APS011 APPLICATION NOTE

SOURCES OF ERROR IN DW1000 BASED TWO-WAY RANGING (TWR) SCHEMES

Version 1.2

This document is subject to change without notice

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1 INTRODUCTION

1.1 Overview

DecaWave's DW1000, a multi-channel transceiver based on Ultra Wideband radio communications, allows very accurate time-stamping of messages as they leave from and arrive at the transceiver.

This allows the construction of a number of different system topologies in the area of real time location systems and proximity measurement devices.

The simplest of such topologies is where two nodes communicate between themselves, exchange messages and based on transmit and receive timestamps of those messages they can calculate the round trip time of the signal between the two nodes and hence the time of flight and therefore the distance between the two nodes.

A complete description of DecaWave's two-way ranging protocol is described in other documents available from DecaWave. This Application Note focuses on the sources of error in the reported timestamps and what corrections / mitigation strategies the system designer can employ to report as accurate a result as possible.

1.2 About this document

This document deals with two fundamental sources of error: -

- Errors related to clock drift in the two nodes
- Errors related to incident signal level at a node

These are dealt with in individual sections.

Other application notes are available from DecaWave and you should contact your local representative or info@decawave.com for more information.

2 RANGING ACCURACY IN THE PRESENCE OF CLOCK DRIFT

2.1 Introduction

In the case of tag-to-anchor two-way ranging, there are a number of sources of error due to clock drift and frequency drift.

In order to have a robust ranging solution these errors either need to be eliminated or controlled. Some parameters in the ranging scheme can exacerbate the ranging error if not chosen correctly.

If we consider two ranging capable devices, device A and device B, each device has a DW1000 with a free running crystal oscillator and a microprocessor. We assume that each oscillator has a fixed frequency error e_A, e_B with respect to the nominal oscillator frequency.

The frequency errors or offset on each device will give rise to a clock drift relative to the nominal frequency as shown in Figure 1.

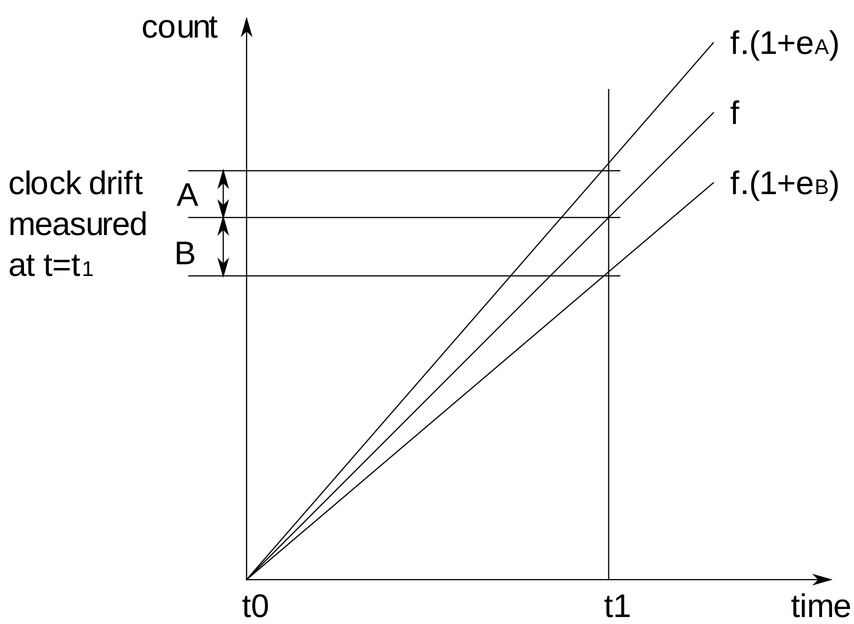

Figure 1: Clock drift due to frequency error in device A and device B

A frequency drift is when the frequency error on any device is not fixed, but changes over time.

2.2 DW1000 oscillator and quartz crystal

In a DW1000 based design the combination of a quartz crystal and the circuitry within the DW1000 is classified as a room temperature crystal oscillator (RTXO).

An example of an RTXO warm-up at oscillator turn-on is shown in Figure 2, taken from [3]. There are frequency jumps of +/- 0.5 ppm before the RTXO stabilizes.

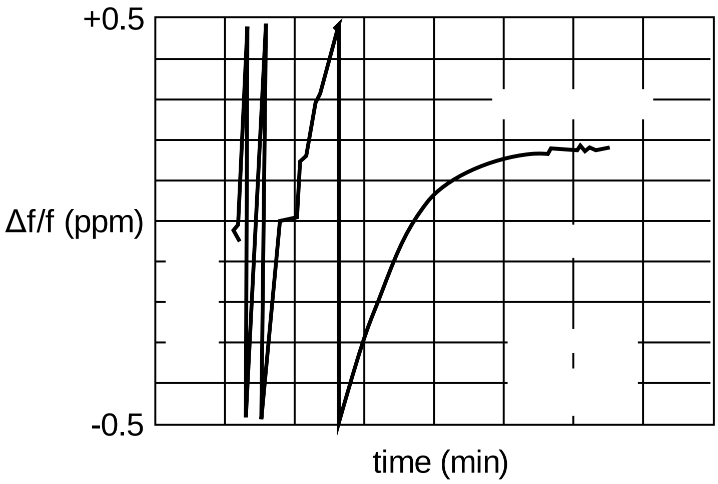

Figure 2: RTXO frequency change at turn-on

DecaWave's EVB1000 evaluation board, two of which are included in our EVK1000 evaluation kit, uses such an RTXO. Measurements of the frequency of the crystal oscillator on the EVB1000 were taken during crystal warm-up and are plotted in Figure 3. This shows a similar effect of frequency jumps before it reaches stability.

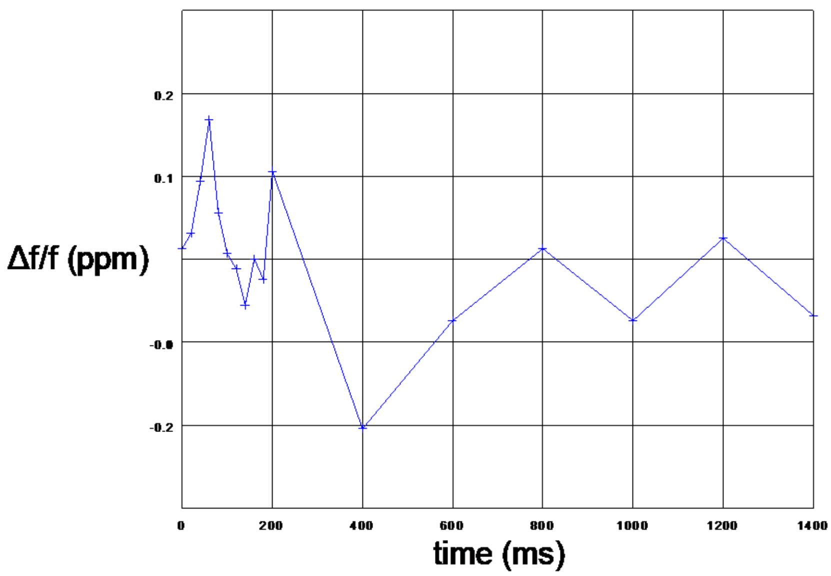

Figure 3: EVB1000 crystal oscillator start-up in the frequency domain.

2.3 Two-way ranging (TWR) with clock drift

Consider the ranging scheme shown in Figure 4; the start of the ranging transaction begins by device A sending a message to device B. Now device B waits a known amount of time and sends a response back to device A.

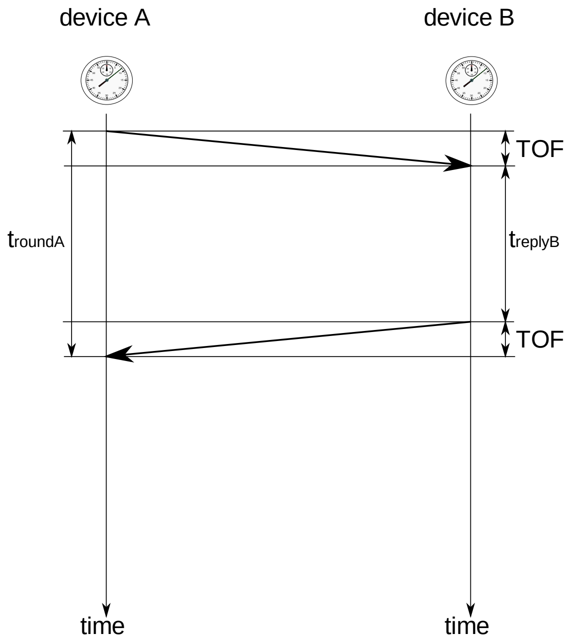

Figure 4: Two-way ranging scheme

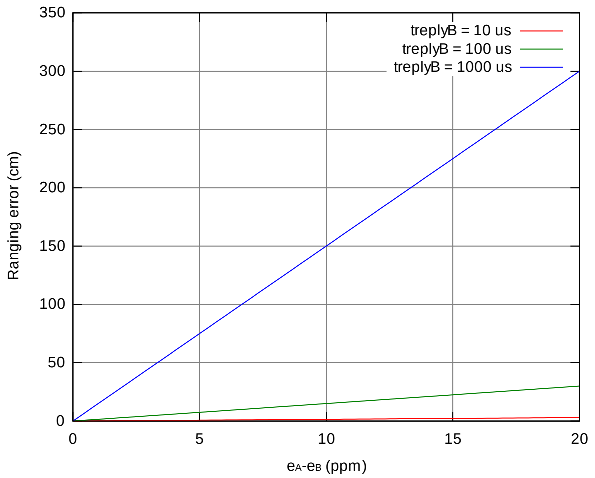

Figure 5: Ranging error in TWR scheme

The dominant error in the ranging accuracy of this scheme is given by,

$$Error = \frac{1}{2} t_{replyB} (e_A - e_B)$$

We can see that there is a strong dependence on t_{replyB} in this equation. A plot of this error is shown in Figure 5.

For practical values of t_{replyB} and frequency offset, the error in the accuracy of the range is large.

2.4 *Symmetric double-sided two-way ranging (SDS-TWR[4]) with clock drift*

The error in ranging accuracy in the simple two-way ranging scheme is large even with small frequency offsets. An alternative scheme to minimize the error by introducing another message in the ranging transaction is shown in Figure 6.

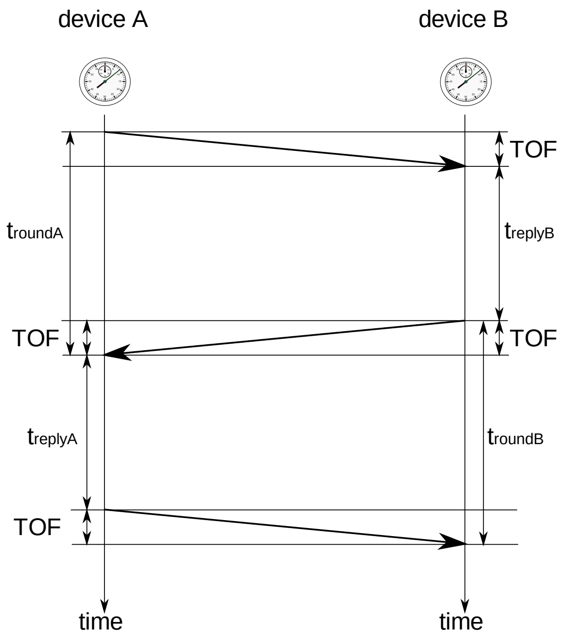

Figure 6: Symmetric two-way ranging scheme[4]

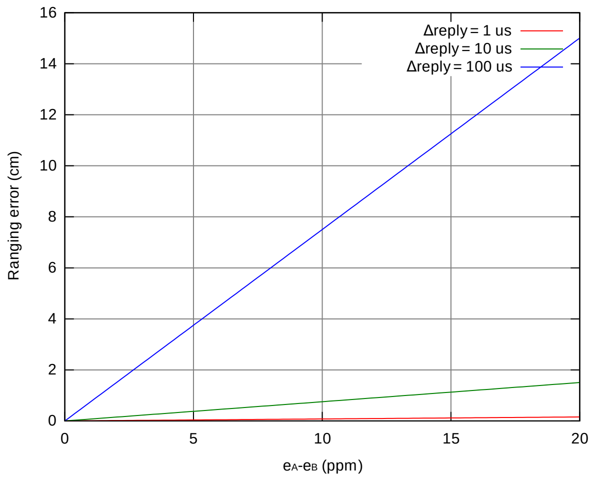

Figure 7: Ranging error in SDS-TWR scheme[4]

The dominant error in the ranging accuracy of this scheme is given by;

$$Error = \frac{1}{4}\Delta_{reply}(e_A - e_B)$$

Now we can see that the dependence on t_{replyB} has been eliminated, the error is now dependent upon Δ_{reply} , which is the difference between t_{replyA} andt_{replyB}. As a result, the error in the ranging accuracy is much smaller as plotted in Figure 7.

2.5 *Symmetric double-sided two-way ranging (SDS-TWR[4]) with frequency drift*

For lowest power operation, battery powered devices remain in the SLEEP mode with the crystal oscillator off, so to perform a ranging transaction, the device is switched on, the transaction is completed and the device is switched off again.

In this case the ranging transaction is performed while one of the devices is transitioning through the crystal warm-up phase. This means there is a frequency drift on one of the devices during the ranging transaction. The frequency error on device B remains constant.

We assume that the cumulative error of the frequency drift on device A can be approximated as two separate frequency errors, e_A, e_{AD} as shown in Figure 8.

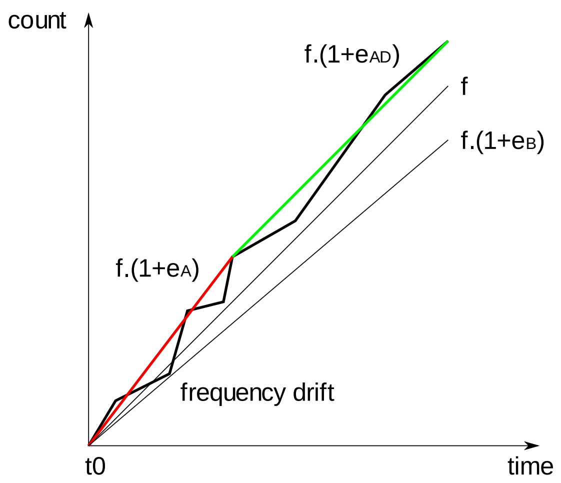

Figure 8: Frequency drift in device A during quartz crystal warm-up

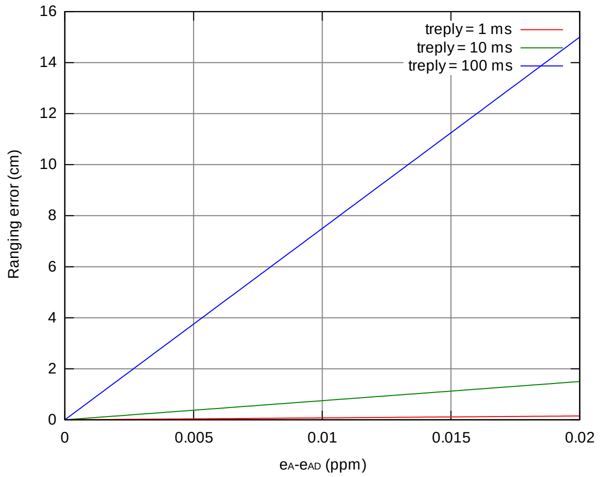

Figure 9: Ranging error of SDS-TWR[4] scheme with frequency drift in device A

The dominant error in the ranging accuracy with frequency drift is now given by: -

$$Error = \frac{1}{4} t_{replyA}(e_A - e_{AD})$$

Now due to the frequency drift, the error in the ranging accuracy is dependent upon t_{replyA}, this error is plotted in Figure 9.

The deceptive problem with this ranging error is that it will be slightly different on each oscillator start-up and from crystal to crystal. In essence this can be considered as a random frequency offset, therefore its effect needs to be minimized.

3 Ranging accuracy vs received signal level

3.1 Introduction

Ideally there should be no relationship between the reported timestamp of a received signal and the received signal level. In practice a bias which varies with received signal level (RSL) can be observed in the reported time-stamp compared with the correct value and this leads to a bias in the calculated time of flight based on those time-stamps. This is illustrated in Figure 10 below where the red line, labelled “Ideal” indicates the ideal result (constant) and the blue line, labelled “Actual” indicates the actual measured result (which varies with received signal level).

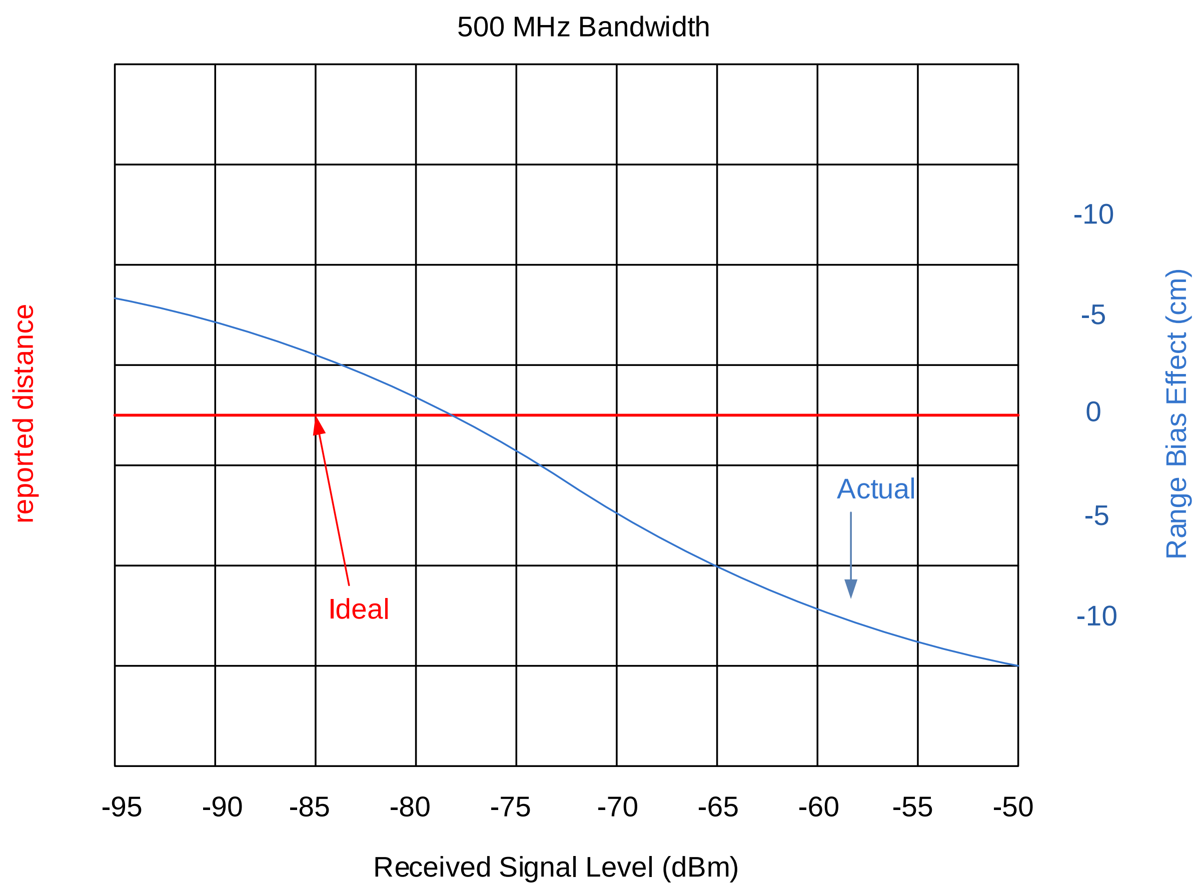

Figure 10: Diagram illustrating the effect of range bias on the reported distance

For most applications this bias can be ignored, however higher precision ranging applications must correct for this effect. This can be achieved in software by applying a correction factor.

3.2 DecaRanging Implementation

DecaRanging ARM-based source code, which includes DW1000 driver code, includes range bias adjustment software to allow for this effect. This allows DecaWave's EVK1000 two way ranging demonstration kit to achieve its target accuracy.

The DecaRanging ARM based source code takes a simple approach to compensating for this range bias effect. The reported range from the TWR operation is used as an index to a table of range adjustment figures which are used to adjust the reported range to allow for the effect. This adjusted figure is then reported as the result of the TWR operation. Table 1 gives a sample of such a table where the measured TWR distance is related to the correction factor for a given PRF. These tables can be investigated in the DecaRanging source code.

Table 1: Sample range bias correction table from DecaRanging TWR software for channel 2

Measured TWR distance (m)	Range Bias Correction Factor Applied For channel 2 (cm)	
	PRF 16 MHz	PRF 64 MHz
1.00	-21	-13
1.25	-20	-11
1.50	-19	-11
1.75	-19	-10
2.00	-18	-10

3.3 Design Specific Details

The description of the EVK1000's DecaRanging software above presents a simplified example of compensating for this range bias effect. This explanation describes getting the measured distance of the system and applying a correction factor to correct for the range bias effect, which is dependent on the measured distance.

However, the effect of range bias is actually dependant on received signal level (RSL) at the pins of the chip. This is affected by antenna gain, transmitted power and any other sources of loss or gain in the system. The EVK1000 has a transmit power of -41.3 dBm/MHz and a 0dB antenna gain.

Should your system transmit at a different power level, use a low noise amplifier (LNA) or have other sources of power gain or loss in the system then the correction factor you need to apply will be different. A more in-depth understanding will be required in this scenario

The RSL can be calculated using the formula described in the next section and this can be used in a table relating RSL to range bias figure, also presented in the next section, to determine what range bias correction factor you need to apply.

3.4 Friis' path loss formula and range bias correction value

In the case of a line-of-sight channel, the signal power of the unobstructed first path as it arrives at the receiver can be calculated based on the distance reported by the chip using Friis' path loss formula:

$$P_R\,[dBm] = P_T\,[dBm] + G[dB] + 20\log_{10}(c) - 20\log_{10}(4\pi f_c R)$$

Where: -

- P_R is the received signal level;
- P_T is the transmitted power. In a properly calibrated system, the DW1000 transmits -41.3 dBm / MHz into a 500 MHz bandwidth channel, corresponding to a total power P_T of -14.3 dBm;
- G includes the antenna gains of the transmitting and receiving antennas, as well as any other gain from external amplifiers and / or PCB losses;
- c is the speed of light, 299792458 m/s;
- f_c is the centre frequency of the channel used, expressed in Hertz;

- *R* is the reported distance in meters returned from the TWR operation.

Knowing your system parameters such as antenna gain G, P_T etc. it is possible to calculate P_R the received signal level (RSL). Using this RSL in

Table 2 the range bias correction can be determined.

The reported distance can then be corrected such that: -

Actual distance = Reported distance - Range Bias Correction

Where: -

Actual distance	=	the physical distance being measured
Reported distance	=	the distance reported by the un-corrected TWR operation
Range Bias Correction	=	the adjustment figure in cm taken from Table 2

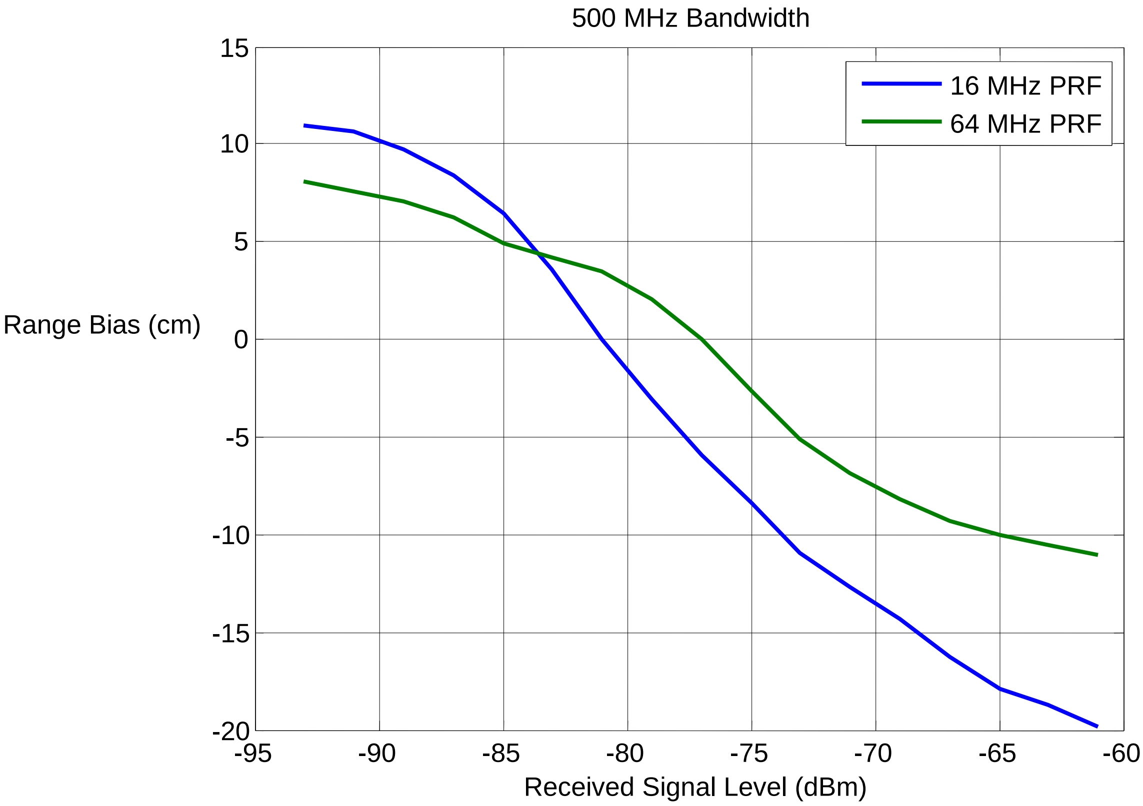

Figure 11: Range bias error for a given received signal level

Table 2: Relationship between RSL and range bias correction factor

RSL (dBm)	PRF 16 MHz 500 MHz (cm)	PRF 64 MHz 500 MHz (cm)
-61	-19.8	-11.0
-63	-18.7	-10.5
-65	-17.9	-10.0
-67	-16.3	-9.3
-69	-14.3	-8.2
-71	-12.7	-6.9
-73	-10.9	-5.1
-75	-8.4	-2.7
-77	-5.9	0.0
-79	-3.1	2.1
-81	0.0	3.5
-83	3.6	4.2
-85	6.5	4.9
-87	8.4	6.2
-89	9.7	7.1
-91	10.6	7.6
-93	11.0	8.1

Figure 11 and Table 2 use an antenna delay calibration (see [2] for an explanation of this) that places the zero point of the range bias (i.e. where the actual and ideal curves in Figure 10 intersect) at -81 dBm for a PRF of 16 MHz and -77 dBm for a PRF of 64 MHz. In this way, the zero point is towards the middle of the range bias variation. This is to ensure we have the minimum error for applications that do not correct for range bias. You may choose to calibrate the antenna delay such that the zero point of the range bias moves towards higher or lower signal levels depending on your application and whether you need accuracy at very short ranges or not.

Table 3 below lists the corresponding calibration distances used for the different channels and different PRFs.

Table 3: Calibration distance for channels and PRF

Channel Number	f_c (MHz)	Bandwidth (MHz)	PRF (MHz)	Calibration Distance (m)
2	3993.6	499.2	16	12.9
2	3993.6	499.2	64	8.1
3	4492.8	499.2	16	11.5
3	4492.8	499.2	64	7.2
4	3993.6	900	16 / 64	8.7
5	6489.6	499.2	16	7.9
5	6489.6	499.2	64	5.0

Channel Number	f_c (MHz)	Bandwidth (MHz)	PRF (MHz)	Calibration Distance (m)
7	6489.6	499.2	16 / 64	5.3

Also included in Appendix B is the corresponding figure and table for the two 900 MHz channels included in the DW1000.

3.4.1 Example Calculation

For a system with the following parameters

G = +1 dB; in the TWR case we must allow for two antenna gains, so +2 dB.
P_T = -14.3 dBm
R = 2 m
f_c = 3993.6 x 10^6 for channel number 2, see Table 3.

and using this formula: -

$$P_R\,[dBm] = P_T\,[dBm] + G[dB] + 20\log_{10}(c) - 20\log_{10}(4\pi f_c R)$$

we find that: -

$$P_R = -14.3 + 2 + 20\log_{10}(299792458) - 20\log_{10}(4 \times 3.1415926 \times 3993.6 \times 10^6 \times 2)$$

$$P_R = -14.3 + 2 + 169.536 - 220.032$$

$$P_R = -62.8 \text{ dBm}$$

Using this result in Table 2 (rounding up to -63 dBm) gives a correction of -18.7 cm for this measurement.

4 Conclusion

4.1 Ranging accuracy in the presence of clock drift

For a two-way ranging scheme, SDS-TWR[4] is the most practical. However, if an implementation executes a ranging exchange during crystal warm-up to reduce power consumption, then the additional error in the accuracy due to frequency drift needs to be minimized.

The guidelines for any ranging implementation to minimize this error are to: -

- Make $t_{replyA}$and t_{replyB} as short as possible. If say t_{reply} was 10 ms, then any additional ranging error would be unlikely to exceed 2 cm.

- Make the difference between t_{replyA} and t_{replyB} , Δ_{reply} as small as possible.

4.2 Ranging accuracy vs. received signal power

There is an error in the timestamp recorded by the DW1000 that is dependent on incident signal level and in particular on high signal levels. This leads to an error in the reported time-stamp and a corresponding error in the distance calculated using that time-stamps unless an appropriate correction factor is applied.

The appropriate correction factor depends on the incident signal power at the chip and is affected by system design elements such as antenna gain, PCB losses and so on. Each system needs to be characterized to establish these gains / losses so that the actual incident signal power can be determined and the appropriate correction factor applied to the reported distance to give the true distance.

Depending on the required accuracy of the distance measurements for the particular application, this correction may not be necessary.

5 REFERENCES

5.1 Listing

Reference is made to the following documents in the course of this Application Note: -

Table 4: Table of References

Ref	Author	Date	Version	Title
[1]	DecaWave		Current	DW1000 Data Sheet
[2]	DecaWave		Current	DW1000 User Manual
[3]	Hewlett Packard		Current	Fundamentals of Quartz Oscillators, Application Note AN200-2
[4]	Nanotron		none	*Nanotron is the owner of the intellectual property rights of the SDS-TWR scheme. The relevant Nanotron patents are EU EP1815267B1 and USA US7843379B2*

6 Document History

Table 5: Document History

Revision	Date	Description
1.0		Initial release
1.1	23/08/18	Updates for new logo and template. And added these revision tables. Also added reference [4] for Nanatron reference.
1.2	17/05/2024	Scheduled update

7 Major Changes

V1.0

Page	Change Description
All	Initial external release

v1.1

Page	Change Description
All	New logo and template.
18	New section for “Further Information”
17	New revision 1.1 and addition to Revision table for Document History.

v1.2

Page	Change Description
All	Modification to footer.

8 FURTHER INFORMATION

Decawave develops semiconductors solutions, software, modules, reference designs - that enable real-time, ultra-accurate, ultra-reliable local area micro-location services. Decawave's technology enables an entirely new class of easy to implement, highly secure, intelligent location functionality and services for IoT and smart consumer products and applications.

For further information on this or any other Decawave product, please refer to our website www.decawave.com.

9 APPENDIX A: DERIVING THE ERROR IN RANGING ACCURACY DUE TO DRIFT

9.1 TWR with clock drift

With the final response message device A can measure the round trip time of the transaction as follows: -

$$t_{roundA} = 2TOF + t_{replyB}$$

And extract the time of flight (TOF): -

$$2TOF = t_{roundA} - t_{replyB}$$

Because of the clock drift, device A actually measures an estimated TOF which is given by: -

$$2\hat{T}OF = t_{roundA}(1 + e_A) - t_{replyB}(1 + e_B)$$

The difference between the true TOF and the estimated TOF gives the error in the ranging transaction: -

$$2\hat{T}OF - 2TOF = t_{roundA}(1 + e_A) - t_{replyB}(1 + e_B) - (t_{roundA} - t_{replyB})$$

Substituting for t_{roundA} yields the final error: -

$$\boldsymbol{\hat{T}OF - TOF = TOF.e_A + \frac{1}{2}t_{replyB}(e_A - e_B)}$$

9.2 SDS-TWR[4] with clock drift

Now each device measures a round trip time as follows: -

$$t_{roundA} = 2TOF + t_{replyB}$$

$$t_{roundB} = 2TOF + t_{replyA}$$

We can extract the TOF by combining these two round trip times as follows: -

$$4TOF = t_{roundA} - t_{replyA} + t_{roundB} - t_{replyB}$$

As before due to clock drift, device A and device B measure estimated round trip times, so the estimated TOF is given by: -

$$4\hat{T}OF = (t_{roundA} - t_{replyA})(1 + e_A) + (t_{roundB} - t_{replyB})(1 + e_B)$$

The difference between the estimated TOF and the true TOF gives the error in the ranging transaction as: -

$$4\hat{T}OF - 4TOF = (t_{roundA} - t_{replyA})(1 + e_A) + (t_{roundB} - t_{replyB})(1 + e_B) - (t_{roundA} - t_{replyA} + t_{roundB} - t_{replyB})$$

$$4\hat{T}OF - 4TOF = (t_{roundA} - t_{replyA})e_A + (t_{roundB} - t_{replyB})e_B$$

If we assume that $t_{replyA} = t_{reply}$ and $t_{replyB} = t_{reply} + \Delta_{reply}$ then: -

$$t_{roundA} = 2TOF + \ t_{reply} + \Delta_{reply}$$

$$t_{roundB} = 2TOF + \ t_{reply}$$

So the error becomes: -

$$4\widehat{T}OF - 4TOF = (2TOF + \ t_{reply} + \Delta_{reply} - t_{reply})e_A + (2TOF + \ t_{reply} - t_{reply} - \Delta_{reply})e_B$$

Which reduces to: -

$$\boldsymbol{\widehat{T}OF - TOF = \frac{1}{2}TOF(e_A + e_B) + \frac{1}{4}\Delta_{reply}(e_A - e_B)}$$

9.3 SDS-TWR[4] with frequency drift

The true TOF is the same as for the SDS-TWR[4] scheme: -

$$4TOF = \ t_{roundA} - t_{replyA} + t_{roundB} - t_{replyB}$$

However, now we have frequency drift in device A, represented by e_A and e_{AD}, so the estimated TOF, based on the round trip time measurements, becomes: -

$$4\widehat{T}OF = \ (t_{roundA})(1 + e_A) - t_{replyA}(1 + e_{AD}) + (t_{roundB} - t_{replyB})(1 + e_B)$$

Again, the difference between the true TOF and estimated TOF gives the error for the ranging transaction: -

$$4\widehat{T}OF - 4TOF = \ (t_{roundA})(1 + e_A) - t_{replyA}(1 + e_{AD}) + \left(t_{roundB} - t_{replyB}\right)(1 + e_B) - (t_{roundA} - t_{replyA} + t_{roundB} - t_{replyB})$$

$$4\widehat{T}OF - 4TOF = \ t_{roundA}(e_A) - t_{replyA}(e_{AD}) + \left(t_{roundB} - t_{replyB}\right)(e_B)$$

If we assume that $t_{replyA} = t_{reply}$ and $t_{replyB} = t_{reply} + \Delta_{reply}$ then: -

$$t_{roundA} = 2TOF + \ t_{reply} + \Delta_{reply}$$

$$t_{roundB} = 2TOF + \ t_{reply}$$

Then the error becomes: -

$$4\widehat{T}OF - 4TOF = \left(2TOF + \ t_{reply} + \Delta_{reply}\right)(e_A) - t_{reply}(e_{AD}) + \left(2TOF + \ t_{reply} - t_{reply} - \Delta_{reply}\right)(e_B)$$

Which reduces to: -

$$\boldsymbol{\widehat{T}OF - TOF = \tfrac{1}{2}TOF(e_A + e_B) + \tfrac{1}{4}\Delta_{reply}(e_A - e_B) + \tfrac{1}{4}t_{reply}(e_A - e_{AD})}$$

10 APPENDIX B: RANGE BIAS FIGURES FOR 900 MHZ CHANNELS

The DW1000 supports two 900 MHz bandwidth channels (Ch 4 & 6). These channels have a different range bias characteristic due to their wider bandwidth.

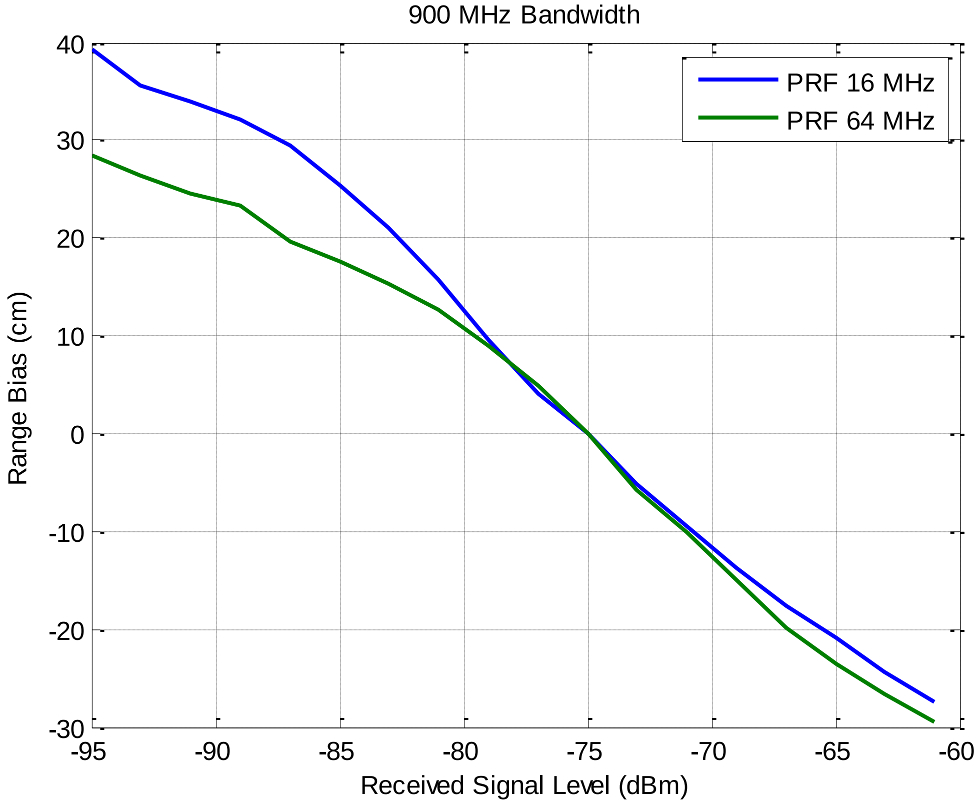

Figure 17: Range bias error vs. received signal level for 900MHz channels.

Table 6: Range bias correction factors vs. received signal level for 900MHz channels

RSL (dBm)	PRF 16 MHz 900 MHz (cm)	PRF 64 MHz 900 MHz (cm)
-61	-27.5	-29.5
-63	-24.4	-26.6
-65	-21.0	-23.5
-67	-17.6	-19.9
-69	-13.8	-15.0
-71	-9.5	-10.0
-73	-5.1	-5.8
-75	0.0	0.0
-77	4.2	4.9
-79	9.7	9.1
-81	15.8	12.7
-83	21.0	15.3

RSL (dBm)	PRF 16 MHz 900 MHz (cm)	PRF 64 MHz 900 MHz (cm)
-85	25.4	17.5
-87	29.4	19.7
-89	32.1	23.3
-91	33.9	24.5
-93	35.6	26.4
-95	39.4	28.4