Laser distance measurement with TDC's

To measure distances with lasers or laserscanners is well established - you will find this technique in geodesic systems, security systems, production control systems and even with golf players. Different methods are available. Small distances are measured by triangulation. Using this method the achieved resolution will be in the range of micrometers, but the maximum range is limited to only a few meters. Up to distances of 100m people often use the phase shift measurement. The laser light is modulated and the phaseshift between outgoing and incoming light gives the distance. To reach a resolution in the millimeter range very high sampling rates are necessary. Only low measuring rates with high current consumtion are possible the consequence.

With Time-to-Digital-Converters (TDC's) you choose the straight way. It is possible to measure directly the time-of-flight of light. The principle is easy - the details are tricky. It is well known that the velocity of light is very high, $2,99792*10^8$ m/s. In consequence one has to deal with very short times. In only one microsecond the light passes 300 meters! High resolution therefore means highest precision in time measurement.

Usually the ray of light will be reflected at an object or mirror. Therefore the light passes the distance twice. So we will have:

1ns	-	150mm distance (reflection)
100ps	-	15mm "
10ps	-	1,5mm "

This is the range well suited for use of the TDC-GP1. This single-chip TDC has a resolution in high resolution mode of 125ps which is equivalent to 19mm distance. See the figure of a typical system for laser distance measurement.

The TDC-GP1 is a very universal intergrated circuit and can be used in different manners. Which mode should be chosen? In the following we look at some modes in detail:

a) Measurement range1 - High Resolution

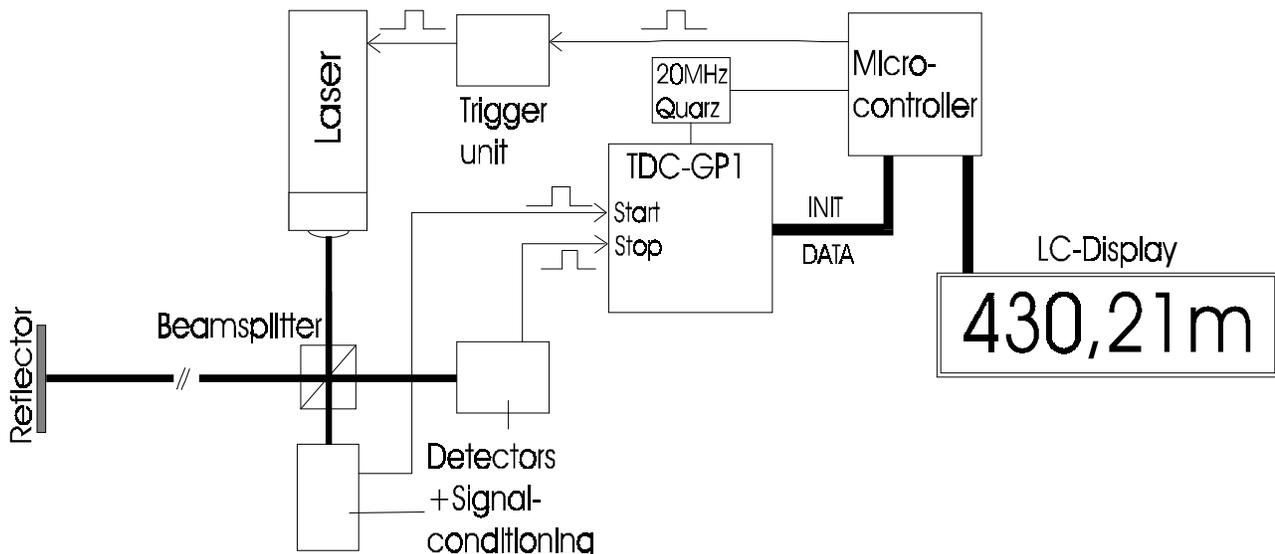| Range:	0,45 - 570m	(1.4 - 1870ft)
Resolution:	19mm	(0.75in)
Standarddev.:	13mm	(0.51in)

In this mode the GP1 runs with one start input and one stop input (stop2 is disabled). The resolution is typically 125ps ≡ 19mm with a standard deviation of about 90ps ≡13mm. The measurement range covers typ. 3ns to ca. 3,8μs. For distance measurement this means a distance range from 45cm to 570m - with the same resolution in the complete range.

What has to be regarded?

- The trigger pulses width for the GP1 must be > 2,5ns.

- The time between first edge of start trigger and fist edge of stop trigger must be > 3ns.

- Without the resolution adjust mode the GP1 has to be calibrated. At low sampling rates the easiest way is to use the implemented autocalibration function. Otherwise separate calibration should be done in regular intervals.

Which are the advantages of the GP1?

- TDC's work together with pulsed lasers - in contrary to the phase modulation principle, where cw lasers are needed. In consequence the current consumption of the system is much less. On the other hand it is possible to increase the puls energy, an important aspect considering long distances.

- The supply current of the TDC-GP1 itself is in the range of only several μA.

- The small TQFP44-package allows compact layout.

- The 4-fold multihit-capability allows the analysis of multiple

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1

reflections with a double pulse resolution of 15ns.

How is the supply current of the GP1 calculated?

In measurement rage 1 the supply current for the GP1 is strongly dependent on the sampling rate and the reference clock frequency. It will be shown on an example:

The measurement rate may be 100 samples per second with a 4MHz reference clock. For the current consumption we find:

max. measurement time = 3,8µs (≡ 570m)

100*3,8µs=380µs actice measurement time

supply current TDC-core = 25mA*380µs/1s=9,6µA   (1)

with clibration the ALU is active for 100*2µs = 200µs

supply current ALU = 5mA*200µs/1s=1µA   (2)

supply current reference clock 90µA/MHz*4MHz = 360µA   (3)

supply current data I/O = 2mA/MB*s*400B/s=1µA   (4)

The total supply current of the GP1 is about 372µA

(=Sum (1)-(4)). The mean part is dominated by the reference clock unit. If it is possible to enable the reference clock only during measurement (50ns for stabile oszillation have to be regarded) the current consumption will be reduced by 360µA*(1s-50ms)/1s=342µA. The result will be a TDC that needs only 30µA!

Typical register contents (reference clock 4MHz):

Reg 0:	0x44	Auto_Cal + Calibrate
Reg 1:	0x4D	HighRes, adjust value
Reg 2:	0x01	Hit1 Stop1 - Start
Reg 3:	0xXX	Default
Reg 4:	0x60	(4MHz(RefClk)/8=500KHz means 2µs)
Reg 5:	0xXX	Default
Reg 6:	0x02	Default
Reg 7:	0x01	Enable 1 Hit at Stop 1
Reg 8:	0x00	Default
Reg 9:	0x00	Default
Reg 10:	0x80	Default

b) Measurement range 2, High Resolution

Range: 9m - >10km   (29ft - >32800ft)

Resolution: 19mm   (0.75in)

Standarddev.:   17mm (by averaging 1mm)

In this mode the TDC-GP1 uses a predevider to extend the measerument range to 200ms.

Again the resolution is typically 125ps (LSB) ≡ 19mm with a standard deviation of typ. 110ps ≡ 17mm. The TDC covers the range of 60ns to **200ms**. Thinking about Laser distance measurement this means a distance range from 9 m to >10km! Finally the optical system and not the TDC's will limit the range.

What has to be regarded?

- The trigger pulses for the GP1 have to last > 2,5ns.

- After the start trigger the deadtime for the fist pulse is two periods of the calibration clock.

- Without resolution adjust mode the GP1 has to be calibrated. At low sampling rates the easiest way is to use the implemented autocalibration function. Otherwise separate calibration should be done in regular intervals.

Which are the advantages of the GP1?

- the complete measurement range up to 200ms is resolved with 125ps. This is equivalent to a **dynamic range of 31 Bit**. The precision of the system will be mainly dependent on the other system components i.e. the optics.

- for long distances the use of pulsed lasers with high pulse energy is necessary for getting a reflected signal with sufficient intensity.

- again multiple reflection can be detected. Three multihits with a double pulse resolution of 2 clock periods can be detected.

- the measurement principle of this mode allows to reduce the standard deviation by averaging. Sampling 100 measurements, the standard deviation can be reduced by a factor $\sqrt{100}=10$ down to 11ps ≡ 1,7mm. As a necessary condition the start and stop signals must not be correlated to the reference clock. Otherwise allways the same quantization step will be measured. The example shown in figure two with only one reference clock for TDC and Microcontroller wouldn't result in a real improvement, two independant quartz crystals should be used.

Typical register contents (Reference clock 35MHz):

Reg 0:	0x54	Auto_Cal + Calibrate + Meas.Range 2
Reg 1:	0x4D	HighRes, adjust value
Reg 2:	0x21	Fincout 1 - Finecount 2
Reg 3:	0xXX	Default
Reg 4:	0x00	(35MHz(RefClk) - 28,5ns)
Reg 5:	0xXX	Default
Reg 6:	0x02	Default
Reg 7:	0x02	Enable 2 Hits at Stop 1
Reg 8:	0x00	Default
Reg 9:	0x00	Default
Reg 10:	0x80	Default

c) Resolution Adjust Mode, High Resolution Mode

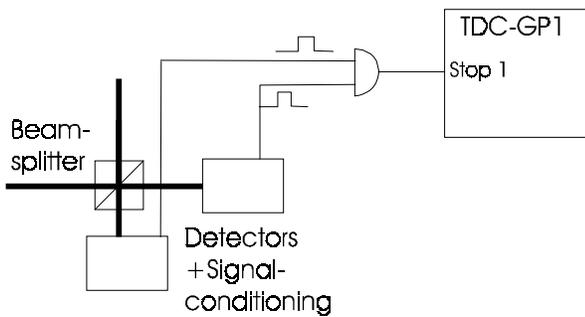**Range:**   2,2m - 285m   (7ft - 935ft)

Resolution: 19mm   (0.75in)

Standarddev.:   17mm   (by averaging 1mm)

In this mode the resolution of the TDC is absolutely fixed by variation of the TDC-cores supply voltage. The core voltage itself is regulated with a PLL.

Im Resolution Adjust Mode no start input is available. Using high resolution one channel is available and the first incoming signal is interpreted as start.

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2

Using the resolution adjust mode the given stochastics allows high sampling rates and a reduction of the standard deviation down to the femtosecond range. The time difference itself must not have any noise, the GP1 itself delivers the necessary statistics of noise for the measurement.

What has to be regarded?

- The first stop signal may arrive 15ns (double pulse resolution) after the start signal. the maximum time is 1,9µs. The measurement range is 2,2m to 285m.

- Multihits: 3-fold with 15ns double pulse resolution.

Which are the advantages of the GP1?

Two features make this mode ideal for laser distance measurement:

- **fixed adjustable resolution, independend on temperature and supply voltage**.

- Standard deviation by averaging in the femtoseconds range.

If the higher current consumption of 25mA is not a problem, then **Resolution Adjust Mode is the best for distance measurement**.

Typical register contents (Referenceclock 20MHz):

```
Reg 0:   0x00                              Default
Reg 1:   0xCD            ResAdj, HighRes, adjust value
Reg 2:   0x12              Hit 2 Stop 1 - Hit 1 Stop 1
Reg 3:   0x5A                         PLL-factor = 90
Reg 4:   0x16        Neg_Phase=1, Clockdivider = 64
Reg 5:   0xXX                              Default
Reg 6:   0x02                              Default
Reg 7:   0x02             Enable 2 Hits at Stop 1
Reg 8:   0x00                              Default
Reg 9:   0x00                              Default
Reg 10:  0x80                              Default
```

Have a look at the errata sheet in the manual, section 5.2!

Overview measurement ranges:

Mode TDC-GP1	High Resol.	Standard-deviation	Meas.-range	(in m)	doublepulse resolution
		in mm	min	max	in m
Meas.range 1	no	26	0,45	1140	1,2(*)
Meas.range 1	yes	13	0,45	570	2,25
Meas.range 2	no	34	9	>10km	1,2(*)
Meas.range 2	yes	17	9	>10km	2,25
Resolution Adjust	no	34	2,2	570	1,2(*)
Resolution Adjust	yes	17	2,2	285	2,25

(*) Hit 2 - Hit1 can be measured down to 0m, Hit 3 - Hit 1 only down to 2,25m

Possible extension:

d) Small distances

Many developers want to control also the closer range. The methods shown up to now have a lower limit between 3-60ns. In principle, smaller time differences are no problem for our TDC's. Discarding the high resolution mode, both stop channels can be used. And the time difference between two stop signals on different channels can be measured down to zero, even negative values! Take an example with resolution adjust mode:
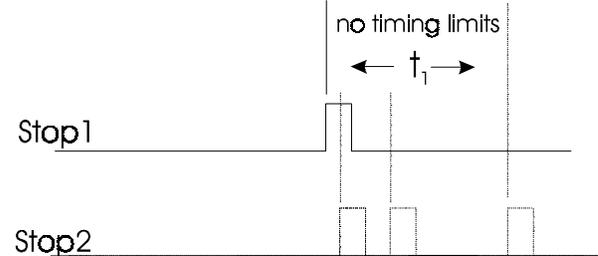
Give the triggersignal for the laser to the stop 1 input, the detector signal to the stop 2 input. In resolution adjust mode the first signal is interpretated as start. The order of signals in this set up is well defined, the start signal is identified. Time differences of 0s now can be measured. The loss in resolution, now only 250ps - can be compensated by sampling.

e) Measure long distances with Resolution Adjust

In the normal resolution adjust mode the maximum distance that can be measured is 600m. But is posiible to measure even longer distances and still use the advantages of this mode. The point is to give the right interpretation to the results.

The principle is as follows: In resolution adjust mode the GP1 continues measuring after time out in a correct way. It is the ALU that cannot continue the value range.

The ALU reacts as follows:

If the range of the ALU is passed (at about 15.360 LSBs) a constant offset of 30.720 LSB is substracted. Besides this offset the result is correct. The way to double the range is easy now. A necessary condition is that one has to know the order of the signals. The correct result must not be negative.

When negative results are read out, these have to be added 30.720 LSB. The value range now is extended to 30.720 LSB which is about 7.8 µs (typ.). The **Range** is extended to **1200m**.

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3

Using the overflow flag (Statusregister 1, Bit 6) the range can be extended to the triple. The interpretation of the data is much more complicated. Please contact acam for details.

f) Laserscanner

Time-to-Digital Converters used in laserscanners have to fullfill highest requirements. The scanning principle demands high measurement rates. In consequence every scanned point can not be measured with high sampling rates. So the TDC should offer high single shot resolution.

The high sampling rate is no problem at all for our fully integrated TDC's. A perfect solution is the new F1 with a sampling rate of $14 \times 10^6/s$. An area of 3500*4000 scan points could be measured in only one second.

And also the single-shot resolution - typ. 75ps $\equiv$ 11mm in high resolution mode - makes the F1 suitable to most industrial applications.

g) Multiple reflections - Improvement of the double pulse resolution

In practice, especially in the field, the laser pulse will find several reflection planes. The detector will output a series of pulses in any time distance.

Maybe the performance of the GP1 will not be good enough for such a system. Only 3 or 4 multihits are allowed and the double pulse resolution is typ. 15ns. With an extended circuit this problem can be solved perfectly as shown in figure 3.

The circuit can be simplyfied enormously by introducing the new F1, an 8.-channel TDC with Pseudo-ECL inputs. Four TDC-GP1 , the ECL/TTL and TTL/CMOS-converter can be replaced by only one chip in th compact PQFP160 package.

The principle behind this circuit is to take a shift-register and distribute the stop-signals to four GP1. The double pulse resolution will be reduced to 4ns (min. 15ns between 1st and 5th hit). It can be reduced even more by increasing the number of used TDC's.

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4