WHITEPAPER: RANGING ACCURACY
ILMSENS GMBH

RANGING ACCURACY ASSESSMENT WITH M:EXPLORE EVALUATION AND UWB EXPERIMENTATION KITS

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AN INFORMATION COMPANY

Contact:
Ilmsens GmbH
Ehrenbergstr. 11, 98693 Ilmenau, Germany

info@ilmsens.com
+49 3677 76130 30

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1. m:explore – Introduction of range accuracy assessment

This case study roughly assesses the achievable range accuracy using only the Ilmsens m:explore evaluation kit and accessories like antennas and cables from the Ilmsens UWB experimentation kit.

The first part concerns random errors in delay measurements done under controlled conditions - using only RF cables and RF attenuators between the sensor's transmitter and receiver(s). Such errors are caused by measurement noise in both amplitude and time base (jitter). Furthermore, the real resolution of the UWB sensor will be calculated.

The second part uses a simple setup, where the distance to a flat metal plate is measured by a laser distance meter and the m:explore sensor with antennas and the results are compared. In both experiments, delay/range errors and uncertainties are quantified.

*Fig. 1.1: **m:explore** evaluation kit - UWB sensor with one transmitter and two receivers.*

1.1. Measurement Hardware

This case study uses only the M-sequence sensor from the **m:explore** Evaluation Kit and RF-accessories from the experimentation kit:

- **m:explore** UWB sensor head SH-3100 (incl. power supply and interface cables)
- Parts of the UWB experimentation kit:
  - Vivaldi antennas: 1 - 6 GHz
  - RF cables: SMA f-f, DC - 18 GHz, 1 m length
  - RF attenuator: 20 dB, SMA f-m, DC - 18 GHz

For more information, please contact Ilmsens or go to our website (see section 4.1).

1.2. Technical Specifications m:explore sensor head

RF properties:

- UWB bandwidth: 0.1 - 6.0 GHz (baseband operation)
- System clock rate: 13.312 GHz
- UWB transmit signal: 12^{th} order M-Sequence / 4095 chips
- RF output power Tx: -7 dBm
- RF input power Rx1/2: 0 dBm max. ***Levels above this may cause damage!*** -14 dBm (1 dB compression point) -24 dBm ***Levels above this may cause nonlinearities!***
- RF ports: SMA female (nominal impedance 50 Ω)

Digital backend:

- Digital interface: USB2.0, High-Speed (480 MBit/s)
- ADC characteristics: 2-channel 14 Bit, sub-sampling pre-scaler 1:512
- Data Processing: configurable synchronous averaging (48x - 262144x)
- Digital correlation for noise reduction done in PC software
- Supported OS: Microsoft Windows™ XP (32-bit), Microsoft Windows™ Microsoft Windows™ 7/8.1/10 (32/64-bit), Debian™ / Ubuntu™ Linux (x32, x64, armhf)

Dimensions, power supply, environment:

- Dimensions (W x H x D): 115 mm x 55 mm x 215 mm
- Power supply rating sensor: DC +12 V, 1 A
- Supply voltage power unit: 100-230 V AC, 50/60 Hz
- Operational temperature: 0° - 40° C (< 90% rel. humidity, non-condensing)
- Storage temperature: -20° - 60° C (< 90% rel. humidity, non-condensing)

2. Random errors of delay measurements using guided waves

2.1. Purpose of the experiment

This experiment tries to quantify limits of delay measurements using an m:explore caused by random errors (such as amplitude noise and timebase jitter) under good conditions. The true delay/range resolution of the sensor system is calculated from the measurements.

2.2. Measurement setup

The sensor's transmitter was connected to either one of its receivers using the SMA cables and a 20 dB attenuator from the experimentation kit (compare Fig. 2.1). The resulting receiver saturation is at the upper end of the linear operating region. This is a desirable condition in many applications - reasonable SNR without non-linear distortions. The measurement was conducted at maximum measurement speed (i.e. using only 48 synchronous averages resulting in approx. 129.6 IRF/s) over the duration of 10 s. In total, over 1000 IRFs were recorded.

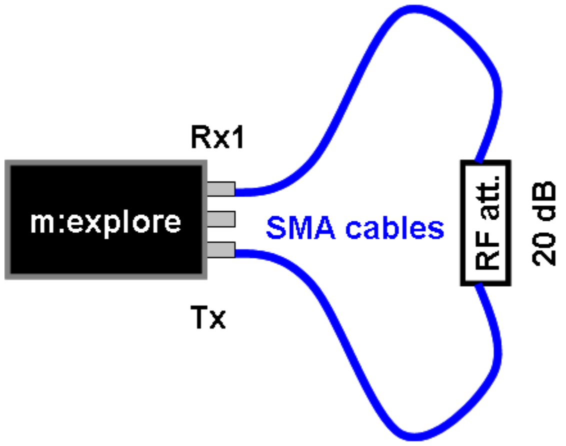

Fig. 2.1: measurement setup for delay accuracy assessment

2.3. Data Processing

Fig. 2.2 shows part of the mean waveform averaged over all recorded IRFs. The raw data was 64x interpolated using FFT interpolation with zero padding. The 3 dB and 10 dB width of the pulse is extracted from the resulting waveform. The SNR of approx. 82 dB was calculated using the maximum pulse amplitude and the RMS noise amplitude after subtracting the mean IRF from all measured IRFs.

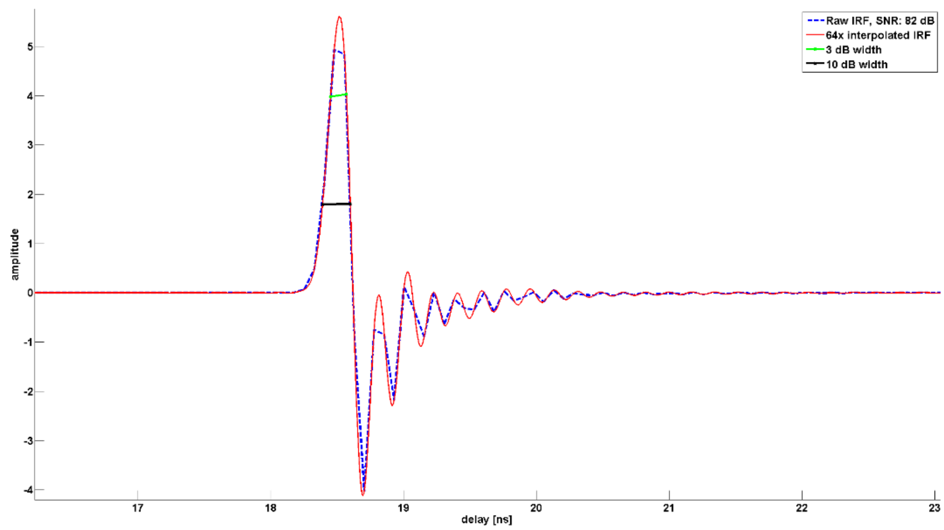

Fig. 2.2: Waveform excerpt of mean IRF measured along RF cables and an RF attenuator

Furthermore, for each of the recorded IRFs the exact pulse delay and amplitude are extracted as well. The location of the pulse maximum is derived from interpolated data using polynomial fitting around the maximum and then calculating the polynoms' maximum amplitude and time position.

The resulting delays' standard deviation represents the RMS random uncertainties of the delay measurement.

2.4. Results

The following results were extracted from measured data. Both receivers were tested and their results coincide very well.

Parameter	in time	in range (in air, 2-way round trip)
3 dB width/resolution	117.4 ps	17.6 mm
10 dB width/resolution	207.8 ps	31.2 mm
RMS delay noise	10.7 fs	1.6 μm

The random delay noise limits any real-world delay measurement, too. The excellent performance of the **m:explore** sensor shows the benefits of the M-sequence technology and its very good timebase stability with very low jitter of less than 20 fs typ.

3. Range accuracy of metal plate measurements

3.1. Purpose of the experiment

This experiment tries to roughly test the accuracy of measuring the distance between antennas attached to an **m:explore** and a small flat metal plate placed at a tripod up to several m away. The true distance of the plate is compared to the result of UWB measurements after some basic calibration which aims at compensating the system-internal delay including the test cables as well as the antenna delay. Just like before, the measurements at different plate distances are analysed wrt random delay variations. Al measurements were done outdoors in an open space to minimise reflections from the environment.

3.2. Measurement setup for system delay calibration

The sensor's transmitter was connected to one Vivaldi antenna from the UWB experimentation kit as was the first receiver. The cables from the exp. kit were used for these connections. The second receiver remained unused. The measurements were conducted at maximum measurement speed (i.e. using only 48 synchronous averages resulting in approx. 129.6 IRF/s) over the duration of 10 s. In total, over 1000 IRFs were recorded for every antenna separation. The receiver was at all times well within its linear operating region.

For the calibration measurement, the antennas were fixed opposite to and facing each other at different distances on a metal beam. Fig. 3.1 shows the antenna placement. The distances between the antennas were measured manually with a precision of approx. ± 1 mm.

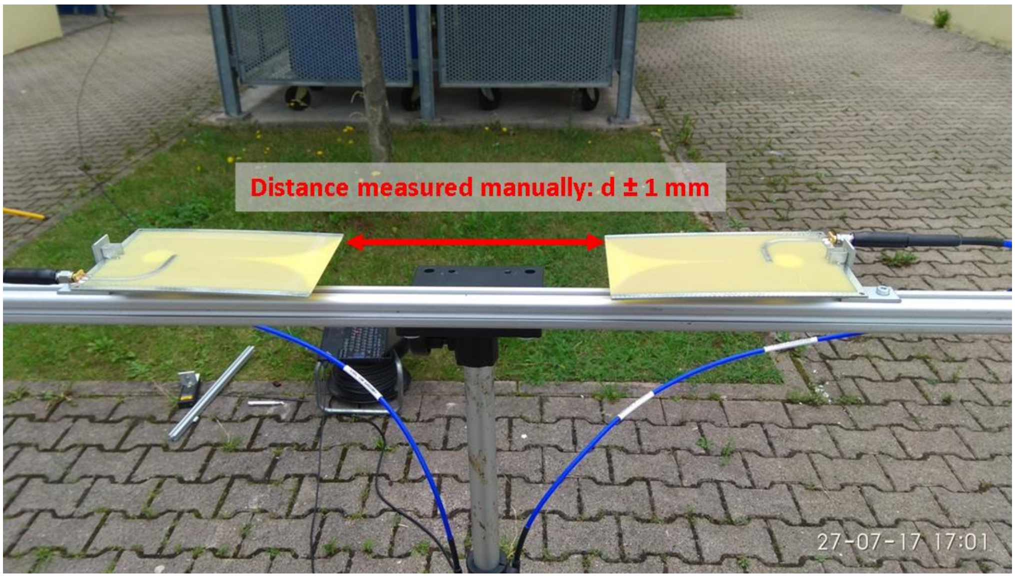

Fig. 3.1: Measurement setup for calibrating the system-internal and antenna delay

3.3. Data Processing for system delay calibration

The processing was done in a similar way to section 2.3. The transmitted pulse's exact delay was extracted from the mean IRF, while its random variation was calculated from single recorded IRFs. For each antenna separation measured, the wave propagation time through the air gap was calculated and subtracted from the obtained pulse delay. The remaining value was used as an estimate of the system-internal delay including the SMA cables and the propagation from the antenna's feed point to its front. The results from the different measurements were averaged and the result was used to correct the delays of the metal plate measurements.

3.4. Results of system delay calibration

The following results were extracted from measured data. Please keep in mind, that the manual measurement of antenna separation had an error in the order of 1 mm already.

Antenna separation	SNR	system delay	delay RMS noise
0.100 m	72.4 dB	239.4077 ns	24.0 fs / 3.6 µm
0.205 m	67.4 dB	239.3938 ns	44.3 fs / 6.6 µm
0.305 m	63.7 dB	239.3943 ns	68.9 fs / 10.3 µm
0.398 m	63.9 dB	239.4117 ns	66.7 fs / 10.0 µm
0.500 m	60.7 dB	239.4065 ns	108.6 fs / 16.3 µm
0.605 m	60.4 dB	239.392 ns	97.3 fs / 14.6 µm

Mean system delay according to above table is: 239.4010 ns with σ = 8.6 ps / 1.3 mm

From the low random delay variations it becomes clear that the main source of error is the manual measurement of antenna distances. Another contributor to delay noise was significant wind affecting the antennas during data acquisition (e.g. it caused slightly more delay noise at d = 0.5 m as compared to d = 0.6 m despite similar SNR conditions).

3.5. Measurement setup for metal plate ranging

The sensor's transmitter was connected to one Vivaldi antenna from the UWB experimentation kit as was the first receiver. The cables from the exp. kit were used for these connections. The second receiver remained unused. The measurements were conducted at maximum measurement speed (i.e. using only 48 synchronous averages resulting in approx. 129.6 IRF/s) over the duration of 10 s. In total, over 1000 IRFs were recorded for every plate position and calibration. The receiver was at all times well within its linear operating region.

Antennas were placed parallel (next) to each other with a separation of 10 cm (this results in a feed point separation of 20 cm). A laser distance meter with claimed precision of ± 1.5 mm was mounted in the middle between the antennas looking into the plate's direction. Everything was fixed on a metal beam on a tripod.

The metal plate was placed on a tripod, too. To extract the laser meter's offset, the metal plate was at first put directly at the front of the antennas (with an uncertainty of about ± 1 mm) and the distance was measured. At the same time, the laser point on the plate was marked to enable a reasonable alignment between tripods at different distances despite a slightly uneven ground. Compare Fig. 3.2 through Fig. 3.5. The tripod with the plate was placed manually at various distances from the sensor, which was measured by the laser meter. It was made sure that the laser point was close (δ < 2cm) to the marked spot on the plate so that the antennas were looking into the right direction. For each distance, 10 s of data were recorded.

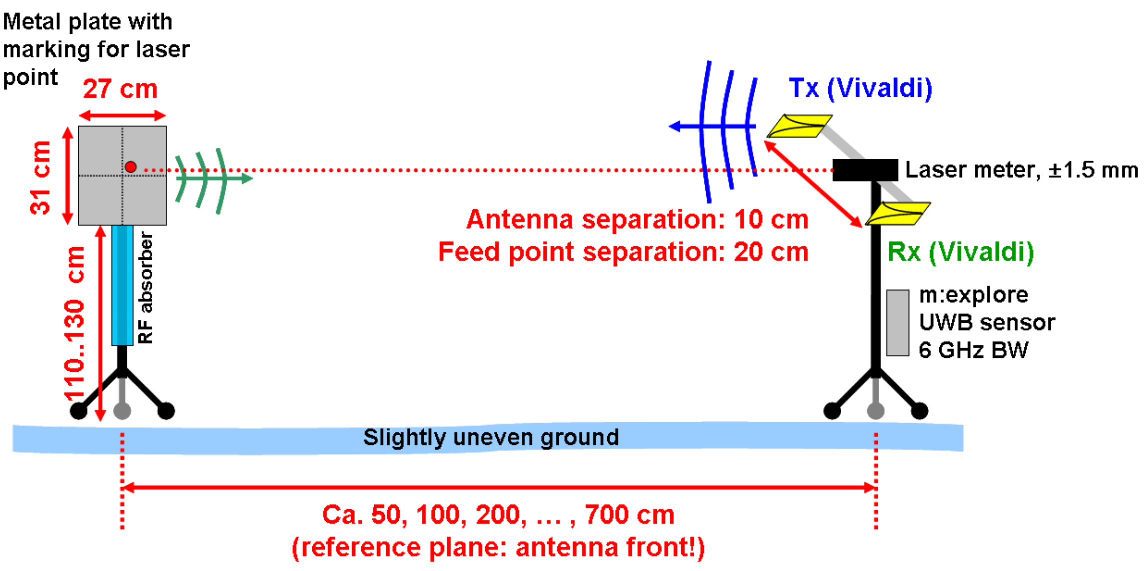

Fig. 3.2: Metal plate measurement setup diagram

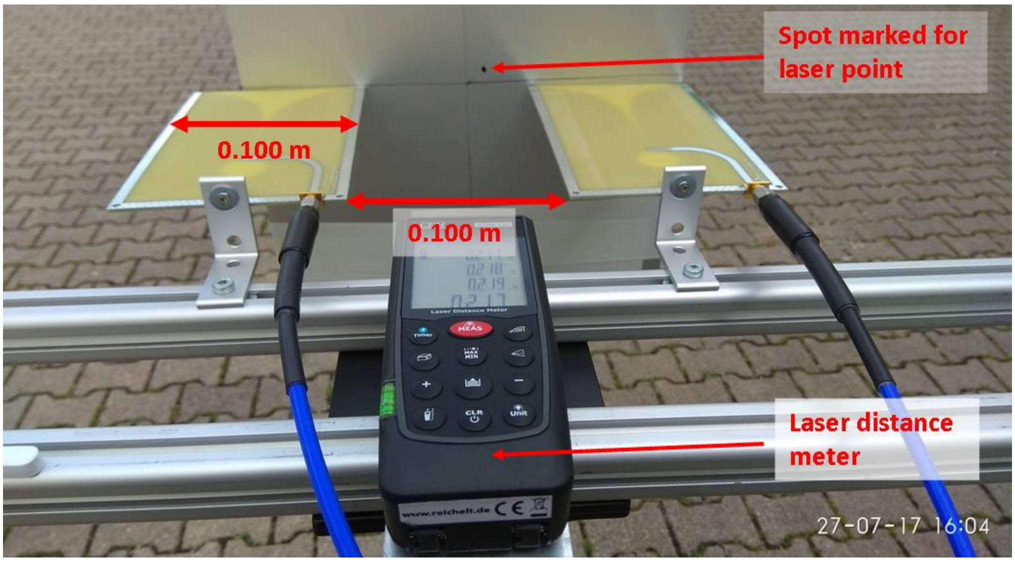

Fig. 3.3: Antenna and laser meter placement for pate measurements

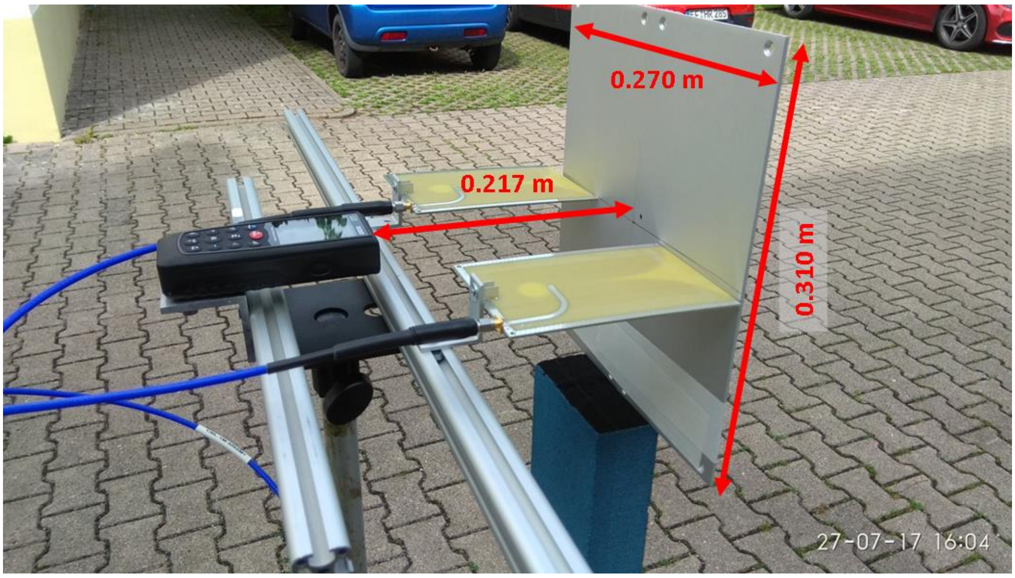

Fig. 3.4: Laser meter offset

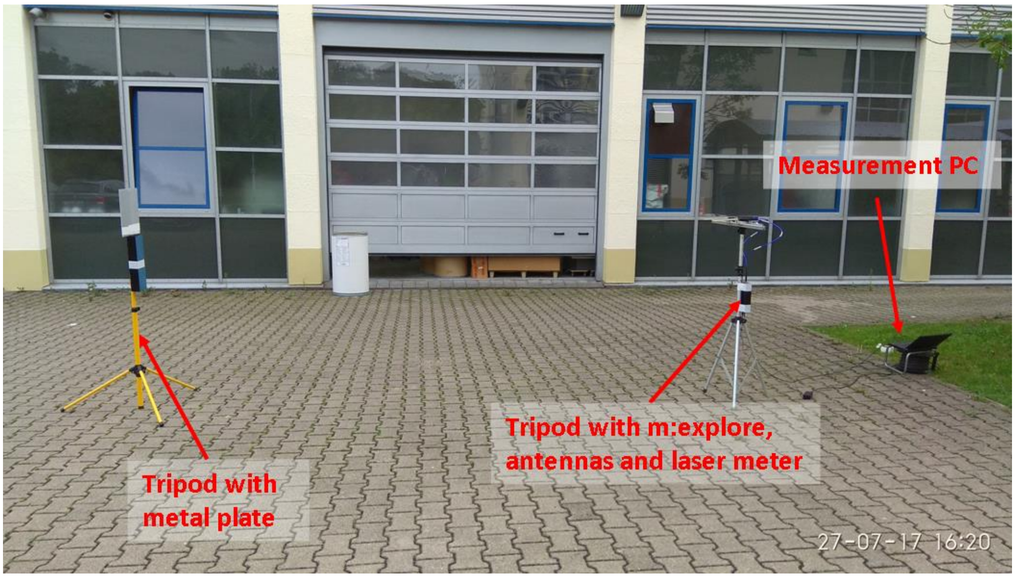

Fig. 3.5: Metal plate measurement setup photo

3.6. Data Processing for plate ranging

The processing of each measurement was done in a similar way to section 2.3. The plate reflection's exact delay was extracted from the mean IRF, while its random variation was calculated from single recorded IRFs. In order to correctly identify the plate reflection and separate it from clutter (e.g. antenna crosstalk), a background measurement with no plate was conducted first. The averaged IRF from this measurement was then subtracted from all plate measurements. The obtained delay value was corrected with the system delay from section 3.4 and than used as two-way round-trip time for the plate's range in air. The antenna separation was taken into account when calculating the range from the delay. The extracted value was compared to the laser result after correcting the laser offset of 0.217 m.

3.7. Results of system delay measurements

The following results were extracted from measured data. Sources of uncertainties will be discussed below.

Laser (corr.)	m:explore	Abs. error	Rel. error	range RMS noise	SNR
0.478 m	0.4777 m	0.26 mm	0.05 %	0.03 mm	57.1 dB
1.009 m	1.0032 m	5.75 mm	0.57 %	0.09 mm	47.6 dB
1.912 m	1.9127 m	0.69 mm	0.04 %	0.17 mm	38.5 dB
2.878 m	2.8790 m	1.05 mm	0.04 %	0.47 mm	30.5 dB
3.973 m	3.9678 m	5.17 mm	0.13 %	0.72 mm	26.0 dB
5.015 m	5.0100 m	5.02 mm	0.10 %	1.51 mm	20.9 dB
6.093 m	6.0821 m	10.87 mm	0.18 %	1.83 mm	18.6 dB
6.995 m	6.9822 m	12.78 mm	0.18 %	2.27 mm	17.0 dB

As can be expected from theory, delay noise increases with decreasing SNR due to the influence of amplitude variations on the exact delay extraction. It should be noted, that an SNR improvement of more than 10 dB would still be possible by suitable Tx or Rx amplifiers because the Rx was only at 20% saturation (mainly caused by antenna crosstalk). No additional amplifiers were used here because they are not part of the experimentation kit. However, the RMS noise is always well below the absolute error and does not play a dominant role. The relative ranging error is always well below 1 % despite the rough measurement setup with all its imperfections. Some of these uncertainties (in order of importance) will shortly be mentioned here:

Manual placement of tripod and size of plate

The plate was moved manually on an uneven ground. Even though it was made sure the antennas were facing approx. the middle of the plate, its orientation (tilt, yaw) could not be controlled exactly. When interpreting the reflection pulse of the plate, its first maximum was used to extract the delay as shown in Fig. 3.6. However, orientation of the plate influences the time shape of its reflection and the first pulse maximum may deviate significantly from the true wave delay. Another factor wrt to time shape of the reflection is the size of the plate. In an ideal case, an infinitely large plate would be required, or at least a plate much larger that all wavelengths involved (the lower cutoff of the Vivaldi antennas is between 500 MHz and 1 GHz). Such a plate was not available at the time of the experiment.

One could improve testing and processing methods by using a precision linear positioner to move the plate (this way, orientation does not change) and improved delay results may be obtained by analysing the reflection's envelope instead of its first maximum.

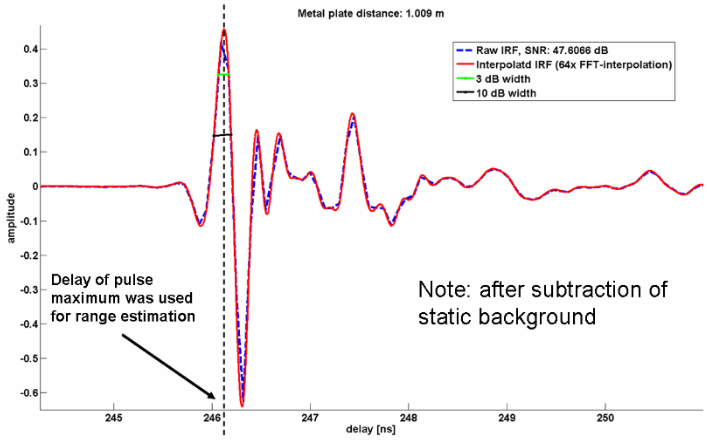

Fig. 3.6: Waveform excerpt of mean IRF measured at a plate distance of approx. 1 m

Influence of wind on metal plate

During the outdoor measurements, a significant wind was blowing around the experimental area from time to time. It sometimes moved the metal plate slightly back and forth during the 10 s measurement. This could even be observed in the data when looking at the extracted pulse delays from single IRFs rather than the delay of the mean IRF. Fig. 3.7 shows an example of slower delay variations of 3 mm_{pp} during the measurement influenced by wind.

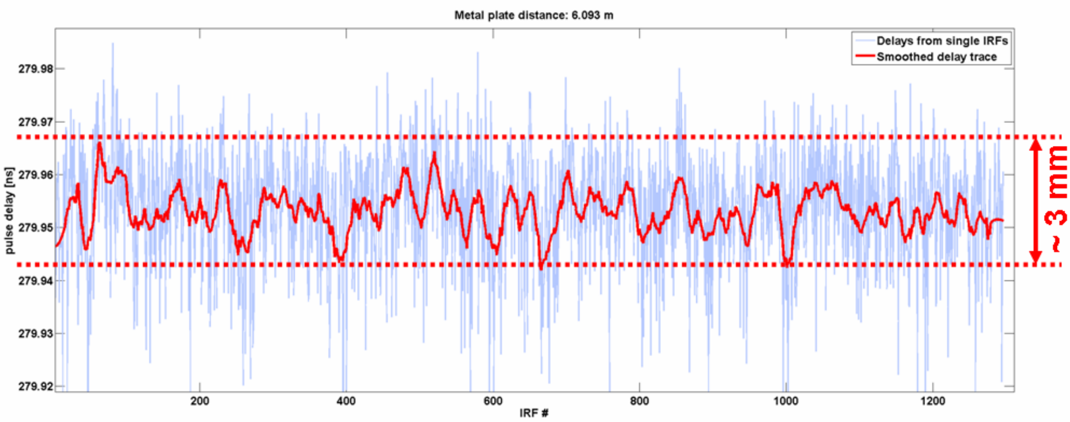

Fig. 3.7: Delay variation over 10s measurement time influenced by wind

Uncertainties of laser distance measurement

The manufacturer of the laser meter specifies an accuracy of ± 1.5 mm. However, the error is known to increase with distance due to SNR decrease and widening of the laser reflection point.

When repeating the laser measurement several times to test random variation, results coincided at short distances (below 3 m) while giving varying values (± 2 mm) at larger distances. This happened in situations with low and stronger wind as well.

4. Further resources and revision history

4.1. Further resources

For further information please visit our website at www.ilmsens.com. There you can find our latest products, documentation, and application white papers.

For purchasing information on the **m:explore** Evaluation Kit and the UWB experimentation kit you can go to our webshop at https://www.uwb-shop.com/shop/.

If you need assistance with the device, the software, or UWB measurement technology feel free to contact us at:

Ilmsens GmbH
Ehrenbergstraße 11
98693 Ilmenau
Germany

Tel.: +49 3677 76130-30
Fax: +49 3677 76130-39
Email: info@ilmsens.com

4.2. Document revision history

Rev.	Date	Author	Description
1.0	07/2017	Her	Initial revision for the **m:explore** case study