Accurate time interval measurement electronics for pulsed time of flight laser radar

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***Abstract*-A time-to-digital converter for pulsed time-of-flight laser radar devices has been developed and six units have been constructed and tested thoroughly. The time interval between the start and stop pulses is digitized coarsely by counting the 100 MHz clock oscillator pulses. The +/-10 ns uncertainty is improved to +/-10 ps by means of an analogue interpolation method based on the discharge of a known capacitance by a constant current.**

The TDC is very stable due to the symmetrical construction of the interpolation unit, which cancels out the drifts of the two time-to-amplitude converters. The measured drift of all six TDCs is less than +/- 10 ps in a temperature range of –10°C - +50°C, and some units have even zero drift. The single-shot precision of a TDC is between 6 and 12 ps, and can be improved by averaging successive single-shot measurement results, and about 70 fs precision can be obtained if about 65000 results are averaged. The linearity of the TDC is better than +/-20 ps in a measurement range of 0 – 1.3 μs.

I. INTRODUCTION

The time interval measurement electronics form the heart of a laser device placing limitation on its ultimate performance in terms of precision, linearity and stability. The time interval between two pulses, a start pulse and a stop pulse, can be measured analogically, digitally or an interpolating method. The analogue method is usually based on measurement of the voltage change in a capacitor which is (dis)charged by a constant current over the time interval. The precision of the analogue method is excellent, but it suffers from poor stability and linearity, and thus its measurement range is usually short, no more than a hundred nanoseconds. The digital method is based on counting the clock cycles of a reference oscillator. It is linear over a wide measurement range, but its precision is limited by the uncertainty attached to the +/- 1 clock cycle. This can be improved by averaging, but mm-class precision is not realistic in fast laser radar systems used for profiling purposes.

A suitable way to construct the time interval measurement electronics is to use a synchronous digital method in which the clock cycle uncertainty is improved by an interpolation method of some kind, e.g. the, Vernier, delay line or Nutt methods [1] – [10].

This paper describes a time-to-digital converter (TDC) based on the digital time interval measurement principle, in which an analogue interpolation method for the above purpose. The digital method allows a large linear measurement range and the analogue time interval method gives excellent precision over the short range. All the digital parts are integrated into an ECL-ASIC circuit, which reduces the size and power consumption of the electronics. The construction of the TDC and the performance of six tested items are briefly described below.

II. CONSTRUCTION OF THE ELECTRONICS

The operating principle and block diagram of the TDC are shown in Fig. 1. It consists of an external 100 MHz crystal-based oscillator, a start-stop logic (SSL), an 8 bit counter and an analogue interpolator unit. All the digital parts except the oscillator are integrated into the ECL-ASIC circuit. Construction of the digital part needs 450 gates and, 11 ECL-level and 17 TTL-level I/O cells.

The SSL divides the time interval between the start and stop pulses into three parts T1, T12 and T2, where T1 is the time interval from the rising edge of the start pulse to that of the next clock pulse but one and T2 is correspondingly the time interval from the rising edge of the stop pulse to that of the next clock pulse but one. The measured time interval T can be obtained from the Equation

$$T = T1 + T12 - T2 \qquad (1)$$

The 8-bit counter can accurately digitize the length of the time interval T12, which is synchronized with the reference oscillator. The analogue interpolator unit (AIU) measures accurately the length of the time fractions T1 and T2, which varies randomly between 10 and 20 ns, provided that the arrival of the start-stop pulse pair is random with respect to the 100 MHz oscillator.

The AIU consists of two identical time-to-amplitude converters (TAC) and two 10-bit analogue-to-digital converters. The operation of the TACs is based on measurement of the voltage change in a capacitor when discharged by a constant current during the time T1 or T2 [11]. The output voltage range of the TACs is adjusted in such a way that the 10 ns time change in T1 or T2 does not correspond to the full scale change from 0 to 1023 in the A/D conversion. Instead the TACs are adjusted so that the digital output words (N1 and N2) vary between 31 and 980, for example, which causes the distribution width (DW) to be 950, i.e. 950 channels contain data. One bin or channel thus corresponds to 10 ns/950 = 10.53 ps. This adjustment ensures that when the outputs of both TACs drift due to temperature changes, for example, the output voltages of the TACs remain inside the input voltage range of the A/D converters,

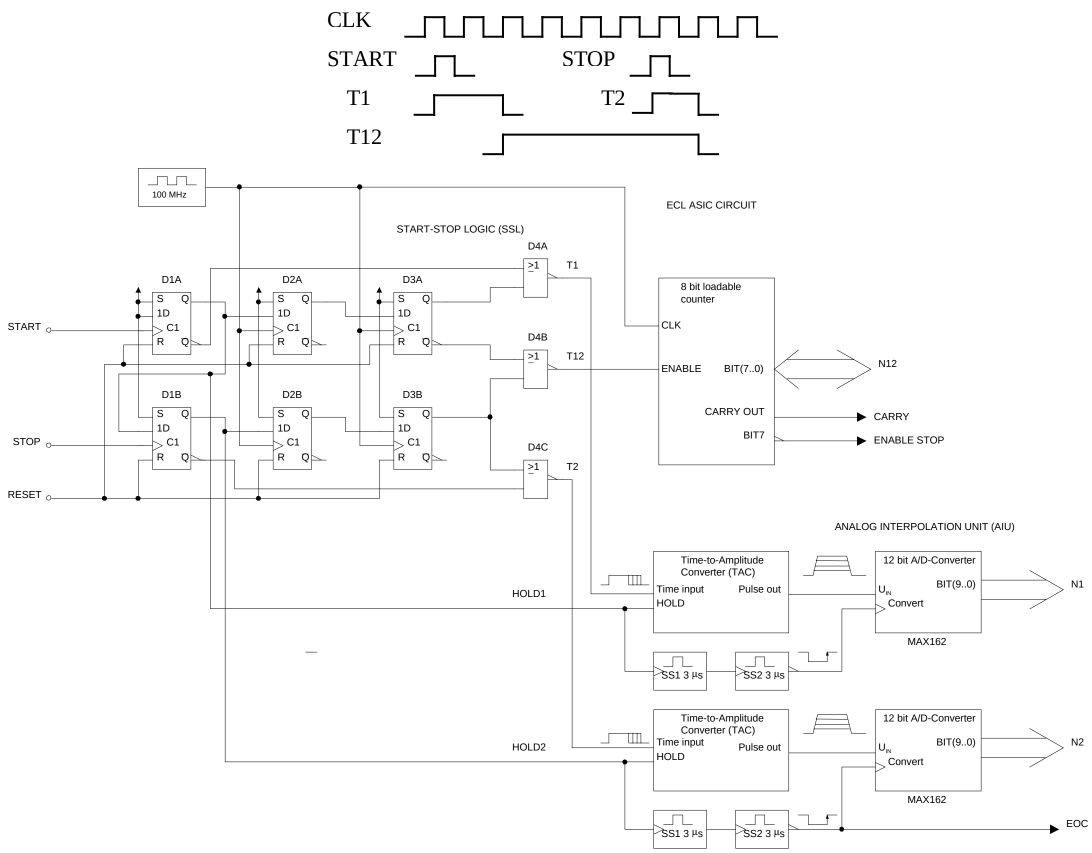

Fig. 1. Operating principle and construction of the TDC.

which is essential for obtaining good stability. The identical construction and common reference voltages of the TACs leads to approximately identical temperature drift, and because the difference between T1 and T2 is calculated in the final result, the drifts cancel each other out.

The output of the TACs contains non-linearities, which detract from single-shot precision and accuracy, but these can be improved by averaging successive measurements. The outcome is better the more results are averaged, because eventually the whole time ranges of both TACs come to be included, and this converts the TAC non-linearities to an offset –type constant error which is independent of the time interval T and can be easily compensated for.

When the A/D conversion in the TAC2 is finished, and end of conversion (EOC) signal is sent to the system controller. A PC, µ-processor or hardware controller reads three bytes N1, N2 and N12 from TAC1, TAC2 and the 8-bit counter, respectively, and calculates the final single-shot result according to the Equation

$$T = 10\,ns \cdot N12 + \frac{10\,ns}{DW} \cdot (N1 - N2) = \frac{10\,ns}{DW} \cdot (DW \cdot N12 + N1 - N2) \qquad (2)$$

The measurement time of the TAC consists of the settling time of the amplifiers and the conversion time of the A/D converter. The total dead time is less than 10 µs, which leads to a maximum measurement frequency of about 100 kHz.

TABLE I
MEASURED PRECISIONS THE OF SIX TDCS (δ-VALUE IN PS)

	Number of averaged measurements				
Unit	1	16	256	4096	65536
TDC#1	6.72	1.53	0.41	0.14	0.06
TDC#2	7.87	1.93	0.45	0.15	0.07
TDC#3	9.47	2.01	0.55	0.16	0.08
TDC#4	7.67	1.64	0.39	0.13	0.06
TDC#5	12.00	2.76	0.73	0.20	0.07
TDC#6	10.20	2.03	0.53	0.15	0.07

The measurement range of the TDC is 2.56 µs, due to the 8-bit counter, but it can be extended by adding external counters.

All the electronics are constructed on an E1- size (10 cm * 16 cm) printed circuit board see the photograph of the TDC in Fig. 2. Power consumption is about 8.4 W.

III. PERFORMANCE

A. Precision of the TDC

The single-shot precision of the TDC with ideal TACs should be a maximum of 5 ps (δ-value). The non-linearities of the TACs reduce this precision, however, so that it is within the range 6.7 ps – 12 ps for all six units tested here, as

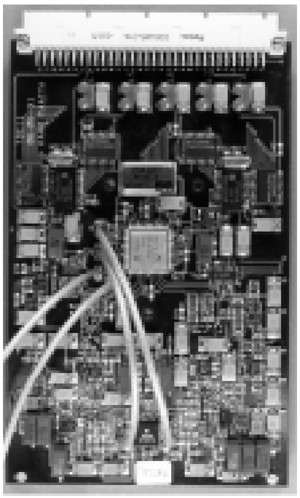

Fig. 2. Photograph of a TDC.

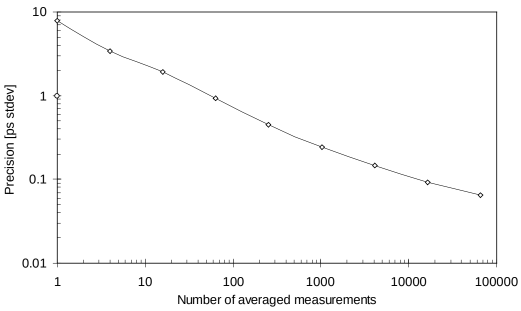

Fig. 3. Precision of TDC#2 as a function of the number of averaged measurement results.

summarised in Table I. The single-shot precision shows minor variation within the 10 ns interpolation time. The precision does not deteriorate as the time interval T increases, as was ascertained by measuring the precision using a 100 km optical fibre delay and a TDC with an added external digital counter.

The precision can be improved by averaging successive measurement results (see typical case in Fig. 3). The improvement takes place according to the inverse square root –rule up to 1000 measurements, after which stability problems in the measurement setup slightly reduce the effectiveness of averaging. A precision of about 70 fs can be achieved when about 65000 single-shot measurements are averaged.

B. Linearity of the TDC

The linearity of the TDC was measured using two pulse generators, a start pulse generator triggered by a white noise source and a stop pulse generator with a fixed frequency of 600 kHz. The time interval distribution in this case is as much as from 0 to 1/600 kHz = 1.67 μs [12]. The measured linearity of TDC#2 is shown in Fig. 4.

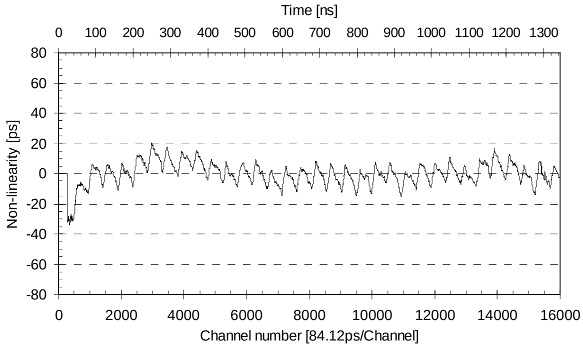

Fig. 4 Non-linearity of TDC#2.

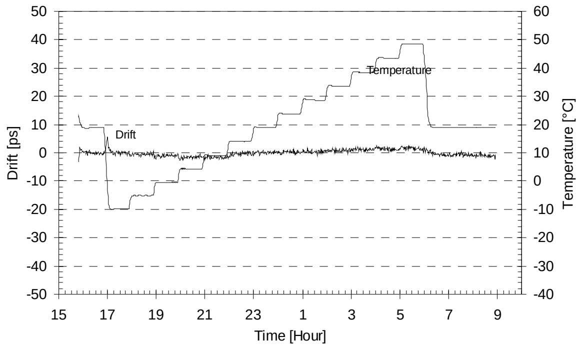

Fig. 5. Temperature drift of TDC#2.

TABLE II
TEMPERATURE STABILITY OF THE TDCS AT AMBIENT TEMPERATURES VARYING FROM -10°C TO +50°C

Unit	Drift
TDC#1	+/- 6 ps
TDC#2	+/- 4 ps
TDC#3	+/- 4 ps
TDC#4	+/- 6 ps
TDC#5	+/- 10 ps
TDC#6	+/- 7 ps

The TDC has a periodic non-linearity, the amplitude and period being about 20 ps and 40 ns, respectively. The reason for this lies in the ASIC circuit, although its specific origin is unknown at the moment. The non-linearity has a local minimum when the two least significant bits (lsbs) of the counter are 00, and a local maximum when the lsbs are 01. The other 5 TDCs have periodic non-linearity of same kind and magnitude.

C. Stability of the TDC

The stability of a TDC is measured with respect to time and ambient temperature. The drift of TDC#2 with respect to changes in ambient temperature between –10°C and +50° C is shown in Fig 5.

Although the measured drift of each TACs in the above temperature range is about 210 ps, the overall effect is almost

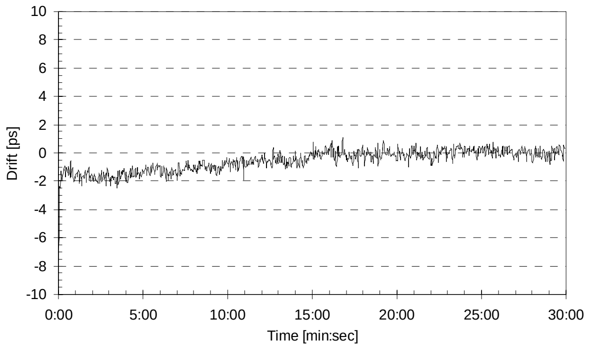

Fig. 6. Stability of TDC#2 after switching the power on.

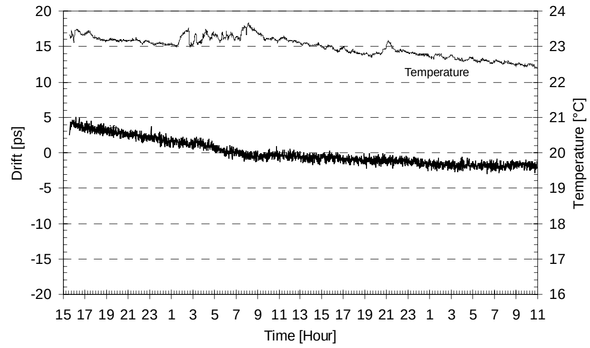

Fig. 7 Long term stability of TDC#2.

TABLE III
STABILIZATION TIMES OF THE TDCS AFTER POWER ON

Unit	To +/- 3 ps	To +/- 1 ps
TDC#1	0	5 min
TDC#2	0	0
TDC#3	0	6 min
TDC#4	4 min	15 min
TDC#5	0	0
TDC#6	0	11 min

zero. The reason for this drift is the fact that the TACs are of identical construction, which leads to cancellation of the drifts due to the subtraction operation N1 – N2 that is performed when the final result is calculated. A summary of the stabilities of all six TDCs is presented in Table II. All of them have a small temperature drift, within +/- 10 ps/60°C.

A TDC is stable directly after power on as seen in the example in Fig. 6. The maximum measured drift of the other five TDCs after power on is +7 ps, as shown in Table III, but they all stabilize after 15 min.

The long-time stability of TDC#2 is shown in Fig. 7. The TDC drifted about 8 ps during two days of measurement on account of the temperature dependence of the measurement setup. The delay in the 155 ns coaxial cable varied during measurement as the temperature of the laboratory altered by about 1°C.

IV. CONCLUSIONS

A time-to-digital converter has been developed and six examples of it have been tested thoroughly. The TDC consists of an integrated digital counter with a 10 ns uncertainty, which can be improved to 10 ps by means of an analogue interpolation method. The TDC has excellent stability with respect to ambient temperature changes, due to the identical construction of its time-to-amplitude converters, so that their large temperature drifts cancel each other out.

The linearity of the TDC is not as good as expected, because it suffers from a 40 ns periodic non-linearity of amplitude 20 ps. The origin of this non-linearity lies inside the ASIC circuit, which contains all the digital parts of the electronics except for the reference oscillator.

The size of the TDC is 10 cm * 16 cm and its power consumption is about 8.4 W. The interpolation unit is constructed of surface-mounted components, but integration is in progress. The next, totally integrated version of the TDC will probably be available in the near future.

V. REFERENCES

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