measurements t_{cal1} and t_{cal2} it is possible to calculate the gradient and the offset, and thus the unknown time difference t_{meas} via two points on the measuring line.

These two points on the line offer the following results:

$$\mathbf{t_{meas} = (t_{cal2} - t_{cal1}) * (V_{meas} - (2 * V_{cal1} - V_{cal2})) \,/\, (V_{cal2} - V_{cal1})}$$

where the gradient is:

$$\mathbf{(t_{cal2} - t_{cal1}) \,/\, (V_{cal2} - V_{cal1})}$$

and the offset is:

$$\mathbf{(2 * V_{cal1} - V_{cal2})}$$

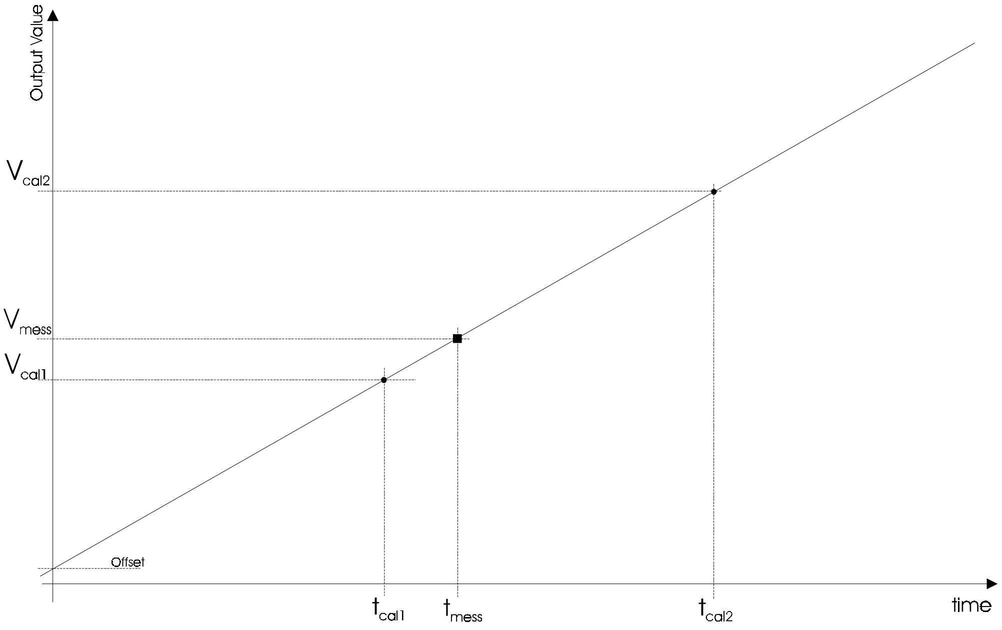


Figure 5 – Graphical representation of the calibration.

Digital delay time TDCs have the pleasant feature that the measuring characteristics is really a straight line. There are no precision problems due to integral non-linearity, which are standard with analog TDCs. The integral non-linearity lies far below 1 LSB, and this greatly simplifies the calibration arithmetics.

1.3.2 - Hardware methods for the adjustment of the resolution

The methods we will introduce here are based on the fact that temperature variations can be completely compensated by voltage. A regulation of the operating voltage takes place via a phase locked loop (PLL). The voltage controlled oscillator (VCO) is located on the chip. Its frequency is compared to a precise reference; the resulting error is amplified and used to change the VCO frequency in order to keep it almost constant at a value:

$F_{VCO} = n \bullet F_{REF}$

If F_{REF} = 5MHz and n = 256 then F_{VCO} = 1.28GHz

1.3.2.1 - Resolution lock

The Resolution Lock method applies if both the PLL and the measuring system are located on the same chip. A full cancellation of the temperature dependence, however, cannot be achieved, but good circuit construction and good board layout allow a suppression factor around 100 to be consistently reached. This method can reduce temperature dependence to about 30 ppm/K, as compared to an uncorrected CMOS temperature gradient of typically 3000 ppm/K.

During operation in the Resolution Lock mode, it is mandatory to continuously calibrate the system. There are two reasons why: (a) Resolution is not entirely independent of temperature, and this can lead to obvious errors during larger temperature variations and longer measurement times. (b) Differences occur from chip to chip regarding the matching of the PLL and the measuring unit. Consequently, identical adjustments on different chips can lead to different measurement resolutions.

This method is suitable to make resolution values less dependent upon temperature, so that the calibration cycles can be drastically reduced up to i.e. 1 time per 5 minutes with significant advantages in applications requiring high measuring rates.

1.3.2.2 - Resolution adjust

The Resolution Adjust method is the consequent conversion to a fully PLL regulated resolution. Measuring circuit and PLL are very closely knit via circuit and layout. As the name suggests, one can adjust the resolution precisely via software, regardless of the specimen. The adjusted resolution becomes completely independent of temperature.

No more calibration of the measuring circuit is necessary. As soon as the PLL has locked, the resolution becomes stable. The absolute precision of the resolution only depends upon the used reference oscillator at this point.

One should however realise that not every resolution is compatible with the full permittable temperature range. Before setting the resolution parameter, potential temperature variations should be considered, since they need voltage margin for compensation. The voltage margin results from (a) the time resolution of the chips at standard conditions (e.g. @ 5 V, 25 °C) and (b) its voltage dependence (approx. 20 % / V at 5 V).

A careless choice may end up in an undefined resolution. This would be the case e.g. when regulated voltage is close to maximum permitted voltage (say 5 volts) and temperature rises so high, that voltage being regulated right up to 5 volts, the high end, becomes insufficient. The PLL comes to the limit and then locks off.

> ***Example: If a resolution is adjusted, which should be held over the entire temperature range of a TDC, i.e. -40°C up to +85 °C, the following parameters should be considered:***
>
> ***Over the entire range, without any regulation, the resolution will vary by approx. 31%, (approx. 10% in the "top range" from ambient to +85 °C and approx 20% in the "bottom range" from -40 °C to ambient,***
>
> ***One needs a voltage regulation margin of app. 0.5 V in the top range and app. 1 V in the bottom range; if one adds 0.5 V as a security on both ends, one will need 1 V of margin in the top range and 1.5 V in the bottom range.***

As one can see, the resolution choice has limits. Otherwise, the PLL can't hold the resolution any longer. When aware of this, good solutions however can always be found that fulfil all the requirements.

1.3.2.3 - Special delay elements

In a third type of resolution adjustment, the simple basic gates are not just used for the fine quantification. Instead, additional transistors are put to the gates, so as to control the delay time of each delay element. This control takes place via an analog voltage in the control entrance of the delay elements. The control voltage is gained via a phase discriminator which compares the phase of the reference clock to the clock of the delay elements.

This kind of TDC has a variant, which operates in the following way: the external reference clock is not compared to the internal clock of the phase, but instead a feedbackless delay line having a number of N individual units (i.e.32) is controlled in such a manner as to yield a total delay equal to one period of the reference clock. A comparison takes place here via a phase discriminator, and the delay time of the delay elements are controlled accordingly.

1.4 - Custom specific solutions

Digital delay time TDCs have other additional (big) advantages:

- ☐ They use exclusively digital elements and can be implemented by using a pure digital process.
- ☐ Being entirely digital, they offer the possibility of implementing additional complex digital electronics on the same chip.

These advantages lead to some consequences:

- ☐ Standard TDCs with high level digital intelligence are more than simple measuring converters (i.e. internal high performance calculation units, with various measuring modes etc.)
- ☐ Specific consumer solutions can be developed without big expense, quickly and without greater risks
- ☐ After appropriate choice of the measuring core, one can fall back on ASICs (**A**pplication **S**pecific **I**ntegrated **C**ircuits) increasing the probability to work properly at first attempt and thus yielding big advantages in cost and time-to-market.

The potential of custom-specific solutions, exactly matching specific needs, should not be underestimated. Indeed, they speed up the product development.

Things taking place in the digital world, any other digital function may be integrated side by side to the TDC on the same and single chip. Many successful development projects (chips that worked right from the start) have been realised. A serious limit to this approach is the minimum production quantity required. Dependent on complexity of the chip, you need an annual consumption of 5 to 50 thousand units in order to pay for development and mask cost.

1.5 - Power supply

A very important argument in favour of TDCs is the power consumption of such chips. Digital delay time TDCs implemented in a CMOS process allow an average power consumption in the micro ampere range to be reached, bringing a large number of battery operated applications to existence.

It is then mandatory to be familiar with the parameters and operating mode that have a direct impact on the TDC current drain. An estimate of the consumption can then be performed. Please, keep in mind that the following explanations always apply to digital CMOS TDCs.

1.5.1 - When does a TDC need power?

This question can be easily answered: during measurements, or more precisely, when the high speed measuring unit or other parts of the chip enforce action. In the periods between action – and they are generally much larger – the chip only drains the quiescent or leakage current, usually in the nanoampere range. The power consumption of the TDC cannot be estimated at a flat rate. It is dependent upon the operation mode and the measuring rate in which the chip is operating.

One can vary the power consumption by four orders of magnitude through different parameter setting on the same chip. Careful thought must guide the choice of the operating mode.

No flat estimate of consumption must be made.

1.5.2 - The current consumption

A complete TDC chip naturally has several power consuming elements in it:

- A TDC-measuring core
- A coarse counter ("pre-devider") when operating in the extended range mode
- An ALU for the arithmetic processing of the measuring results
- An I/O structure, especially the calibration clock entrance and the data output

As an example, the TDC-GP1, based on a 0.8 µm CMOS process and having a 5V voltage supply, yields the following electric current values

TDC-measuring core:	20 mA (during active measuring time)
Pre-devider:	50 µA/MHz
ALU:	10 mA (during calculation)
Calibration clock input:	40 µA/MHz
Data bus (8 Bit):	2 mA/Mega access/sec.

For further details about current consumption and calculation method, please refer to the following examples that generally apply to all possibilities and operating conditions of the TDC-GP1 by acam-messelectronic.

1.5.3 - Examples

Example 1

Measuring cycle:

A time difference of 1µs (average value) was measured 10.000 times per second in the basic measuring range.

Additional conditions:

- The time difference was calibrated on-chip using the ALU, which required 2 µs.
- The calibration clock frequency was 1 MHz.
- The 16 Bit results were read out via an 8 Bit bus.

The following are the individual components of power consumption:.

Measuring core is active for 10 ms/s or 1 % of the cycle, thus

$$I_{meas} = 20\ mA \bullet 0.01 = 200\ \mu A$$

No pre-devider is used because the measurement takes place in the basic measuring range.

ALU is active for 20 ms/s or 2% of the cycle, thus

$$I_{ALU} = 10\ mA \bullet 0.02 = 200\ \mu A$$

Calibration clock input frequency is 1 MHz thus

$$I_{cal} = 40\ \mu A$$

Data bus accesses are 20.000 / second, thus

$$I_{bus} = 40\ \mu A$$

There are several additional sources contributing to the current drain, i.e. the occasional calibration, to be considered. A budgetary amount is

$$I_{various} = 20\ \mu A.$$

Here, the total current consumption is approximately = 500 µA.

Example 2

As a second example we would like to show the lower limits of the power consumption; the case reproduces a really existing product.

Measuring cycle:

Once every 2 seconds a measurement takes place in the extended measuring range with an average measuring time of 600 µs. During every measurement a calibration takes place.

Additional conditions :

- ☐ Results are calibrated on-chip using the embedded ALU, then the 32 Bit result is read out.
- ☐ The calibration clock is set to 2 MHz and becomes active during the measurement for approximately 50ms. This time is needed because the clock is also the source for other parts of the circuit.

The following are the individual components of power consumption:

Measuring cycle is active for 1.5 µs (see Fig. 4, pg. 7), i.e. for 3 calibration clock periods on average incl. calibration. The active time in the extended measuring range is nearly independent of the measuring time. The resulting current drain is then

$$I_{meas} = 20\ \text{mA} \bullet 1.5\ \text{E-6} \bullet 0.5 = 15\ \text{nA}$$

Pre-divider is active app. 600 µs per measurement, thus

$$I_{PD} = 50\ \mu\text{A} \bullet 0.0006 \bullet 0.5 = 15\ \text{nA}$$

ALU is active for approximately 2 µs per measurement, thus

$$I_{ALU} = 10\ \text{mA} \bullet 2\text{e-}6 \bullet 0.5 = 10\ \text{nA}$$

Calibration clock input is active for approximately 50ms/measurement, thus

$$I_{cal} = 2 \bullet 50\ \mu\text{A} \bullet 50\text{e-}3 \bullet 0.5 = 2.500\ \text{nA}$$

Data bus accesses are 8 every 2 second, thus

$$I_{bus} = 10\ \text{nA}$$

The other additional sources contributing to the current drain have a budgetary contribution of

$$I_{various} = 150\ \text{nA}$$

The current consumption results in approximately 2.7µA with a supply voltage Vs of 5 V, and 1.9 µA at Vs = 3.6 V.

It is in fact remarkable that practically the entire power consumption originates in the calibration clock entrance. The measuring circuit and other consumers do not play a major role. If it were possible to adjust the runtime of the calibration clock with the necessities of the TDC in this example, 5 ms would be comfortably feasable including the oscillator stabilising time. As a result the entire power supply of the chip would remain in the nanoampere range.

The second highest consumer, i.e. the quiescent supply current, should be given consideration. The value is quite imprecise and can vary by several 100% from chip to chip. Individual runaways in the micro ampere range may appear. These runaways are limited to fewer than 0.01% in number, which means that fewer than 1 chip out of 10'000 will have a consumption in excess of 1 µA quiescent supply current.

Be aware that the low power consumption cannot be realised in the Resolution Adjust or in the Resolution Lock Mode because the PLL continuously needs some 15-25 mA.

Obviously, when all requirements are fulfilled and the corresponding factors are optimised, digital delay time TDCs can operate with minimum power consumption, enabling their use in a great number of critical battery applications.

2 – Quality of the results

Almost every developer has his own experience about interpreting measured results, greeted as fantastically good, or abhorred as erroneous. Regardless of good or bad, wrong measurements usually have consequences. Either the reality catches up with you at some point in time (when it was "too good"), or else, a good idea is thrown away although the circuit construction is actually useable (apparent measuring quality "too poor"). So, one goes ahead, searching for other solutions that are more expensive and waste valuable time that one just does not have.

In addition, TDCs have the problem of not being well known components, so that no up-to-date comparison values can be offered to evaluate the results. An example shows what we mean:

A customer tested a TCD and was not happy with the standard deviation of 7 LSB he got. Nor were we.

He was going to discard the use of the chip, but during a phone conversation, the mismatch was traced back to an erroneous lecture of the manual.

With some suggestions and hints, the standard deviation was reduced down from 7 LSB to 0.8 LSB in a straightforward manner, and all the obstacles against the use of the chip disappeared.

The present chapter will give an explanation of possible measuring errors, offer an overview of the expected inaccuracies with TDCs, describe “popular“ error sources and inform the user on what he can accomplish with these devices. The values used here are "real life" and have been tested and measured many times.

2.1 - Stochastic errors

Stochastic errors are all those errors that can be traced back to quantisation noise and other noise, and can be characterised by standard statistical parameters like for instance the standard deviation.

In fact, the standard deviation is generally a good measure for the qualification of stochastic errors and can be defined as the averaged square error over a number of measuring results. The necessary formulas for calculation can be found in every mathematics formula collection.

The stochastic errors can be divided into two groups of errors

- ☐ Noise effects (thermal noise)
- ☐ Quantisation errors

2.1.1 - Noise effects

The delay time of a gate is the base for TDCs measurements. It is subject to noise. This noise cannot be avoided, and it depends upon process and temperature. However, it plays a minor role as compared to quantisation errors. Its actual influence depends upon the absolute delay time of the measuring unit, and if short intervals are measured, it is practically inexistent.

The following guideline should apply:

Measuring time < 5 µs: practically no noise exists. The standard deviation is independent of the time difference and is approximately in the range of 0.5-0.7 LSBs.

Measuring time > 5µs to 15 µs: Standard deviation increases slowly at a 0.05 LSB/µs rate. Due to the quadratic sum, the noise increase takes place over a square root function.

Measuring times above 15µs should be performed only exceptionally in the basic measuring range mode, and with measuring time larger than 50 µs, further effects add, reducing measurement quality even more.

Be aware that only the active time of the measurement core is relevant. For longer time lags the extended measuring range mode should be chosen, because now, the core-active time depends on the period of the clock rather than on the measured time lag itself. Active time is smaller or equal two clock periods. Using e.g. a 5 MHz clock frequency, this will be 400 ns, far below 5 µs, let alone 15 µs.

Noise effects always have good statistical character, because they are spread out evenly and can therefore be well handled by mathematics, especially through averaging.

2.1.2 - Quantisation errors

Quantisation errors also belong to the stochastic error sources but they need careful handling, because they can lead to systematic error effects.

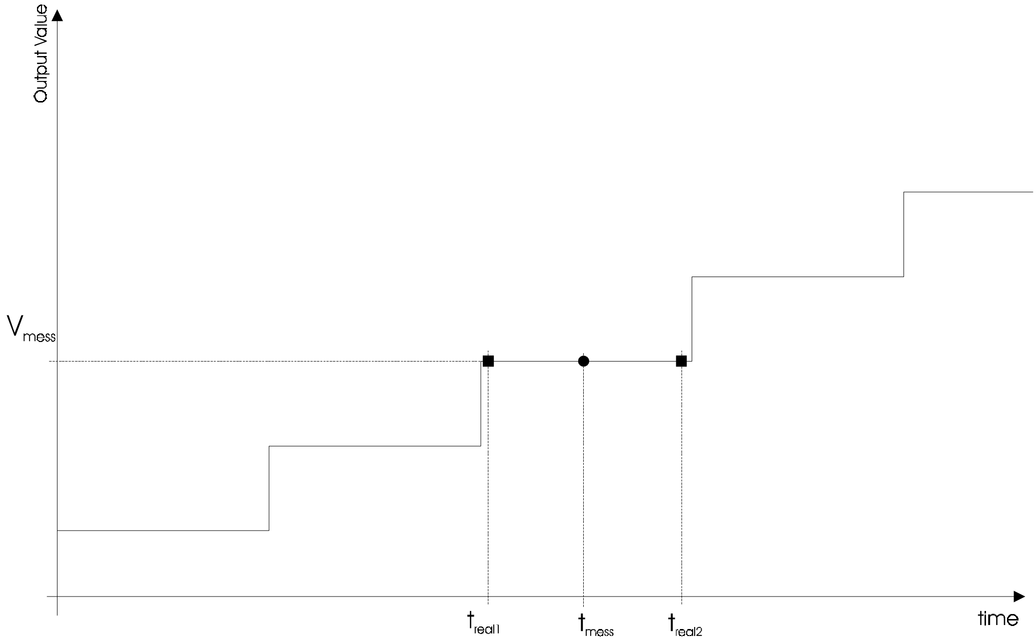


Figure 6 - Systematic results of quantisation errors

Quantisation errors definitely have a systematic character when special measuring conditions occur, and these errors cannot be eliminated via statistical methods like averaging.

Let us consider an ideal converter, having a straight line characteristic, but quantised, see figure 6, t_{real1} and t_{real2} both result in the same measuring value V_{meas}, which then will be associated to t_{meas} as a standard result.

Even though both input values differ by about 1 LSB, they are both associated with the same output value (or measurement result). The difference between the measured and the actual value can mount up to ½ LSB, and this is a systematic effect, which means that the time t_{real1} will always be measured ½ LSB too high and t_{real2} always ½ LSB too low.

The effect, that has just been described, is unfortunately often displayed as Offset error of the chip, which at closer sight it is not.

Example: A consistent time difference is measured with the software calibration method. While the temperature varies, the LSBs, whose width depends on temperature, wander over the consistent time difference, and the same happens with the calibration values. After adding all quantisation errors, the results can vary up to 4 LSBs, which may seem like an incredibly large offset variation over temperature in the beginning.

When these errors cannot be accepted, several countermeasures can be taken like operating in the Resolution Adjust Mode, or using the extended measuring range that can reduce the effect drastically via the pre-divider, given the pre-divider clock is asynchronous (!) to start and stop.

As we will show in a later chapter, it is possible to create measurement precision better than 1 LSB by averaging the measuring results. Systematic deviations however cannot be removed by averaging. The effect described above is systematic. It can only be compensated by use of specific circuit solutions or system modifications.

As long as all quantisation errors are evenly distributed over the entire characteristic (which means that the measured time differences are evenly distributed), this contributes to the standard deviation a value of:

$1/\sqrt{12} = 0.29$ LSBs.

2.2 - Systematic errors

Systematic errors are errors in the measuring system which always have same value and same sign during equivalent time measurements. There are many possible causes. E.g., poor power supply may result in same voltage drop at same time difference. In some cases, multiple causes are interfering with each other in a complex manner, adding up into systematically erroneous measured values.

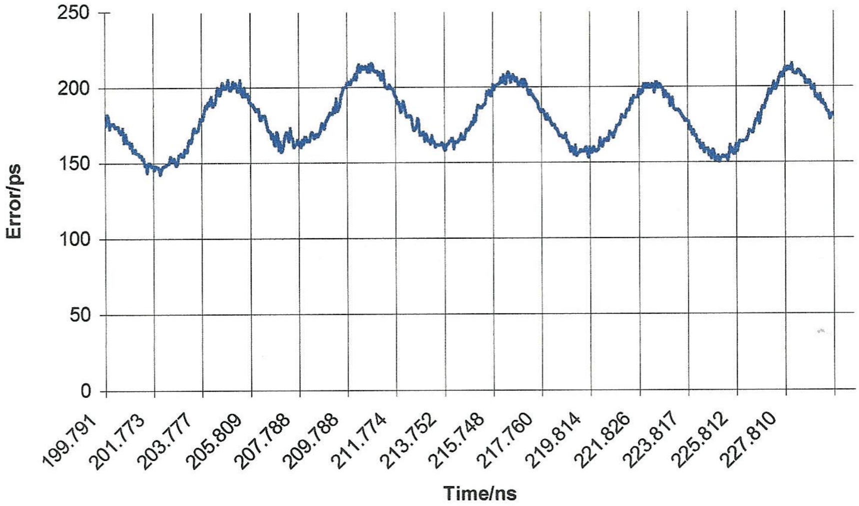


Figure 7 - Graph of systematically TDC measurement errors

The TDC, the data-out of which is displayed in figure 7, has a resolution of approximately 70 ps. By averaging 1000 measured values, we have succeeded in suppressing the noise so that a systematic measuring error of about 1 LSB in magnitude clearly appears. Increasing the averaging rate would further smoothen the noise out, but would not eliminate the 1 LSB systematic error.

The above graph can help us to understand something else. Considering a fixed time lag value, the corresponding standard deviation can be guessed to be some 3 or 4 picoseconds (from the noise). This is what you would call the resolution. Be aware that this is not the same thing as the precision. Due to the systematic error, the precision in that example is worse than 150 ps.

It is often very simple to get a narrow resolution, whereas it takes hard work to generate precision, so one tends to cheat a bit.

If one is familiar with the value and the direction of a systematic error, it becomes possible to correct the measured value. In the example above, the error is strictly bound behind the decimal point, so that a table correction would yield good results.

When describing systematic errors, the chip manufacturer is supposed to publish serious and meaningful values and diagrams for evaluation and correction purposes. The establishment of such error graphs is time consuming and necessitates sophisticated equipment.

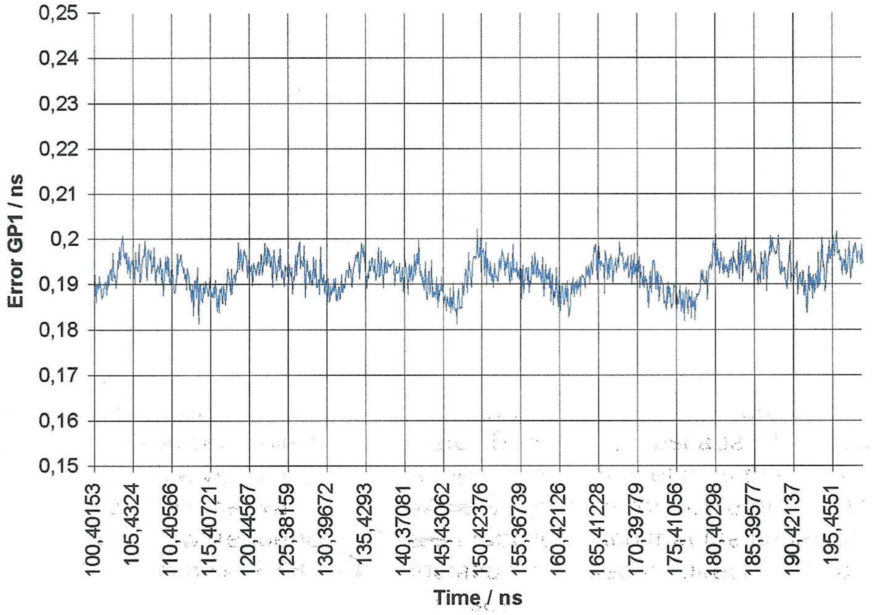


Figure 8 - Systematic errors of the TDC-GP1

Figure 8 displays proof of the systematic errors of the TDC-GP1 where the systematic effects are clearly below 10 ps, and the identifiable systematic error can be traced back to the used reference equipment for the most.

Good TDCs can reach systematic errors of well below 10 ps

2.3 - Offset errors

Offset errors belong to the group of systematic errors. While the systematic errors discussed above are a more or less complex function of of the observable, offset errors are constant. They just need to be subtracted from the measured value. The offset value corresponds to the measuring result at time difference exactly zero. Offset errors emerge from inevitable mismatch between various paths in and outside the chip.

In conclusion, offset errors are generally not very harmful. In most cases an offset correction of the entire measuring path takes place anyway, since the offset errors originating from the rest of the circuit are generally larger than those inside the TDC.

Of course, it is preferable to minimise the TDC generated offset and especially its temperature dependence. The aim is to get them below those of the rest of the system. Good TDCs reach an absolute offset error below 1 LSB and a temperature dependence around 0.05 LSB – 0.5 LSB, according to chosen parameters and ambient temperature (see manual TDC-GP1).

2.4 - Averaging

If the single-shot resolution of the TDC is not sufficient, one can average measurements. This requires, of course, the possibility of having access to multiple shots or runs, That possibility is frequently given, perhaps more often that you would expect.

A wonderful example is the frequency counter. The period length (averaged length of a time difference) can be defined up to few picoseconds by measuring many (maybe million) periods (= consistent time difference). The measuring equipment would not be capable of doing this in one individual period. Instead, this is a perfect job for TDCs that are comparable to gigahertz counters.

Averaging can only reduce noise effects (quantification noise, thermal noise). Systematic errors cannot be averaged out. Averaging would strip noise away and make systematic deviations clearly visible. A nice example can be found in 2.2 , where high average rates reduce the quantification noise to 2-3 ps, so that systematic errors can be clearly identified.

2.4.1 - Statistical conditions for successful averaging

Averaging can always take place when the measuring task permits it. If you want to improve the precision of the results, it is mandatory to consider several conditions so that nothing goes wrong.

It is important not to collide with systematic effects of quantisation errors (see 2.1.2). If every measurement hits the same LSB on the measuring characteristic, averaging becomes meaningless.

When averaging, the measured time difference or the measured characteristic must be noisy, so that the averaged time difference can be spread out over several steps of the quantisation characteristic. The best results would be a homogeneous spread of individual results over an area of LSBs, as shown schematically in figure 9.

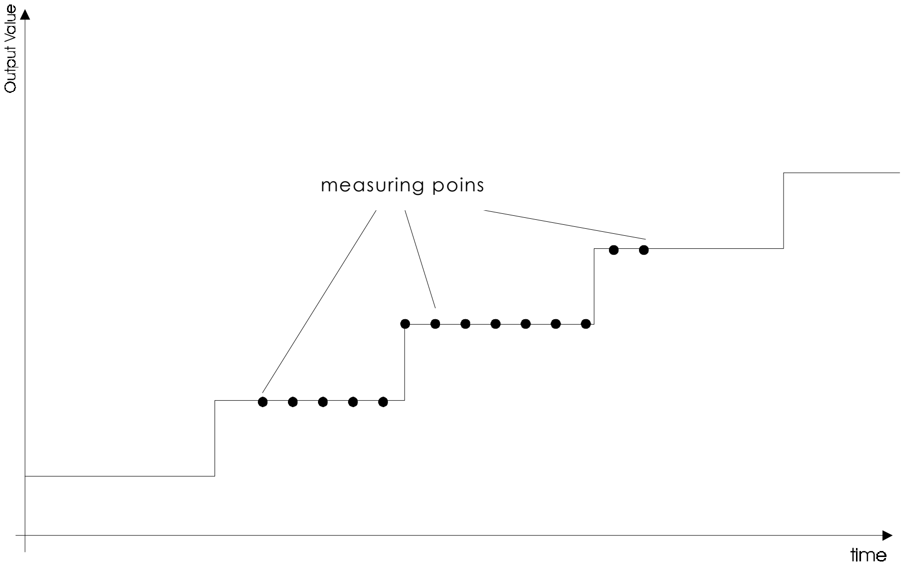


Figure 9 – Schematic representation of results spreading.

2.4.2 - Increasing precision through averaging

If the requirements described above are fulfilled, the standard deviation of a measure can be reduced according to the square root of the average rate. As an example, the 200 ps standard deviation of a TDC can be lowered to 20 ps by averaging 100 measurements because of a reduction by the factor $\sqrt{100} = 10$.

Averaging will improve considerably the standard deviation and (when systematic errors are absent) the precision, theoretically down to zero. In practice, it is the systematic errors that will constitue the lower limit of precision, and this will greatly depend upon the chosen TDC.

In the Resolution Adjust Mode the TDC-GP1 systematic errors are << 10 ps (probably < 2 ps), so that it is safe to operate up to this limit.

With corresponding average rates the standard deviation of the TDC-GP1 can be improved down to femtoseconds (10^{-15}s) since the measurement principle generates the necessary statistical features (almost) perfectly by itself.

The limits of a stable standard deviation for this device is around 150 fs (femto seconds) !

Standard deviation ought not to be confused with precision, that may be around 1ps – 2ps.

3. - Applications

3.1 - Tracing back physical values to time differences

TDCs are almost universal products and this is the reason why the applications spectrum is so broad. TDCs can be applied in all areas where physical values can be traced back to time differences, and this occurs more often than one would expect.

Several examples where this takes place are:

- ☐ Tracing back the difference between two or more marks by measuring the time of flight (light, microwave, sound).
- ☐ Tracing back the gas or liquid flow to a time difference by measuring the time of flight of an ultrasonic burst.
- ☐ Tracing back the temperature to a time difference by measuring the time consistency of an RC-unit with a temperature dependent resistor.
- ☐ Tracing back a weight to a time difference by measuring the time consistency of an RC-unit with a force dependent capacitor or else with a strain gauge.

The digitisation of physical values take place – as always in the field of metrology – via an intermediate physical quantity, which is time in the case of the TDCs. Figure 10 shows hows the process take place.

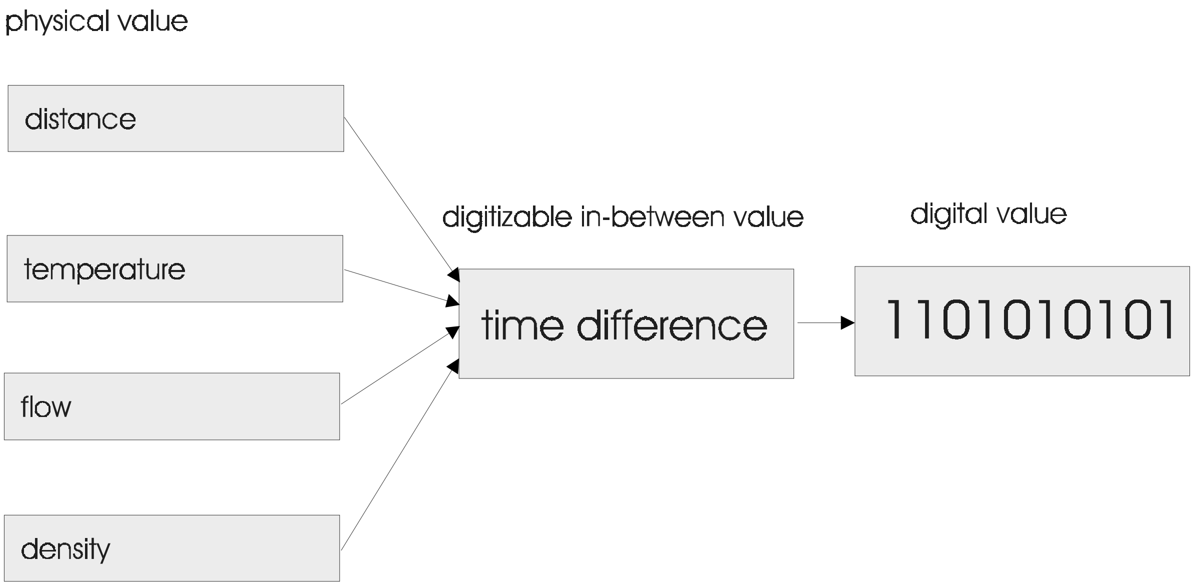


Figure 10 – Measure of various physical parameters by using a TDC

We now move to some more concrete examples where we will see how TDC technology is being used.

3.2 - Fundamental research in physics

Why are we surrounded by matter rather than anti-matter? What happens 10^{-30} sec. after collision between particles? What type of force holds the world together?

These and similar questions, which seem to fascinate the layman but otherwise have them look upon everything calmly, is what experimental physics tries to conquer in very large experiments. For almost all of these experiments, a time difference must be measured with high precision, i.e. when reconstructing the flight path of a particle. Since these types of experiments have been performed for decades and the time measurement has always needed to be very precise, TDCs have been used in great quantities in the past. This area is the origin of high precision time measurement and is also the segment where the first TDCs were used. We will now display the use of TDCs in the drift chambers.

In order to transfer matter into conditions so extreme that answers for the above mentioned questions can be generated, it is necessary to increase particle energy, which means to accelerate particles close to the speed of light. Today, large ring accelerators consist of two circular tubes; in one tube particles are accelerated clockwise, counter-clockwise in the second, and every time the particles run through the tubes they collect more energy.

The largest accelerators generate energies comparable to an electrical field of several billion volts. When the particles reach their final energy state, the two counter-rotating particles collide in a reaction chamber. Like in real life, the thing practically explodes and all elementary particles will fly apart. The resulting fragments are identified in detectors, whose size can easily reach that of a building. A typical detector consists of a drift chamber, and TDCs are needed in combination with these drift chambers to reconstruct the flight path and the speed of the fragments. Fig. 11 gives you an idea what a detector section looks like.

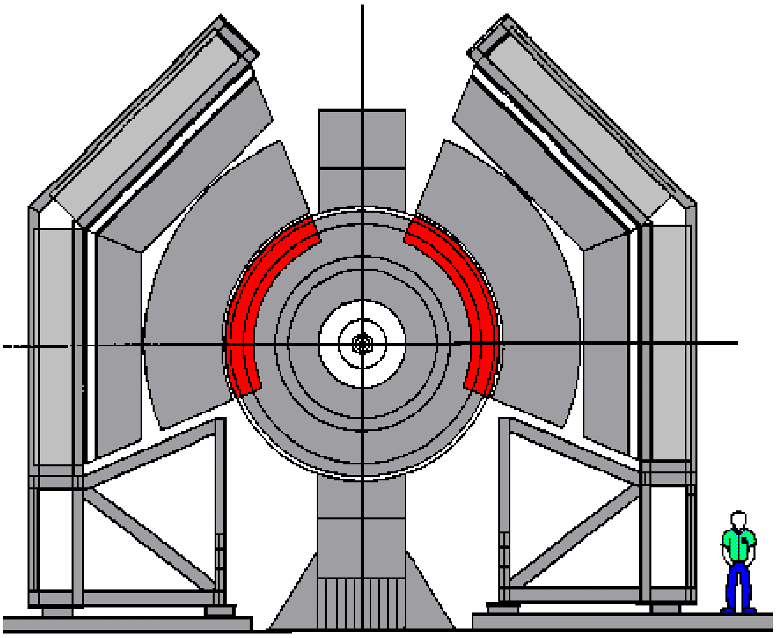


Figure 11- Typical example of a calorimeter used for high energy research

The collision point is the centre of the crosshair, and the detectors are arranged circularly around the collision point.

A drift chamber consists of gas filled tubes in which a live wire is strung. If a particle hits a gas molecule in one of these tubes, a cloud current is generated which drifts along the wire due to the electrical field (that's why it is called drift chamber). If the cloud current reaches the wire, an electrical pulse is generated, and the time from the collision of the particles to the hitting of the wire by the current cloud is measured by the TDCs. Figure 12 displays the result of such a collision.

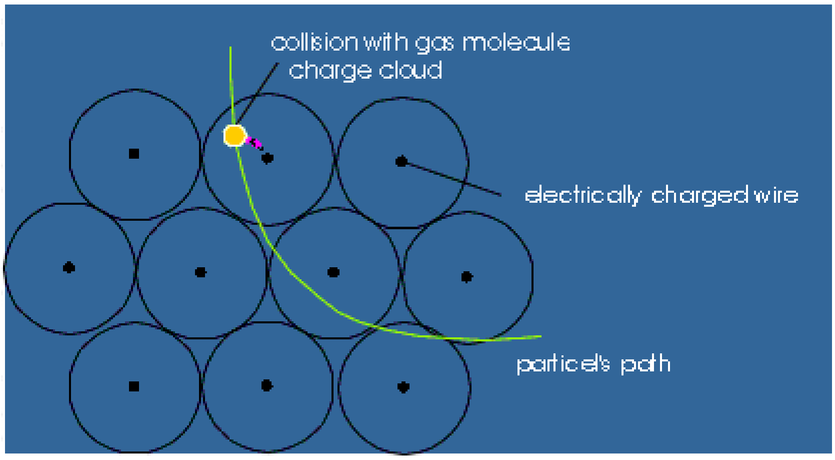


Figure 12 - Cross-section of a drift chamber

Since some of these experiments require several hundred thousands of these gas filled tubes, availability of a reliable, precise, energy efficient and inexpensive TDCs is very important. The required resolution is around app. 500 ps - 1 ns and can be reached with today's multi-channel single chip TDCs without any problem.

The advantages of using a TDC in this application are:

- Direct conversion from time to digital values. No need for time-to-analog converters with the following analog-to-digital converter
- Multichannel - the Acam GP1 offers 2 stop channels, the Acam F1 offers 8 channels in one IC.
- Multihit-Capability - the Acam GP1 can sample up to 4 stop signals per channel. Queuing the two channels yields 8-fold multihit capability
- High rates - as the ATMD-system demonstrates, it is possible to register up to 2.5 million measurements per second with the GP1

These characteristics make the TDC an ideal tool also for time-of-flight mass spectroscopy, fluorescence spectroscopy, analysis of photoelectrons and many more scientific applications.

3.3 - Ultrasonic flow measurement

Technical solutions without mechanically moving parts are "a must" when high reliability, little maintenance and long life are needed. Measuring methods have been established for liquid and gas flow measurement, and one of the most popular uses ultrasounds. Fig. 13 displays how such measurement is implemented.

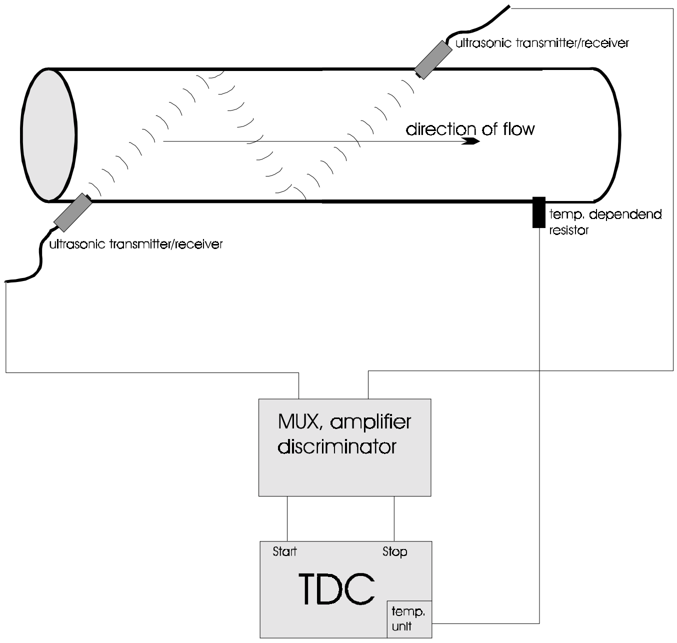


Figure 13 – Simplified model of an ultrasound flow meter

An ultrasonic pulse is sent out in the flow direction of the medium and a second against the flow direction, and the flight time of the ultrasonic pulse between transmitter and receiver is then measured. Piezoelectric transducers are generally used as ultrasonic transmitters and receivers because they are well suited for both functions. Due to the Doppler effect a time difference proportional to flow speed of the medium is generated, and a TDCs is used to measure the time of flight of the ultrasonic pulse.

Typical characteristics for this application are the rather large time differences, ranging approximately from 20µs to 1 ms, but the time differences due to the Doppler effect only amount to few nanoseconds. This small time difference with simultaneously high measuring time must have a resolution of up to 1-2%. This results in requirements for resolution ranging from 100 ps or less, and in order to reach this resolution it is necessary to apply averaging techniques, increasing the TDC basic resolution. Systematic errors, however are not permitted to exceed this value, otherwise, malicious errors will sum up over time.

The necessary dynamic area for measurements is 22 to 24 Bits. This high dynamic range, which would pose problems for some A/D converters, is part of the TDC “everyday business“ and can be conquered without any difficulty. It is common to work with the "extended range" measuring procedure, which permits the measurement of large time differences still offering the basic TDC resolution. There are no process limits in the dynamic area. If one relies on the relative variation of two measurements (ratiometric method), as is the case with flow measurements, customary quartz oscillators can be used as coarse counter clocks, since the frequency drift of the oscillator is cancelled out arithmetically.

If we wanted to measure the absolute time with an even higher precision, we had to use a frequency standard rather than an ordinary quartz as a coarse counter clock. Measurements with an absolute precision of up to 30 Bits can thus become feasable.

This is a good example which displays the precision that can be obtained in time measurement.

To compete, an A/D converter would have to measure 5 nV within 5 volts ! We believe that no such AD-converter exists. Modern TDCs, however, are capable of doing this job.

Small power consumption plays a major role in flow measurement techniques because most equipment is battery operated, and a long-time flawless operation without battery replacement is mandatory, condition easily met by using CMOS TDCs.

You need to measure temperature because sound velocity depends on it. This task is taken in charge by the TDC, too, due to the fact that temperature can very easily be traced back to a time difference. The TDC-GP1 offers this possibility with its additional "RLC ports". The necessary external circuitry (see manual TDC-GP1) is simple and inexpensive, and a precision up to approximately 0.1 K can be reached. If higher precision is needed, you should replace the external bipolar transistors by low R_{DS}-ON MOS-FETs. The limiting factor ist not time difference but parasitic effects, especially the temperature-dependent emitter base voltage.

The Time-of-Flight (also known as Transit-time) method uses the change in sonic velocity with and against the direction of flow. The result can be calculated by the following formula:

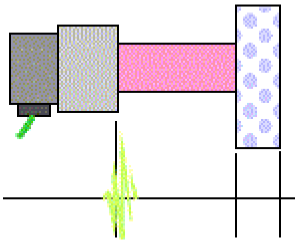
$$v = d \bullet (t_2 - t_1) / (2 \bullet t_1 \bullet t_2) \approx c^2 / (2d \bullet \cos b) \bullet (t_2 - t_1)$$

As an example, if we want to measure a flow of 0.5m/s in water (c=1480 m/s at 20°C) with a resolution of 0.5% by using a distance between the two ultrasonic transducers of 100 mm at an angle of 45°, we will obtain a time difference of 33 ns and the resolution needed will be 165 ps; this is not a problem for the TDC-GP1 and further advantages are:

- ☐ Small size single chip-solution in TQFP44-package with 2.7V to 5.5V supply voltage.
- ☐ Very large dynamic range. GP1 allows measurements up to 100 ms with a resolution of 110 ps; this equals a 30 Bit dynamic range that exceeds the requested 24 Bit.
- ☐ You can increase the resolution by averaging; the standard deviation can be reduced down to several picoseconds !
- ☐ Industrial operating range from -40°C to +85°C but even +100°C is possible.
- ☐ For handheld battery operated devices a low current consumption is essential. By using the GP1 in the extended measuring range with only one measurement plus calibration per second, the current drain at 5V supply will be only 3µA.
- ☐ The capability to easily measure temperature with a resolution of 1 K in the standard configuration, to compensate for the sound velocity dependence on temperature.

3.4 - Ultrasonic thickness measurement

Non-destructive material inspection methods based on ultrasound are well established in production quality control. The thickness control of metal sheet, pipe walls or synthetic foils are good examples. Material thickness by way of ultrasound flight time measurement on an echo - once again, precise time measurement is the key to that.

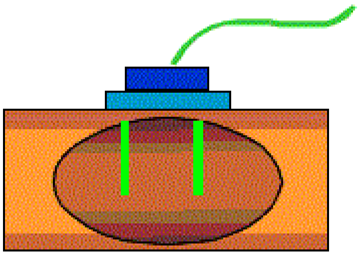


The sound velocity in aluminium is 5100m/s (@ 20°C) and an ultrasonic pulse is reflected on both, the entry wall and the back wall.

As an example, let us take a sheet of 1 mm aluminium; the difference in travel time for the two reflected pulses is 2•d/c = 3.9 µs. For a desired resolution of 0.1 %, time must be resolved to 390 ps. The TDC-GP1 can easily match this requirement.

3.5 - Ultrasonic density measurement

Process control is an essential part in chemistry and food industries. Especially the accurate measurement of the density of fluids is a challenge to engineers. With changes in concentration of the fluid, the density varies and so does the velocity of sound. This means that we can measure indirectly the density through time of flight.



The velocity of sound in water is 1483m/S (at 20°C). Many chemical solutions show a modified sonar velocity depending on concentration between 1200m/s and 1800m/s, and a 20 mm distance between ultrasonic transmitter and receiver gives delays between 10µs and 20µs.

With shorter distances of the transducers and an upper limit for velocity of sound of 10.000m/s, we find delay times of a few microseconds. The typical resolution of currently available devices is about 0.1 m/s. This equals to a resolution in time of 500 ps , not any problem for the TDC-GP1.

3.6 - Magnetostrictive positioning

The contact-less registration of positions, driving movements etc. is a need for industrial automation, where quite often a precision in the µm range is required. Corresponding devices need to be robust, inexpensive, and "zero maintenance". For quite a few years, a method has been known, which uses ultrasonic delay time on a wire to determine position, as shown in figure 14.

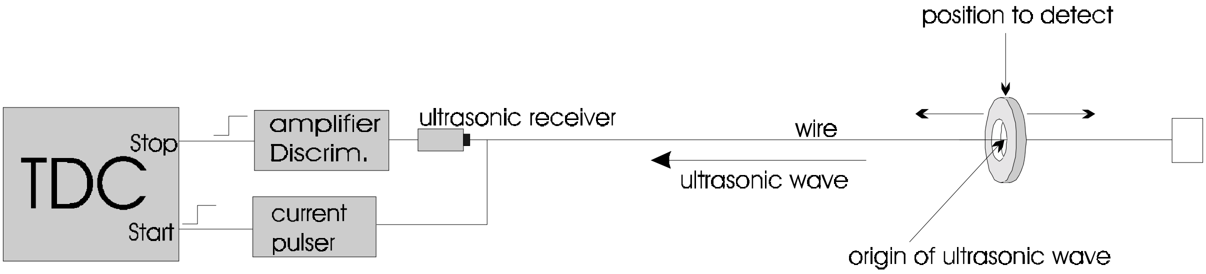


Figure 14 – Principle of operation for a magnetostrictive positioning system.

A wire is strung over the entire length of the positioning equipment. A strong permanent magnet is situated at the position to detect.

Microsecond current pulses, several amperes strong, are sent on the wire at regular intervals (e.g. 1 kHz). They create a sudden magnetic field around the wire. At the position of the magnet, there is a shock interaction between magnetic fields, which releases mechanical energy inside the wire. The energy propagates as an ultrasonic wave into both wire directions at a speed of approximately 2700 m/sec. At the “dead“ end, the impulse is absorbed, whereas at the “active” end, it is detected by an ultrasonic receiver. The time lag between the original electric current pulse and the reception is measured by TDC. Distance is then determined arithmetically.

This method allows a positioning precision of 2-5 µm to be reached, which equals to an ultrasonic delay time of 800..2000 ps, and this is well within the measuring range offered by TDCs. Due to their high resolution, situated slightly above most requirements, TDCs are ideal for time difference measurement; in addition, TDCs are extremely compact in comparison to past solutions, they are ten times more precise while using only 1/10 of the power. All these features contribute to the increasing popularity of TDCs.

3.7 - Laser distance measurement

Laser is best choice for measuring many types of distances. Due to its excellent focussability, its constant and uninfluencable velocity and some other advantages, it constitutes a modern length meter even for rather large distances. The pulse laser method is particularly well suited, as it combines high output power (several watts) with safety to the eye. A broad field of applications opens, ranging from distance meters, speed meters and security devices to airborne landscape mapping. The accessible distances range from a few meters up to several kilometres.

In addition to this classic time-of-flight method, TDCs are also very well suited for the no less classic phase comparison method, performed on amplitude modulated laser beams, where TDCs offer low power consumption and low cost.

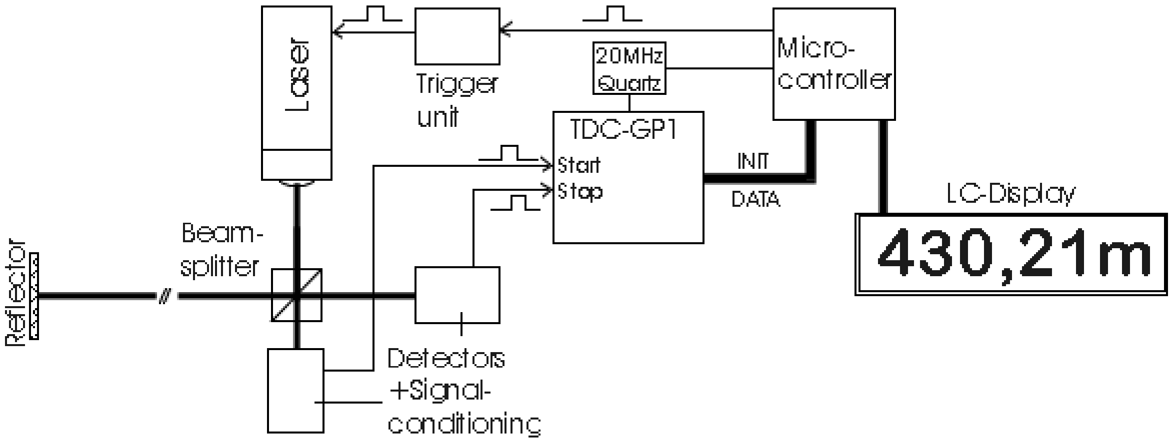


Figure 15 – Typical set-up for laser distance measurement.

Light, or more general electromagnetic wave is, till proof of the contrary, the fastest medium nature has to offer. Any type of information or energy transport can take place no faster than at speed of light.

Measurement of light velocity in vacuum gives a value of 299'792'485 m/s. The precise measure of a distance at this speed necessarily involves a delay time process that results in a very small measured time. If a precision similar to a normal measuring tape (about 1 mm) is to be achieved, then a delay time of 3 ps has to be resolved. When using a reflector this value is doubled.

This time difference is below digital delay time TDC achievement. Luckily it is not all as difficult because:

- Often centimeter resolution is sufficient for typical laser applications, so that we are already in the familiar area.
- It is possible to resort to averaged results to achieve the required precision
- Time difference measurement is not the only source of error. The signal path including measuring distances results in 30-50 ps standard deviation in good measuring conditions and circuit implementation. The standard deviation is therefore in the same range as today's good TDCs, so that even a 5 ps TDC would not drastically improve the final result.

Considering all of these circumstances, we can conclude that TDCs are ideal for laser distance measuring and are increasingly applied in this area as well in geodesics, in security systems, production controls or just on the golf course, where the measuring of distances with lasers or laser scanners is well established.

By using the reflective mode both transmitter and receiver are placed close to each other. The distance to be measure is calculated by:

$$d = c \bullet t/2$$

where c = light velocity.

If the measured distance is 1 kilometre, the time of flight will be 6.7µs. If the resolution has to be 1 cm we need a time resolution of 67 ps. This can be achieved by our standard TDC-GP1 by sampling over only 4 measurements. By averaging over many samples, a resolution of 1 mm can be possible at distances up to 14 km !

3.8 - Measuring strain gauges with TDCs

Up to now, measuring strain gauges and load cells have required the use of high-grade analog amplifiers or high-end A/D-converters with up to 24 bits resolution. By the use of TDCs (Time-to-Digital Converter), the measurement is moved into time domain, making possible to convert the entire electronics into a digital single-chip solution. This technique offers a wide range of temperature and supply voltage with a considerable cost reduction in comparison to current solutions.

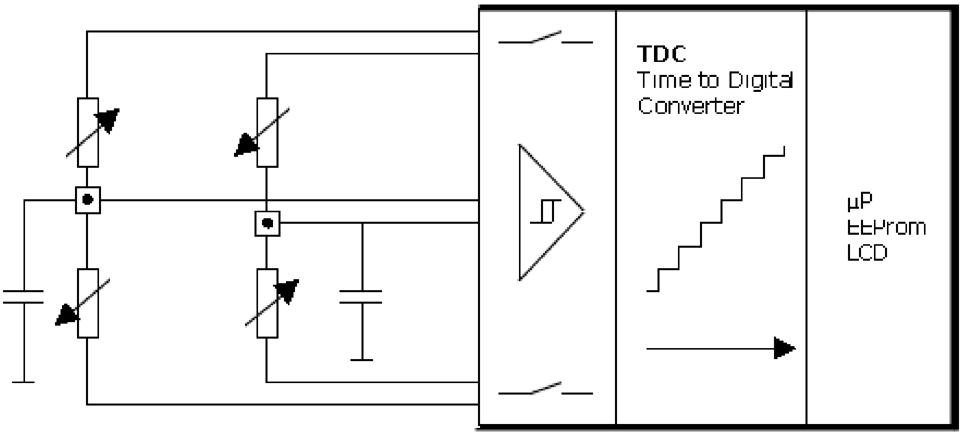


Figure 16 – Strain gauge TDC measuring principle of operation.

The schematic diagram of figure 16 shows the fundamental set-up of such a single-chip solution. The complete external circuit for the bridge is shown and the known bridge-circuit is slightly modified:

☐ At the bridge measuring points, a capacitor (5..50 nF) is added.
☐ The bridge supply is wired separately for each bridge arm.

Pulses are applied to the bridge ends, and the R-C combination determines the width of these pulses, thus giving a measure of the strain gauge resistance. Of course, the pulse width is digitised with high precision and linearity using a TDC.

When post-processing the time data, the influence of the absolute resistance values and temperature dependence are compensated, similarly to analog circuits, and inference factors from the capacitors, trigger voltage and supply voltage are suppressed.

Using this kind of conversion, it is possible to implement a system that does not need a full bridge. Rather, two untrimmed strain gauge resistors of one bridge arm are sufficient. Even a T-rosette with only one strained resistance can be evaluated; in this case, the second strain gauge resistor is needed exclusively for temperature compensation. The compensation techniques are strong enough to provide the same precision as in the half-bridge case; the only drawback is a 50% increase in measure time, a minor concern in most applications.

It is very easy to connect more than one bridge to the same single chip thanks to the digital nature of the measurement unit. This offers a big chance to reduce cost and space.

Using modern semiconductor manufacturing technologies, it is possible to achieve a time resolution in the range of 15..30ps. The examples presented in the following are based on a TDC realised in a 0.35µm CMOS process characterised by a resolution of 30 ps. The essential advantage of this measuring principle is that time can be measured with much better precision than voltage.

TDCs can be designed easily to achieve a resolution of 26 bit. So they are perfectly suited for signal conversion of sensors characterised by low output signal values. For example, a 500 ohm strain gauge varies within no more than 1 ohm at maximum strain, but this very small 0.2% change can be easily measured by a TDC.

Digitising strain gauges with TDCs offers a high degree of freedom in configuration, because resolution, update rate and current consumption can be chosen in a wide range. With the same electronic circuit, it is possible to implement a very fast converter with 350 effective scale divisions at 65 kHz update rate and 10 mA current consumption, or a very precise converter with 100'000 effective scale divisions at 4 Hz update rate and 10 mA current consumption, or a low-current converter with 40 µA operating current at a reduced update rate of 1 Hz, capable of 6000 effective scale divisions.

The current drain is split between strain gauge and electronics. Due to pulsing, the digital strain gauges need (in the worst case) only half the current in comparison to analogy strain gauges. A 500 Ohm bridge supplied with 5V needs about 5 mA at maximum update rate, with current consumption decreasing linearly with the update rate. The current consumption of the electronics totally depends on the semiconductor technology used. The data shown in the following table are based on a 0.35µm CMOS process and on a display rate of one value per second.

R-gauge (Ohm)	Strain (µ)	Effective number of Bits	Bridge Current (µA)	Circuit Current (µA)
350	1000	14.6 (1)	238	380
1000	500	12	23	172
1000	1000	11.5	3	25

(1) at display rate 0.5 Hz in the low power mode

cf. "Current calculator" in www.picostrain.com (online or download)

This table gives some examples of the dependence of current consumption at full scale output signal upon gauge resistance and number of scale divisions. The total current is the sum of the currents into the strain gauge and the electronics. It is proportional to the measuring rate. Ten times the rate means ten times the current.

If a lower update rate and lower precision can be accepted, this results in a current drain in the range of few µA. That is convenient for battery or solar cell supply systems.

The last example represent a typical battery driven application with strain gauge load cells in the segment of low cost scales, where it is customary to deal with very low output signals. A CR2032 battery with 180 mAh will drive the scale in example 3 for over 5 years when used two and a half hours a day!

There is another advantage coming from low current consumption. Even with 350 Ohm strain gauges, the power dissipated in the strain gauge itself can be kept below 1 mW, and the temperature drift due to self-heating is nearly eliminated.

Use of technologies based on smaller and faster structures, say 0.15 µm, in comparison to the 0.35µm process from the example above, will reduce the supply voltage and increase time resolution, and furthermore it will lower the strain gauge current consumption. Using a 0.15 µm process will reduce the total current consumption by a factor of 4.

The method used for compensating the parasitic effects guarantees a high stability against influences of temperature and supply voltage. The temperature long-term drift of capacitors and input trigger threshold variations are cancelled out, as well as any disturbances caused by the output resistance of the pulse amplifier are suppressed. Here some results from the laboratory showing the error at max. strain (1000µ)

$\Delta T_{electronics}$	60 K (20 °C – 80 °C)	0.5 – 0.7 µstrain
ΔV_s	2 V (3 V – 5 V)	1,5 µstrain

When measuring temperature drift, the strain gauge load cell itself was kept at constant temperature. The supply voltage drift is of systematic nature and can be corrected to 0.2/0.5µ. Even with a laboratory set-up, built with components that are not developed for this purpose, we could achieve results competitive to DC bridge amplifiers. With future developments, we expect drastic improvement in performance, because the limiting factors are well-known.

Based on this measuring principle, it is possible to built a pure digital ASIC, and for a given measurement task, the entire electronics can be reduced to a single chip. The number of bridges, resolution, update rate and current consumption, can be designed according to customer’s needs. Specific algorithms for data processing can be implemented on-chip. For data output, different digital solutions can be provided like LCD display drivers, serial or parallel data lines and frequency outputs.

When a very flexible device is needed, it is possible to integrate a microprocessor core together with memory (EEPROM, Flash). Using this approach, solutions like programmable multi-channel amplifiers or solar-driven scales will be possible.

3.9 - Frequency and phase shift measurement

In many applications the value to be measured (capacitance, resistance, weight, density, pressure, ...) is converted to a frequency change or phase shift. Typical examples are capacitive or inductive proximity sensors or piezoelectric weight cells.

As an example, the frequency measurement with TDC-GP1 can be easily implemented connecting the frequency signal (should be TTL) both to the start and stop inputs. In this way, you directly measure the period, and depending on the requested accuracy, this can be realised with lowest current consumption, ideal for battery driven equipment. The following table shows some typical values for accuracy and current consumption obtainable in the two measuring ranges.

	Measuring range 1		**Measuring range 2**	
	Minimum	Maximum	Minimum	Maximum
Period	3 ns	6.7µs	60 ns	100 ms
Frequency	333 MHz	150 kHz	16.7 MHz	10 Hz
Resolution	4%	0.05%	0.5%	10^{-7} (1)
Current (2)	400 nA	400 nA	400 nA	5000 nA
Accuracy	0.11%		0.015%	

(1) One LSB = 120ps (2) Calibration clock active during measurements only

In the same way, it is possible to measure the jitter of a frequency signal or the phase shift between two signals at a rate of up to 2.5 million measurements per second.

4. Short TDC Dictionary

The emphasis is on "short". It is not our goal to increase the TDC cookbook by 20 pages. The dictionary contains some special terms that are often used in connection with TDCs and require some explanation. We will not, however, include such common terms as calibration, status register, overflow, etc. In this chapter, the reader should be able to look up terms encountered here for the first time.

Absolute delay time TDC

Part of the family of digital delay time TDCs, where the absolute delay time of digital gates is used for the fine quantification. The resolution of the TDC corresponds to the delay time of the used gates.

Auto calibration

A calibration method where a calibration value is automatically generated by a TDC. By using the Auto Calibration function, calibration values are generated directly after a measurement. These serve to normalise the measured raw value.

Auto noise

TDC internal circuit unit where, due to a pseudo coincidence, an additional time delay is added to the measured time difference. The same time difference is added to the calibration value connected to the same measurement. So it falls out during normalisation, but it does help to eliminate quantisation effects when averaging close time differences (see TDC-GP1 Manual, Chapter 2.3.2e).

Differential non-linearity (DNL)

Differences in the width of individual LSBs on a measurement characteristic. Due to the special characteristics of the converter processes, LSBs never have an identical width regarding Pico seconds. The DNL is described in an absolute manner in Pico seconds or in a relative manner as a percentage variation between the narrowest and the widest LSB. Fig. 15 shows a characteristic with a large DNL.

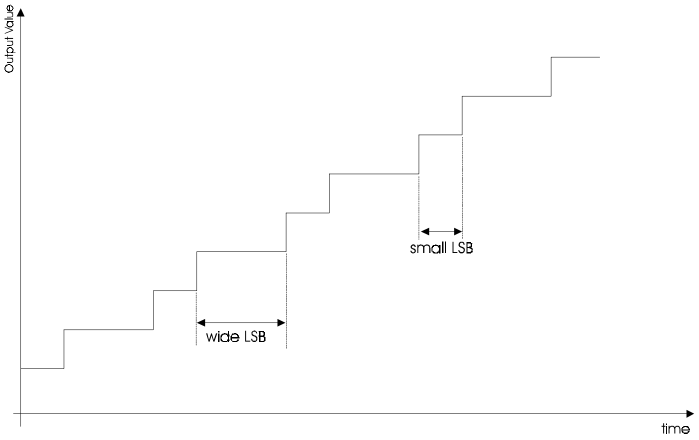


Figure 15

Example of differential non-linearity

Digital delay time TDCs

Part of the family of TDCs that use the delay times of digital gates in order to determine time differences.

Double pulse resolution

Parameter characterising multi-hit TDCs. If the stop entrance during a measurement is supposed to accept more than one stop impulse per run, these pulses must have a minimum interval between them to be distinguished. The minimum time interval (between active flanks) is called double pulse resolution (see manual TDC-GP1 2.3.1).

Integral non-linearity

Max. deviation of the quantification characteristic over the entire measuring range from an ideal straight line. In practice, the measurement characteristic is approached linearly by least squares. The max. deviation between characteristic and fit line is called integral non-linearity. It is usually measured in LSBs. Fig. 16 displays the correlation graphically.

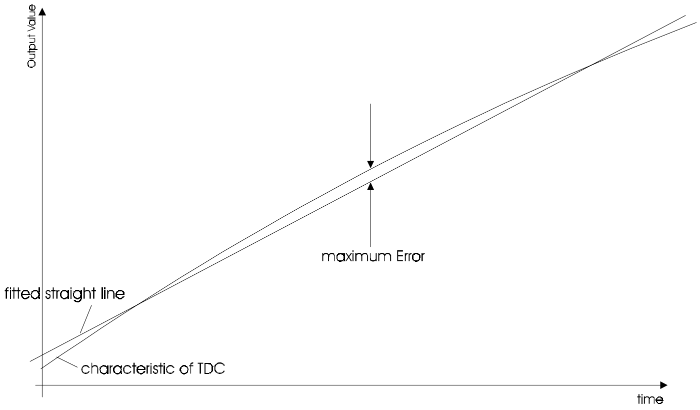


Figure 16

Example of integral non-linearity

Multi-hit capability

The capability of a TDC to measure more than one time difference of a stop entrance during a measurement run. The TDC-GP1 is a multi-hit TDC, because it can measure up to 4 time differences (hits) on every stop entrance.

Relative delay time TDC

Part of the group of digital delay time TDCs. The relative time difference between two digital gates with little variation in delay time is used for time difference measurements. The result is a realisation of relative delay time TDCs far under the min. delay time of the gates.

Resolution adjust

Special operation mode, in which the resolution of the TDC can be adjusted via register. The resolution is independent of outside influences and corresponds exactly to the selected value in the register.

Resolution lock

Special operation mode where the resolution is stabilised independently of outside influences (temperature variations). The resolution cannot be precisely adjusted but is simply stabilised on a selected value. The remaining temperature dependence in resolution may be of approx. 30-50 ppm/K.

Retrigger capability

If the start entrance receives several starts before the first stop arrives, a retrigger-capable TDC can begin a new measuring run with every incoming start, discarding previous start signals, until stop signals begin to arrive. The time differences from the last start to the stops are measured (see manual TDC-GP1 1.14f).

RLC measuring

The measuring of:

• Resistivity	R
• Inductivity	L
• Capacity	C

can easily be traced back to time difference measurements. The RLC measuring unit offers most of the necessary circuitry, with little need for external components.