Chapter 1

Time Interval Measurement Literature Review

The transmitted pulses from the level measurement instrument are electromagnetic waves and are travelling at close to the speed of light. Since these pulses only have to travel a very short distance to the target medium (a maximum of 20m there and back), the time interval (TI) between the transmitted pulse and the received echo(s) is very short. Accurate TI measurement is therefore a crucial part of the pulse radar system.

The user requirements specified that the instrument should be accurate to 0.2% of the full scale distance, which in this case is 10 m. This gives us a required accuracy of 2 mm. The resolution also needs to be very high at 2 mm. In the time-domain this corresponds to a resolution of about 10 ps. This means that we need to be able to measure TI's very precisely and resolve them accurately to 10 ps.

1.1 Introduction

TI measurement is the measurement of the elapsed time between some designated START and STOP phenomena [4]. In the case of the pulsed radar system these phenomena are the transmitted pulse and the received echo. Detectors are used to detect the presence of these pulses and a time discriminator is used to extract the timing information from the pulses relative to these events and delivers a pulse of standard amplitude or width or both to the timing circuit [17]. In other words the time discriminator defines the points on the time-axis between which the TI is measured. The START and STOP inputs can either be separate or on a single common input. The input pulses cannot have infinite rise-time so the timing usually occurs when the pulse crosses a certain threshold [14].

A time-interval metre (TIM), time-to-digital converter (TDC) or Time counter (TC) then converts the measured interval into a digital value, which can then be displayed in a decimal form.

A one shot measurement is the TI between a single transmitted and echo pulse. The resolution of the one shot measurement is therefore limited by the resolution of the analogue system or the least-significant-bit (LSB) of a digital system. The resolution can be improved upon by TI averaging in analogue systems and by interpolation in digital systems.

TI averaging assumes that the factors limiting the resolution in the analogue system are random and that multiple constant measurements would let the random factors tend to zero thereby increasing the resolution.

The process of interpolation involves calculating estimate values between the discreet time data and obtaining a better resolution limited only by the noise [4].

The important specifications to consider in time interval measurement and for time interval metres are: [14, 4]

- 1. Minimum interval The minimum time between consecutive pulses.
- 2. Minimum dead-time The minimum time between the stop pulse and the next start pulse.
- 3. Minimum pulse width The shortest pulse the TIM will recognise
- 4. Measurement range The longest possible time the instrument can measure
- 5. Non-linearity of the conversion process
- 6. Quantisation step or LSB
- 7. Readout speed How fast the instrument can produce a result

This section will describe various techniques and methods of achieving precise and accurate TI measurement with specific reference to the pulse radar level measurement instrument.

The techniques which will be described are:

- 1. Time-stretching followed by a counter
- 2. Time-to-voltage conversion followed by analogue-to-digital conversion
- 3. The Vernier Method
- 4. Time-to-digital conversion using tapped delay lines.
- 5. Direct on-chip time-to-digital conversion

Comparisons will then be made between analogue and digital techniques and the concepts of averaging and interpolation will also be discussed.

1.2 Time-stretching followed the by counter method

There are two time-stretching methods that have been investigated. The first method is a special sampling technique that is used by Vega Instruments described in [2, 16] and a technique involving the charging and discharging of a capacitor [14, 17].

1.2.1 Vega Sampling Technique

This method involves two pulse trains. The first pulse train contains the transmitted signal with a certain pulse repetition interval (PRI) = T1. The second pulse train is a reference or sampling signal and has a slightly longer PRI = T2.

The pulses are Gaussian in shape and are 1 ns in length as can be seen in Figure 1.1. Matlab was used to simulate the time expansion.



Figure 1.1: A Single Gaussian Pulse of 1 ns in Length



Figure 1.2: Transmitted train of Gaussian Shaped Pulses

Figure 1.2 shows the pulse train of Gaussians for the transmitted pulse and figure 1.3 shows the pulse train of Gaussians for the reference pulse plotted on the same set of axes as the transmitted pulse train.



Figure 1.3: The Transmitted Signal and the Reference Signal

Note that since the red reference signal has a longer PRF, that it starts to overlap the blue transmitted signal more and more.

The next step requires taking each point on the transmitted signal (blue) and multiplying it point-for-point with the reference signal (red). This is done by using a double-diode mixer. Points that do not overlap yield a zero result and the overlapping points plot out the curve seen in figure 1.4.

The time-expansion factor is given by the formula 1.1:

$$K = \frac{T_1}{T_2 - T_1} \tag{1.1}$$

The result is an intermediate frequency. It must be noted, therefore, that the closer the PRI of the reference signal is to the PRI of the transmitted signal, the longer the time expansion will be.

The signal in figure 1.4 is then passed through an integrator, which takes the integral of each individual "spike" (as seen in the green borders). The result is then a time-stretched version of the original pulse train as seen in figures 1.5 and 1.6.



Figure 1.4: The point-for-point multiplication of the transmitted signal and the reference signal



Figure 1.5: The output after integration



Figure 1.6: The extended output signal after the integrator

1.2.2 Charging and Discharging a Capacitor

As can be seen in figure 1.7, this method involves taking a capacitor and charging it with a constant current during the time measurement interval (T) and then discharging it with a much smaller current. The capacitor, therefore, charges up quickly but discharges slowly.

At the START instant, the current $[I_2 - I_1]$ charges up the capacitor in time T. At the STOP instant, the diode (D) conducts the current I_2 to ground and discharges the capacitor in time T_r where $I_2 \ll I_1$. This is shown in figure 1.8. Therefore, the total measured time is $[T + T_r]$.



Figure 1.7: Simplified circuit for time stretching by charging and discharging a capacitor.



Figure 1.8: Plot of the voltage across the capacitor (C) versus time

The expansion factor is given by the formula 1.2

$$K = \frac{I_1 - I_2}{I_2} \tag{1.2}$$

Therefore, the discharging time is stretched to $T_r = K \cdot T$

The total time $T_{tot} = (K+1) \cdot T$ can then be measured from output A by using a counter. The effective LSB of the counter will then be $LSB = \frac{T_0}{(K+1)}$

This method is able to achieve a very good resolution (< 10 ps), however, the disadvantage is the long conversion time. The main sources of error are from non-linearities and quantisation error in the conversion. Averaging can be used to improve the single shot results.

Many modifications have been made to this method to improve its dynamic range and dead-time using single and multiple interpolator circuits in combination with the time-stretching circuit. Auto-calibration and error reduction techniques have also been developed. These modifications have been discussed in several publications [9, 10, 11, 7, 21, 22, 23, 24].

1.3 Time-to-Voltage Conversion Followed by Analogueto-Digital Conversion

The method of dual-conversion is used in many time interval measurement instruments. This method is described by [14, 15, 17, 18] and [20].

The time interval is first converted into a voltage and then the voltage is converted

into a digital value. This is done by charging a capacitor with a constant current during the TI (T), holding the value (Vc) and then performing an analogue-to-digital conversion on the capacitor's voltage. A simplified circuit is shown in figure 1.9.

The charging begins at the START instant and ends at the STOP instant. The resulting voltage is then proportional to the elapsed time period as given by formula 1.3, if the charging is linear [20, Section II].

$$V_c = \frac{I}{C} \cdot T \tag{1.3}$$

The analogue-to-digital conversion takes a finite time which must be accounted for. After the conversion is completed the capacitor is rapidly discharged and the process can then be repeated. This is illustrated in figure 1.10. A more detailed circuit is shown in [15, Section II C]

The process is similar to the pulse stretching technique described in section 1.2.2, however, a counter is not used and the value of the voltage is read directly by the ADC.



Figure 1.9: A simplified circuit for TI measurement using dual-conversion



Figure 1.10: Plot of the voltage across the capacitor versus time.

This method also allows for high resolutions to be achieved. The resolution as well as the speed is limited mainly by the ADC. Dead-time can be reduced by increasing the discharge rate of the capacitor.

This type of time interval measurement is also know as "start-stop". A slight modification to the system whereby the capacitor only charges if a stop instant is detected within the time window, prevents the system from charging up unnecessarily and decreases dead-time. This type of system is know as "start-ready-stop" (SRS).

Modified versions of this concept can also be found in publications [12, 13].

1.4 The Vernier Method

The time interval measurement techniques mentioned in sections 1.2 and 1.3 have used analogue circuits. The Vernier method is a digital technique and is described in [1, 14, 17]. It follows a similar approach to the Vega time stretching technique mentioned in section 1.2.1 and is a method of digital time stretching.



Figure 1.11: Block diagram of the Vernier method

As can be seen in figure 1.11, the Vernier method uses two startable oscillators with different frequencies $f_1 = \frac{1}{T_1}$ and $f_2 = \frac{1}{T_2}$. f_1 and f_2 differ only by a small amount. The resolution is therefore $r = T_1 - T_2$. The startable oscillators are triggered by the START and STOP instances respectively. As can be seen in figure 1.12, if one make the period T2 shorter than the period T1, the number of periods in the stop channel will gradually catch up to the start channel. When the stop channel has caught up with the start channel and the two oscillators are in phase, the coincidence circuit is triggered which stops the counters and switches off both oscillators. The oscillators are then disabled. The numbers stored in the counters, n_1 and n_2 , are then used to calculate the the time interval according to equation 1.4.

$$T = (n_1 - 1) \cdot T_1 - (n_2 - 1) \cdot T_2 \tag{1.4}$$



Figure 1.12: Diagram showing the signals of the Vernier method

Accuracy and resolution using the Vernier method can be very high if the startable oscillators are stable and if the difference in frequency between them is small. Careful shielding is required to prevent the two oscillators from locking onto one another and having identical periods. The maximum conversion time for this method is given by the formula $CT = \frac{T_1 \cdot T_2}{r}$.

1.5 Time-to-digital Conversion Using Tapped Delay Lines

The tapped delay line is made up of a series of delay cells with have the same propagation delay (τ). The time interval is measured by sampling the state of the delay line while the pulse propagates through it during the time between the START and STOP instances [8].

There are several configurations that are used. These have been described in [14].

The first configuration uses a series of latches as seen in figure 1.13. Each latch ideally has a propagation delay τ_l . The edge of the START pulse propagates through the latches until the STOP pulse stops the propagation. The state at the output is then sampled and the total time interval can be calculated by taking the sum of the propagation times of all the latches have been set to a high state or $(k \cdot \tau_l)$, where k is the highest position of the latch storing a high state.



Figure 1.13: A tapped delay line using latches

A series of buffers can also be used to create a delay line. Each of the buffers should ideally have the same delay τ_{b1} . As can be seen in figure 1.14, the START pulse propagates through the delay buffers and enables each of the flip-flops. The STOP pulse then clocks the flip-flops and the output is sampled. Each of the flip-flops that was enabled by the propagating pulse shows a high state. Once again the time interval can be determined from the flip-flop in the highest position with a high state.



Figure 1.14: A tapped delay line using buffers and with simultaneous sampling

The next configuration interchanges the inputs of the clock (>) and data (D) as seen in figure 1.15. This circuit monitors the input of the STOP pulse. The START pulse propagates through the buffers and samples the state of the stop pulse. When the STOP pulse is present, the nearest flip-flop changes its state from low to high. The time interval is then determined from the flip-flop in the lowest position with a high state.



Figure 1.15: A tapped delay line using buffers and sampling the stop input

These delay line techniques are a direct time-to-digital conversion. The conversion process is very fast. The dead-time in the circuit is equal to the time it takes to reset all the flip-flops. If the flip-flops are all reset in parallel then the dead-time becomes very short. The measuring range is proportional to the number of latches and/or buffers in the delay line.

This technique is able to achieve a good resolution, which can be improved by using

two delay lines with slightly different delays. This is known as a *differential delay* line [3, 5, 6].

This method is usually implemented in CMOS, bipolar ECL or GaAs technology. CMOS is the most common due to its low power and manufacturing cost [8].

1.6 Direction On-Chip Time-to-Digital Conversion

Many of the methods mentioned in this study have been implemented on chips. This gives the advantage of lower power consumption and compactness. However, designing circuits for on-chip manufacturing can be expensive and time consuming, especially when in small volumes and when there is trial and error involved.

This section, therefore, investigates commercially available TDC chips. Which could be used to measure the short time intervals we expect in the radar level measurement instrument.

There was only one manufacturer of time-to-digital converter chips that could be found at the time that this document was compiled. ACAM Messelectronic have been researching time interval measurement in the picoseconde range since 1996. They have several time-to-digital converter chips on offer with the option of custom chips as well.

| Model | Resolution | Range |
|---------|--------------------|---------------------------------------|
| TDC-GP1 | 125 ps | 2 ns - 7.6 $\mu {\rm s}$ |
| TDC-GP2 | $50 \mathrm{\ ps}$ | $3.5 \text{ ns} - 1.8 \ \mu \text{s}$ |
| TDC-F1 | $70 \mathrm{\ ps}$ | 0 ns - 3.9 μs |
| TDC-GPX | 81 ps (I-mode) | Endless |
| " | 41 ps (G-mode) | $0~{ m ns}$ - $>10~\mu{ m s}$ |
| " | 27 ps (R-mode) | $0~{ m ns}$ - $>10~\mu{ m s}$ |
| " | 10 ps (M-mode) | $0~{ m ns}$ - $>10~\mu{ m s}$ |

Table 1.1: Types of time-to-digital converter chips available

1.7 Analogue vs Digital Techniques

Digital methods offer good linearity over a wide dynamic range. This means that the measurements are stable over a long time interval. However, the single shot resolution is limited to the frequency of the clock oscillator being $\pm LSB$. Higher resolutions are possible with higher clock rates but this requires higher power and is difficult to implement [19]. Analogue methods are able to achieve higher resolutions than digital ones, however, the standard uncertainty is not so good [14]. Analogue methods use simple low cost technology, which is an advantage. On the downside, analogue circuits suffer from temperature sensitivity, time drift and are more prone to external disturbances. This needs to be corrected by performing calibrations. Analogue methods are also more difficult to implement in integrated circuit technology.

In order to obtain the advantages of both methods, a combination can be used. This is discussed in section 1.9.

1.8 The Effects of Averaging

Averaging can be used to improve the single-shot resolution error of $\pm LSB$ when the time interval is repetitive and has a repetition frequency that is asynchronous to the instrument's clock. In other words, the start and stop instances must be random with respect to the clock.

It can be shown that the improvement in resolution is related to the number of time intervals averaged by equation 1.5.[4]

$$Resolution = \frac{\pm LSB}{\sqrt{N}} \tag{1.5}$$

Therefore, for an improvement factor of 100, e.g. 100 ps from 10 ns, N must be equal to 10000.

The resolution is ultimately limited by the noise in the system. The main problem with time interval averaging is the long time it takes to make a reading which can be inconvenient

In analogue systems the things limiting linearity and stability are also usually random in nature. Averaging several results leads to these phenomena tending to zero which will give better results.

1.9 Interpolation Methods

Interpolation methods are used when a long measurement range and high resolution is required for time interval measurement. Interpolation methods make use of the advantages from both analogue and digital techniques. The long measurement range is provided by a digital counter driven by a clock with $LSB = T_0$. The counter will remain stable over the measured time interval, provided that the clock signal is stable. The high resolution is provided by the interpolator which measures the fractional part between each clock pulse.

When interpolation is used, the time interval is divided into three intervals. This is achieved by means of a circuit like the one in figure 1.16. The resulting time fragments are then called T1, T12 and T2.

As can be seen in figure 1.17, T12 is divisible by T_0 and is therefore measured by the counter. The two shorter intervals are measured by one or more fine time-to-digital converters. The time-to-digital converter can utilise any of the methods mentioned in the previous sections 1.2.2,1.3,1.4 and 1.5 in order to achieve the high resolution. Since the time interval for the fine time-to-digital converters is often less than $2T_0$, the circuit does not contribute much instability which is usually associated with analogue circuits.

If the interpolation is performed in two succeeding steps, it is referred to as single interpolator. If the interpolation is done at the beginning and at the end by two separate but identical interpolators, it is called a dual-interpolator.



Figure 1.16: Flip-flop circuit to generate T1, T12 and T2



Figure 1.17: A logic diagram for the outputs of the flip-flop circuit

1.10 Conclusion

Several techniques have been investigated that are able to achieve the fast time timing and accuracy that we need for the radar level measurement instrument.

Both analogue and digital techniques were investigated and their likely performaces were noted. Analogue methods seem to be able to achieve higher resolutions but their long term stability is a problem. Digital methods showed good stability and fast conversion times. Interpolation methods could be implemented to combine the advantages both analogue and digital techniques.

Digital techniques seem to be preferred over the analogue techniques due to their better stability and linearity over the whole measurement range. Although analogue techniques are able to provide good resolutions, the digital options that are now available can be used in combination with averaging, channel splitting and parallelism to achieve the same resolutions with reduced complexity.

Bibliography

- [1] R G Baron. The vernier time-measuring technique. *Proceedings of the IRE*, pp: 21–30, 1957.
- [2] Peter Devine. Radar Level Measurement The Users guide. Vega Controls Ltd., 2000.
- [3] J F Genat and F Rossel. Ultra high-speed time-to-digital converter. French Patent 84 07344 US Patent 4 719 608, Priority 1984, 1984.
- [4] Hewlett-Packard. Hewlett-Packard Application Note: 200-3 The Fundementals of Time Interval Measurement. Hewlett-Parkard Company, 1997.
- [5] D R Hoppe. Differential time interpolator. US Patent 4,433,919, Priority: 7, September 1982.
- [6] D R Hoppe. Time interpolator. US Patent 4,439,046, September 1982.
- [7] Jiun-Lang Huang and Kwang-Ting Cheng. An on-chip short-time interval measurement technique for testing high-speed communication links. 19th IEEE Proceedings on VLSI Test Symposium, 1:380–385, 2001.
- [8] J Kalisz, R Szplet, J Pasierbinski, and A Poniecki. Field-programmable-gatearray-based time-to-digital converter with 200 ps resolution. *IEEE Transactions* on Instrumentation and Measurement, 46:51–55, 1997.
- [9] Josef Kalisz, M Pawlowski, and R Pelka. A method for autocalibration of the interpolation time interval digitiser with picosecond resolution. Journal of Physics. E: Scientific Intrumentation, 18:444–452, 1985.
- [10] Josef Kalisz, M Pawlowski, and R Pelka. A multiple-interpolation method for fast and precise time digitizing. *IEEE Transactions on Instrumentation and Measurement*, 35:163–169, 1986.
- [11] Josef Kalisz, M Pawlowski, and R Pelka. Error analysis and design of the nutt time-interval digitiser with picosecond resolution. Journal of Physics. E: Scientific Intrumentation, 20:1330–1341, 1987.

- [12] Josef Kalisz, M Pawlowski, and R Pelka. Improved time-interval counting techniques for laser ranging systems. *IEEE Transactions on Instrumentation and Measurement*, 42:301–303, 1993.
- [13] Josef Kalisz, M Pawlowski, and R Pelka. Precision time counter for laser ranging satellites. *Review of Scientific Instruments*, 65:736–741, 1994.
- [14] Jozef Kalisz. Review of methods for time interval measurements with picosecond resolution. *Metrologia*, 41:17–32, 2004.
- [15] K Maatta and J Kostamovaara. High-precision time-to-digital converter for pulse time-of-flight laser radar applications. *IEEE Transactions on Instrumentation and Measurement*, 47:521–536, 1998.
- [16] Juergen Motzer. A puls radar gauge for level measurement and process control. Microwave Syposium Digest, 3:1563–1566, 2000.
- [17] D Porat. Review of subnanosecond time-interval measurements. IEEE Transactions on Nuclear Science, 20:35–51, 1973.
- [18] Elvi Raisanen-Ruotsalainen, Timo Rahkonen, and Juha Kostamovaara. Time interval measurements using time-to-voltage conversion with built-in dualslope a/d conversion. *IEEE International Symposium on Circuits and Systems*, 5: 2573–2576, 1991.
- [19] Branka Medved Rogina. Time interval measurement with application to electronic/optoelectronic circuits and systems. 10th Mediterranean Electrotechnical Conference, 2:738-741, 2000.
- [20] Andrew E. Stevens, Richard P. van Berga, Jan van der Spiegel, and Hugh H. Williams. A sub-nanosecond time-to-voltage converter and analog memory. *IEEE International Symposium on Circuits and Systems*, 1:268–271, 1989.
- [21] B Turko. A modular 125ps resolution time interval digitizer for 10 mhz stop burst rate and 33 ms range. *IEEE Transactions on Nuclear Science*, 26:737–745, 1979.
- [22] B Turko. Space borne event timer. IEEE Transactions on Nuclear Science, 27: 399-404, 1980.
- [23] J D Wielwald. A camac high resolution time interval meter. IEEE Transactions on Nuclear Science, 20:242–245, 1973.

[24] Tian Xia and Jien-Chung Lo. On-chip short-time interval measurement for high-speed signal timing characterization. 12th Asian Test Symposium, 1:326– 331, 2003.