Distance Measurements and Limitations Based on Guided Wave 24 GHz Dual Tone Six-Port Radar

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***Abstract*—In the following, a continuous wave (CW) radar system based on the Six-Port principle will be shown for measurement tasks at enclosed systems needing micrometer accuracy as well as high update rates like tank level monitoring or hydraulic cylinder piston control. To exceed the ambiguity limit of such an interferometric system, a dual tone approach is used. The system will be presented with measurement results at 24 GHz within a WR42 waveguide to prove the feasibility of the proposed concept. Furthermore, considerations on timing will show the potential as a low-latency system, capable of high measurement data update rates, and different influences on the system performance and limitations of such a system will be discussed in comparison to similar setups.**

***Index Terms*—Distance measurement, Interferometry, Phase measurement, Radar, Six-Port, Waveguide**

I. Introduction

An interesting field in industrial measurement setups is measuring distances within a waveguide or structures with similar propagation conditions. Such systems can be used to observe the piston position of a hydraulic cylinder [1] or to probe fluid levels within tanks [2] and should be capable of remote sensing due to the harsh environment, e.g., strong vibrations or corrosive media.

Alternative solutions to obtain the often required accuracies down to a few tens of micrometers' are laser based systems, which come with the drawbacks of high costs and a short continuous measurement range. Another possibility are frequency modulated continuous wave (FMCW) radar systems, but at the addressed application of waveguide measurements the problem of dispersion arises, and leads to challenging difficulties for FMCW based systems [1], [3], [4]. A second problem with such systems is the required measurement time due to the time needed for the frequency ramp and the following calculations, leading to a measurement system with a high latency and low update rate, which can be critical within the often fast servo loops at industrial applications.

Therefore, the proposed system utilizes a low-cost Six-Port based radar, which analyses the phase to distinguish the distance. The major problem of such systems – the ambiguity – is eliminated by using two discrete frequencies and the resulting beat phase between them. The possibilities and limits in measurement speed and accuracy of this dual tone approach will be explained by system simulations and an appropriate measurement setup using a 24 GHz ISM-band capable Six-Port receiver system.

This publication is an extended version of [5], presented at the 11$^{\text{th}}$ European Radar Conference in Rome, 2014. The extension comprises the study of several limitations of the system due to noisy oscillator, insufficient isolation within the front-end, and multiple targets.

II. The Six-Port Based Radar

Introduced to measure complex voltage ratios [6] and as an alternative solution for power metering and vectorial network analysis [7] in the seventies, the Six-Port network nowadays receives attention in the field of angle-of-arrival as well as distance and vibration measurement purposes [8]–[10]. This is due to the fact that the Six-Port has shown a high phase linearity and accuracy in comparison to common mixer designs.

A. System Concept

While commonly used FMCW based radar system measure a beat frequency to distinguish the distance to the target, the proposed Six-Port based system evaluates the distance dependent phase of the reflected wave at the target. With this technique, there is no need for a time-consuming fast Fourier transformation (FFT), which leads to a fast responding, low-latency system. The drawback that only a single target can be tracked can often be neglected if there is only a single dominant reflection, as at the addressed applications.

The sketch of the proposed radar system is shown in Fig. 1. A frequency-adjustable CW signal is fed into a coupler, where a small portion is fed as a phase reference into the first input port of the Six-Port P_1. The remaining signal power is coupled to the waveguide structure, reflected by the target and guided to the Six-Port's second input port P_2. A circulator is required to divide the received and transmitted signals, because they have to share the same waveguide feed.

The core of the system, the Six-Port interferometer, can be understood as a homodyne IQ-mixer with differential base band output signals B_3 to B_6, forming the base band signal $\underline{z}$ [8]:

$$\underline{z} = (B_5 - B_6) + j(B_3 - B_4). \quad (1)$$

This vector is generated by a cost-efficient and passive structure shown in Fig. 2(a). A Wilkinson power divider and three hybrid couplers superimpose the two input signals P_1 and P_2 with discrete phase shift of 0°, 90°, 180°, and 270°. The

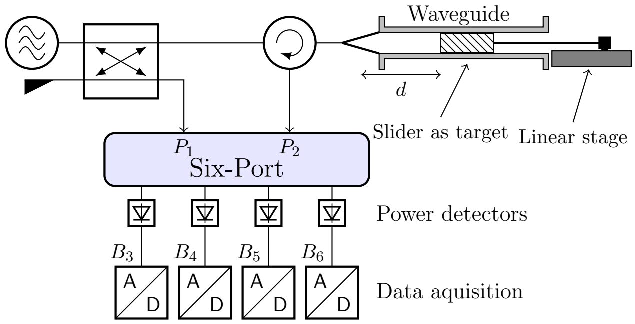


Fig. 1. Measurement setup for waveguide based distance evaluation.

resulting interfered signals are converted to base band by diode power detector forming the differential complex vector $\underline{z}$. To clarify the phase relations, they are depicted in Fig. 2(b).

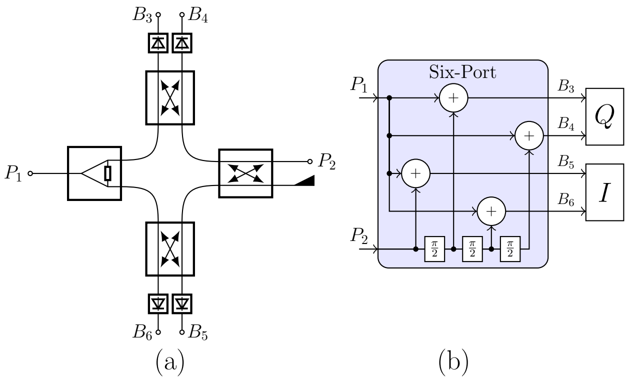


Fig. 2. Implemented Six-Port structure (a) and phase relations (b).

B. Distance Calculation

In the context of a Six-Port radar, the distance d of a target can be evaluated if the used transmission frequency f_{RF} is known and the phase of the complex vector $\underline{z}$ has been determined:

$$d = \Delta\sigma \cdot \frac{c}{2 \cdot 2\pi \cdot f_{RF}} \quad \text{with} \quad \Delta\sigma = \arg\{\underline{z}\}. \tag{2}$$

As in common interferometric approaches, the problem of ambiguity in phase arises, limiting the unambiguous measurement range to half of the wavelength of the used frequency. This ambiguity can be eliminated by measuring the phase difference ($\Delta\sigma_1$, $\Delta\sigma_2$) for two tones (f_1, f_2) with a spacing of f_B between them as shown in [11]. Calculating the difference between the two phase responses, an absolute, coarse distance d_{coarse} can be evaluated:

$$d_{coarse} = \Delta\sigma_B \cdot \frac{c}{2 \cdot 2\pi \cdot f_B} \quad \text{with} \quad \Delta\sigma_B = \Delta\sigma_1 - \Delta\sigma_2. \tag{3}$$

After the determination of this coarse distance information, the period of unambiguity is known and an additional high precision distance evaluation based on the two single tones can be done using (2) leading to a micrometer accuracy distance value, which is unambiguous within a range of d_{max}:

$$d_{max} = \frac{c}{2 \cdot f_B} = \frac{c}{2 \cdot (f_2 - f_1)}. \tag{4}$$

TABLE I

UNAMBIGUOUS RANGES FOR DIFFERENT FREQUENCY SPACINGS WITH A CENTER FREQUENCY OF 24 GHZ AT FREE SPACE PROPAGATION (NO INDEX) AND WAVEGUIDE CONDITIONS (INDEX w).

f_B	single tone	10 MHz	125 MHz	250 MHz	2.4 GHz
$f_{B,w}$	–	12 MHz	154 MHz	307 MHz	2.95 GHz
d_{max}	6.2 mm	15.0 m	1.2 m	60.0 cm	6.3 cm
$d_{max,w}$	7.7 mm	12.2 m	1.0 m	48.8 cm	5.1 cm

C. Waveguide Propagation Related Corrections

A problem arises if the measurement takes place in an enclosed system, e.g. to detect the position of a reflecting target within a waveguide, as the dispersion has to be considered. Due to the field propagation within a waveguide structure, the wavelength λ_w of a transmitted signal within the waveguide depends on the cut-off frequency f_c of the used mode and the free space wavelength $\lambda_0 = \frac{c}{f}$ of the transmitted signal:

$$\lambda_w = \lambda_0 \frac{1}{\sqrt{1 - \left(\frac{f_c}{f}\right)^2}}. \tag{5}$$

This equation can be simplified by assuming single mode transmission, e.g. by using a standardized waveguide within its specification. In this case λ_w depends only on the geometrical width a of the used waveguide and λ_0:

$$\lambda_w = \frac{\lambda_0}{\sqrt{1 - \left(\frac{\lambda_0}{2a}\right)^2}}. \tag{6}$$

It is obvious that the wavelength λ_w has a nonlinear relation to λ_0 for free space. Therefore, the beat frequency f_B has to be calculated from the wavelengths of the single tones $\lambda_{w1}, \lambda_{w2}$ within the waveguide:

$$f_{B,w} = \frac{\lambda_{w1} - \lambda_{w2}}{\lambda_{w1} \cdot \lambda_{w1}} \cdot c. \tag{7}$$

Furthermore, the unambiguous distance measurement range inside the waveguide $d_{max,w}$, which depends on $f_{B,w}$ is limited in this case to

$$d_{max,w} = \frac{c}{2 \cdot f_{B,w}}. \tag{8}$$

A few examples of possible unambiguous ranges at free space propagation as well as within the waveguide are provided in Table I. While at the single tone setup the range is limited by the used RF wavelength, in the case of a dual tone system the unambiguity range can be calculated according (4) and within the waveguide setup according (8), respectively.

III. SYSTEM LIMITATIONS

Although the proposed system shows benefits against the comparable solutions, it has to deal with several problems. Therefore, the influence of the radar coupler, the oscillator and noise will be discussed in the following.

A. Isolation of the Radar Coupler

Like in all radar based systems, the isolation between the transmitted and received signal acts as a strong interferer in detection of the correct target position. A similar effect is caused by the often poor matching of the antenna, which also introduces a static reflection in the receive path superimposing the signal from the target. These effects can be reduced by using a bi-static setup with two antennas, but this is not feasible within the shown setup due to the waveguide-transition.

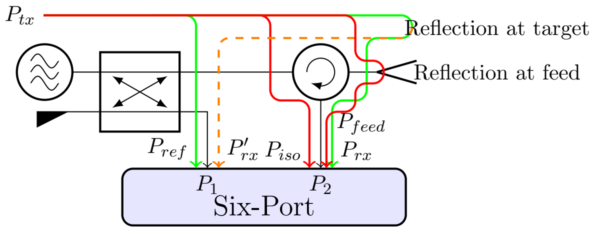


Fig. 3. Paths of RF power distribution.

The main paths of transferred power within the system are depicted in Fig. 3. Besides the desired signals P_{ref} and P_{rx} at the Six-Port there is also a strong static signal P_{iso} caused by low directivity of the circulator and a second static signal P_{feed} due to insufficient matching of the feeding structure. Both of these disturbing signals are even higher, if an additional LNA exists between the circulator and the Six-Port's input P_2. The parasitic target reflection P'_{rx} can be neglected due to high dampening in this path. Secondary static targets or reflections due to the environment are also neglected for simplicity. Nevertheless, they behave like P_{feed}, thus they can added to P_{feed}, if it is necessary to consider them due to their high radar cross section.

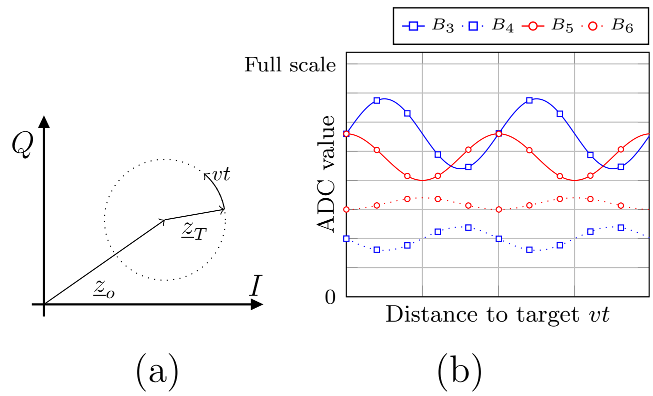


Fig. 4. Complex IQ result (a) calculated from base band signals (b) with offsets due to isolation issues observing a moving target.

However, as long as the static parasitic reflections do not depend on the target position, they will produce only a static complex offset $\underline{z}_o$ added to the target's signal $\underline{z}_T$ at the base band constellation diagram. The measured value will be in this case:

$$\underline{z}' = \underline{z}_o + \underline{z}_T. \tag{9}$$

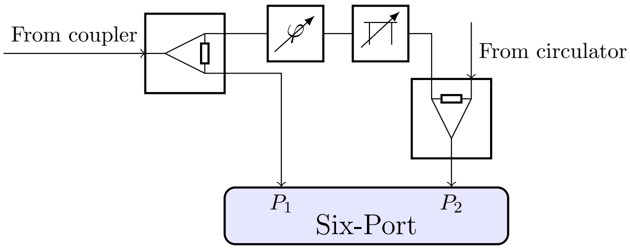


Fig. 5. Variable feed-forward compensation structure to reduce offsets.

This behavior is shown in Fig. 4, where an offset effected signal from a moving target is plotted. The target is moving with a constant velocity v, forming a circle in the constellation diagram. To calculate the distance out of the phase, the offset vector $\underline{z}_o$ can be removed by a simple complex valued subtraction.

The offset vector can easily be measured and digitally compensated if the target moves more than half of the used wavelength, but the offset will significantly decrease the dynamic range of the digitization. Alternatively, this can be done analogously by adding a signal with an appropiate power and phase to the received signal at port P_2, which compensates the sum of $P_{iso} + P_{feed}$. Such systems can be implemented using a variable attenuator and phase shifter, depicted in Fig. 5, to compensate also a slow changing environmental clutter. But this implementation is difficult, because the regulation of phase and amplitude of the compensation signal has to be very accurate and stable. Therefore, the preferable way is to suppress this offset by a sophisticated RF design, e.g. to consider both the isolation issue and the antenna feed reflection to compensate for each other, or to use the static reflection as a bias signal for the detectors to equalize the gain imbalance within the Six-Port junction. Simplified systems, e.g., [12] or [13], based on the same feed-forward idea are already studied and measured but only capable of compensating the isolation P_{iso}.

B. Oscillator influences

For radar based distance measurements, the phase noise of the used oscillator has to be considered. The resulting root mean square (RMS) error can be calculated, according to Parseval's theorem, by integrating the phase noise density spectrum in the used bandwidth. However, this result is only correct, if the transmitted and received signal are completely uncorrelated. Here, it can be shown [14] that there is a range correlation effect, which has a high-pass characteristic and suppresses the phase noise density more than 100 dB for low offset frequencies.

Considering this effect, the RMS phase error σ_{err} can be calculated depending on the phase noise spectrum of the used oscillator, the distance to the target and the used base band bandwidth f_{bw}:

$$\sigma_{err} = \sqrt{\int_0^{f_{bw}} 2 \cdot \underbrace{\mathcal{L}(f)}_{\text{Phase noise}} \cdot \underbrace{4 \sin^2\left(\frac{2d\Delta f}{c}\right)}_{\text{Range Correlation}} \mathrm{d}f} \tag{10}$$

Fig. 6 shows the evaluation of (10), mapped to a distance error, for different target distances over the used base band bandwidth. The underlying phase noise density originates from a PLL stabilized 24 GHz *Silicon Radar* voltage controller oscillator measured with a *Rohde & Schwarz FSUP26* spectrum analyzer at offset frequencies between 0.1 Hz and 1 MHz.

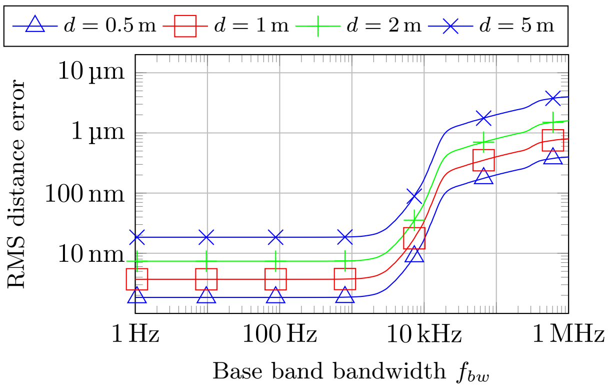


Fig. 6. Distance error due to oscillator's phase noise depending on the used base band bandwidth.

Although the overall accuracy of the system is limited to the error in the single tones, the phase noise does not influence the performance of the system, as the error is below 1 µm at least for measurement distances of only a few meters.

However, the used frequencies have to be known precisely, otherwise there will be a significant error in the measurement. Nevertheless, the required accuracies can easily be achieved using a phase-locked loop (PLL) stabilized oscillator with a stable quartz reference.

C. Limit of unambiguity solution

The shown equation can lead to the assumption that huge unambiguity ranges can easily be achieved by using two narrow spaced RF signals. However, for narrow frequency spacings between the two tones f_B the slope of the transfer function $\frac{\partial d}{\partial \sigma_B}$ becomes very flat and therefore susceptible for noise.

To clarify this circumstance, simulations were done to investigate the effect of noise at different frequency spacings. Therefore, white Gaussian noise was added to the signals before calculating the coarse distance information between the two signals. The error of this calculation has to be lower than a quarter of the larger single wavelength to distinguish the correct ambiguity range for the fine distance evaluation in a second step.

Fig. 7 shows the simulation results of the system using different frequency spacings f_B from 1 MHz to 2.4 GHz at

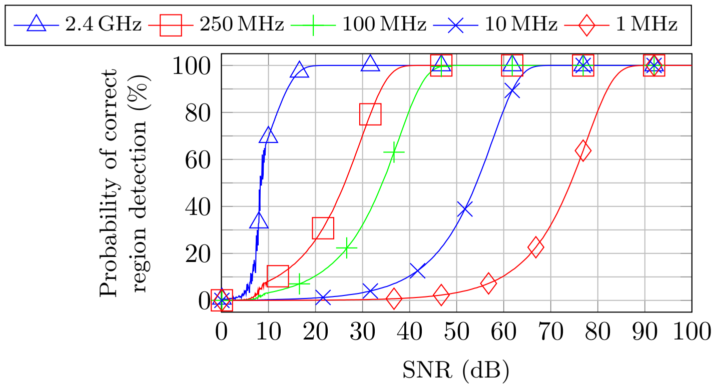


Fig. 7. Simulation results of the usability of the dual tone setup with the influence of additive white Gaussian noise.

different noise levels which are expressed by the signal-to-noise ratio (SNR). The graph shows the probability for an error lower than it is necessary for a correct determination of the unambiguous region. This probability should be nearly at 100 % to develop a usable system. For a bandwidth of 250 MHz, as used in the proposed system achieving an unambiguous range of 50 cm, this means an overall SNR of lower than 40 dB. To achieve reliable measurements in ranges larger than 10 m, an SNR larger than 65 dB has to be reached. The results for the SNR values lower than 10 dB have to be ignored due to mathematical errors within the simulation environment.

The shown considerations are only based on noise effects. Additional errors caused for example by multiple target scenarios or non-linearities have to be taken into account separately. While non-linearity errors can be removed using a calibration, the system is not capable of observing multiple moving targets. However, if they are static, they introduce a removable static offset, described in section III-III-A.

IV. Timing Considerations

The proposed system has the capability of very high measuring rates, as there is neither a time consuming algorithm, nor long acquisition times for an accurate FFT needed. The mainly time consuming parts for the Six-Port radar are to settle the PLL between the frequency steps, to digitize the values, and to calculate the distance value from the phase responses. While the digitizing and calculations can be easily optimized by using fast CPUs, the PLL settling time is difficult to minimize.

Nevertheless, this system is capable of high speed measurement value update rates. In Fig. 8 timing a) shows the normal operation. At first, the two single phases are measured, later the coarse and the accurate fine evaluations are processed. This has the advantage of minimum latency between the two measurements. Therefore, there is no influence due to a moving target between the measurements, which would lead to an error in distance evaluation. In contrast, timing b) offers a possibility to use the PLL settling time between the two frequencies to calculate the accurate but ambiguous distance, while the coarse distance is evaluated after measuring

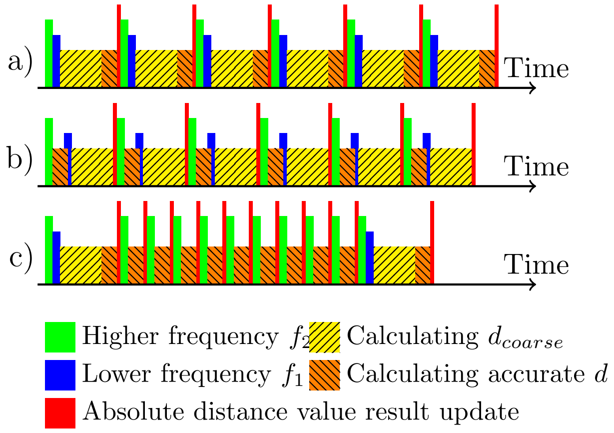


Fig. 8. Different measurement timing strategies for the proposed system.

the second tone. This decreases the latency of the whole measurement procedure by removing idle times.

Surely, it is also possible to perform the coarse evaluation less frequently, as in timing c), e.g. only when initializing the system, and following the phase jumps by remembering the old distance values. In measurement scenarios, as the one described here, where no mechanical target jumps are possible, this is the fastest way to determine the distance. In this case it is also possible to follow targets moving with a very high velocity without getting in trouble using the dual tone concept.

At this inital setup timing a) is used, because the measurement latency is limited by the PC based control anyway. In the next step, the controlling and processing will integrated into a microcontroller to measure the improvements between the different timing strategies.

V. Measurement Results

For concept validation a measurement setup at 24 GHz was built and its results show the convincing performance of the system.

A. Measurement Setup

An *Agilent E8267D* signal generator was used as synthesizer to obtain the two accurate frequencies f_1 and f_2. Nevertheless, other low cost synthesizer based systems have shown similar accuracies [15], revealing that there is no need for a highly stable source and proving the described phase noise influences. The target is positioned by a *PiMicos* linear stage, which can move 15 cm in steps of 0.5 µm. Due to its very precise optical encoder, the stage is also used as position reference for all shown measurements.

The Six-Port front-end, whose main parameters are summarized in Table II, is connected by a coaxial-to-waveguide adapter to the 24 GHz capable waveguide type WR-42 shown in Fig. 9. The used waveguide has a length of 1 m and the measurements were performed in the middle of the structure over the entire length of the stage of 15 cm to provide realistic results.

The data was acquired at a rate of 400 kSa/s after a 8$^{\text{th}}$ order Butterworth low pass filter with a cut-off frequency of 50 kHz.

TABLE II
Measured parameters of the front-end.

Radar coupler	VCO to Feed	-1.8 dB
	VCO to P_1 (reference signal)	-11 dB
	Feed to P_2 (received signal)	-0.4 dB
	VCO to P_2 (isolation)	-40 dB
	Feed to P_1	-60 dB
Six-Port	Gain mismatch at output ports	< 2.5 dB
	Phase error	$< 10°$

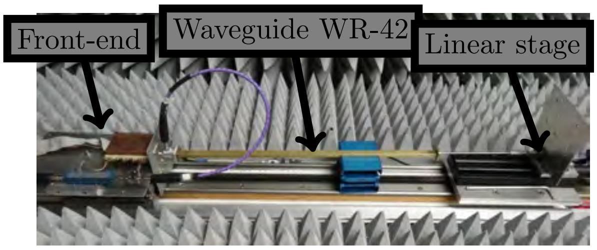


Fig. 9. Measurement Setup

The digitized data are transferred to a PC, where the data processing is done with *Matlab* to simplify the development of the algorithms. In future, the whole calculations will be implemented within a micro-controller to achieve a low-cost, low-power and low-latency signal processing.

B. Measurement Results

Fig. 10 shows the linearized single phase and corresponding beat phase responses at 24 GHz with a spacing of 2.4 GHz. The shortened wavelength of the beat frequency, compared to the free space setup, is clearly visible. Two beat frequency periods are recognizable with a spacing of 5.1 cm corresponding to the value in Table I.

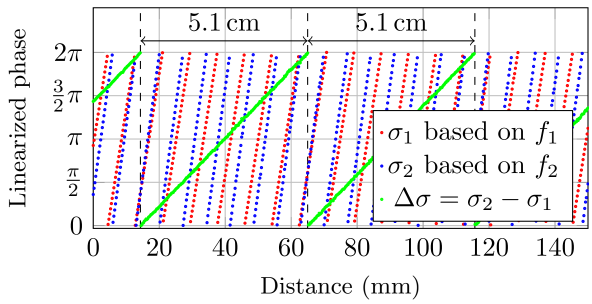


Fig. 10. Linearized phases for waveguide measurements at 24 GHz and a frequency spacing of $f_1 - f_2 = 2.4$ GHz.

From these phase responses, it is possible to detect the ambiguity period of the phase measurement for a single frequency and thus to give an accurate distance information. The results are plotted in Fig. 11 for the first ambiguity period, i.e. the interval from about 15 mm to 65 mm. Due to the high accuracy of the system, the error calculated with respect to the reference system is directly shown. The first plot (a) shows the coarse distance evaluation results for the beat frequency without any compensation or offset correction. The small offset and gain error is compensated in the second plot (b), while in (c) the fine distance evaluation error of one of the single tones is displayed. This is calculated by searching for the correct period of ambiguity in the coarse distance and adding an appropriate offset to the distance evaluation based on a single tone as shown in [16]. The error is below $\pm 25\,\mu\mathrm{m}$ exceeding the accuracy for FMCW, e.g. shown in [17], where a bandwidth of 1 GHz is used achieving a maximum error of 150 µm.

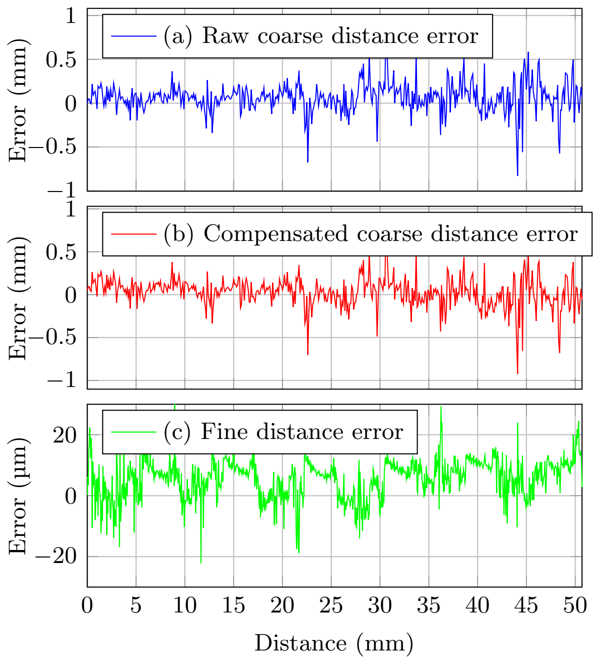


Fig. 11. Waveguide based distance measurements at a frequency spacing of 2.4 GHz within the first ambiguity period of the beat frequency.

To provide an ISM conform and long range capable measurement, a second evaluation with a frequency spacing of only 250 MHz was done. According to Table I this leads to an unambiguous range of approximately 50 cm, although the measurement is limited by the stage to only 15 cm. The results are shown in Fig. 12. Caused by the smaller bandwidth, this measurement has significantly higher errors at the coarse distance detection. In (a) the raw coarse distance evaluation for the beat frequency can be observed. The offset error here is caused by the start position of the measurement, while the gain error can have different influences, e.g. an erroneous calculation of λ_w.

Nevertheless, these linear errors can easily be removed and the resulting compensated coarse distance error in (b) is below a quarter of the value of the single tone wavelengths. Therefore, a fine distance evaluation based on the single phases is possible. The results of this evaluation are shown in Fig. 12(c). Here, the error is higher than for the first measurement, but still below $\pm 40\,\mu\mathrm{m}$ over the whole distance range. The high noise, especially in the mid range, is probably caused by mechanical friction between the slider in the waveguide used as target and

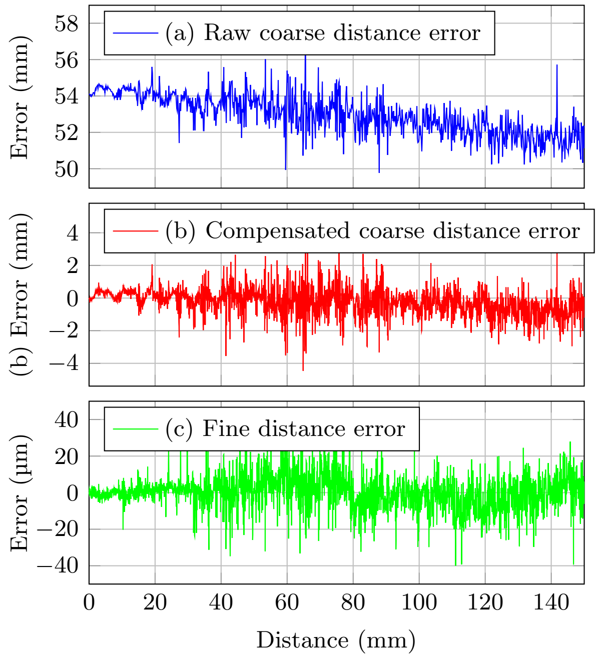


Fig. 12. Waveguide based distance measurement with ISM conform bandwidth of 250 MHz.

the wall of the waveguide, as the error is significantly lower at the beginning of the waveguide within the first distance values.

C. Statistical Analysis

For a better comparison with other systems, Fig. 13 and Fig. 14 show a statistical analysis of the coarse distance error and the overall error, respectively. In both plots (a) depicts a histogram of the achieved error, while (b) shows the cumulative histogram of the absolute value. To distinguish the region for the fine distance evaluation, an error lower than a quarter of the used RF wavelength has to be ensured. Here, this was achieved for more than 99.9 % of all measurements. The slight mean error in Fig. 13 (a) is due to an imperfect gain correction (see Fig. 12 (b)), but it has no influence to the overall system accuracy as long as the error is below a quarter of the used RF wavelength, because the coarse distance is only used to detect the period of unambiguity.

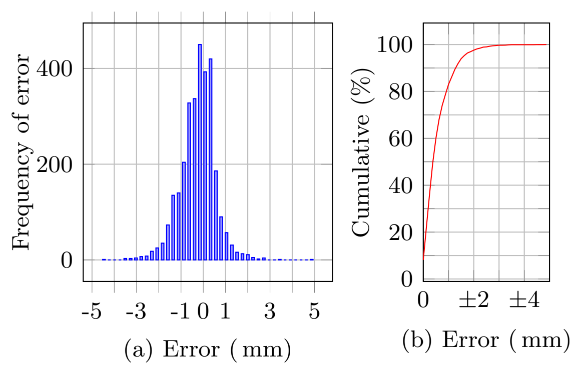
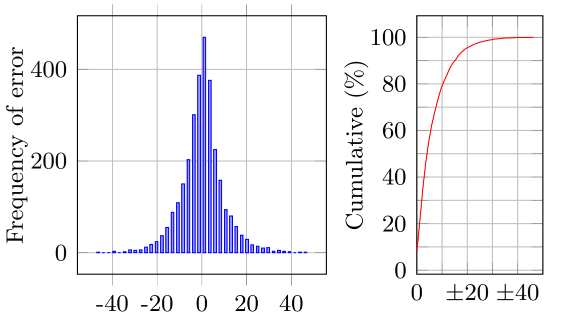


Fig. 13. Histogram of coarse distance detection ($f_B = 250$ MHz).

The statistical analysis of the fine distance evaluation is shown in Fig. 14. The cumulative frequency of measurements yielding an error lower then $\pm 35\,\mu m$ is more than 99.73 %, i.e. within the 3σ range. More than 75 % of the measurement errors are even lower than $\pm 10\,\mu m$.



(a) Error (µm) (b) Error (µm)

Fig. 14. Histogram of fine distance detection ($f_B = 250\,\mathrm{MHz}$).

VI. Conclusion

In this publication a concept for high precision waveguide-based distance measurements has been presented. The system is based on an interferometric Six-Port radar principle, whose unambiguity was realized by a dual tone approach. Measurements in the 24 GHz ISM band prove the theory and show the feasibility of the concept. The precise distance calculation within the waveguide setup shows an error of only $\pm 35\,\mu m$ (3σ) while providing an absolute, unambiguous measuring range of about 50 cm at an ISM conform frequency spacing of 250 MHz. Several points of limitations of the system were discussed, which establishes further opportunities to optimize the system's performance.

Using the proposed system, it is possible to achieve a low-cost and low-latency setup for measuring distances with micrometer accuracy at high update rates, e.g. for tank level monitoring or hydraulic piston control.

References

[1] S. Ayhan, S. Scherr, M. Pauli, and T. Zwick, "FMCW radar in oil-filled waveguides for range detection in hydraulic cylinders," in *Radar Conference (EuRAD), 2012 9th European*, 2012, pp. 63–66.

[2] E. Denicke, G. Armbrecht, and I. Rolfes, "Radar distance measurements in circular waveguides involving intermodal dispersion effects," *International Journal of Microwave and Wireless Technologies*, vol. 2, pp. 409–417, 8 2010.

[3] N. Pohl, M. Gerding, B. Will, T. Musch, J. Hausner, and B. Schiek, "High precision radar distance measurements in overmoded circular waveguides," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 55, no. 6, pp. 1374–1381, 2007.

[4] E. Denicke, G. Armbrecht, and I. Rolfes, "A correlation-based method for precise radar distance measurements in dispersive waveguides," in *Radar Conference, 2009. EuRAD 2009. European*, 2009, pp. 302–305.

[5] S. Lindner, F. Barbon, S. Linz, S. Mann, R. Weigel, and A. Koelpin, "Distance measurements based on guided wave 24ghz dual tone six-port radar," in *European Radar Conference (EuRAD), 2014 11th*, Oct 2014, pp. 57–60.

[6] C. A. Hoer and K. Roe, "Using an arbitrary six-port junction to measure complex voltage ratios," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 23, no. 12, pp. 978–984, Dec 1975.

[7] G. Engen, "The six-port reflectometer: An alternative network analyzer," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 25, no. 12, pp. 1075 – 1080, dec 1977.

[8] G. Vinci, S. Lindner, F. Barbon, R. Weigel, and A. Koelpin, "Promise of a better position," *Microwave Magazine, IEEE*, vol. 13, no. 7, pp. S41 –S49, nov.-dec. 2012.

[9] K. Haddadi, M. Wang, D. Glay, and T. Lasri, "A 60 ghz six-port distance measurement system with sub-millimeter accuracy," *Microwave and Wireless Components Letters, IEEE*, vol. 19, no. 10, pp. 644–646, Oct 2009.

[10] E. Moldovan, S.-O. Tatu, T. Gaman, K. Wu, and R. Bosisio, "A new 94-ghz six-port collision-avoidance radar sensor," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 52, no. 3, pp. 751–759, March 2004.

[11] S. Lindner, F. Barbon, G. Vinci, S. Mann, R. Weigel, and A. Koelpin, "Dual tone approach for unambiguous six-port based interferometric distance measurements," in *Digest of the Impernational Microwave Symposium*, Seattle, USA, Jul. 2013.

[12] J.-R. Yang, D.-W. Kim, and S. Hong, "Quasi-circulator for effective cancellation of transmitter leakage signals in monostatic six-port radar," *Electronics Letters*, vol. 45, no. 21, pp. 1093–1095, October 2009.

[13] S.-G. Kim, H. Kim, Y. Lee, I.-S. Kho, and J.-G. Yook, "5.8 ghz vital signal sensing doppler radar using isolation-improved branch-line coupler," in *Radar Conference, 2006. EuRAD 2006. 3rd European*, Sept 2006, pp. 249–252.

[14] J. Budge, M.C. and M. Burt, "Range correlation effects in radars," in *Radar Conference, 1993., Record of the 1993 IEEE National*, 1993, pp. 212–216.

[15] S. Mann, S. Lindner, F. Lurz, F. Barbon, S. Linz, R. Weigel, and A. Koelpin, "A microwave interferometer based contactless quasi-TEM waveguide position encoder with micrometer accuracy," in *Microwave Symposium (IMS), 2014 IEEE MTT-S International*, June 2014, pp. 1–4.

[16] F. Barbon, G. Vinci, S. Lindner, R. Weigel, and A. Koelpin, "A six-port interferometer based micrometer-accuracy displacement and vibration measurement radar," in *International Microwave Symposium (IMS) 2012, Montreal, Canada*, 2012.

[17] S. Ayhan, M. Pauli, T. Kayser, S. Scherr, and T. Zwick, "FMCW radar system with additional phase evaluation for high accuracy range detection," in *Radar Conference (EuRAD), 2011 European*, 2011, pp. 117–120.

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