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

S. Lindner, F. Barbon, S. Linz, S. Mann, R. Weigel, and A. Koelpin
Institute for Electronics Engineering, University of Erlangen-Nuremberg
91058 Erlangen, Germany
Email: Stefan.Lindner@fau.de Phone: +49 9131/85-28847

***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, extending the unambiguity range to several wavelengths. The system will be presented with measurement results at 24 GHz within a WR42 waveguide to prove the feasibility of the proposed concept.**

***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 having 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].

Alternative solutions to obtain the often required accuracies down to 1 µm are laser based systems, coming with the drawbacks of high costs and a small 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, leading to challenging difficulties for FMCW based systems [1]–[3].

Therefore, the proposed system (Fig. 1) utilizes a low-cost Six-Port based radar, analyzing the phase to distinguish the distance. Furthermore, timing considerations will show the potential as a low-latency system, capable of high measurement data update rates. 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 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.

II. Distance Calculation

A Six-Port-structure can be understood as a homodyne IQ-mixer with differential baseband output signals B_3 to B_6, forming the baseband signal $\underline{z}$ [4]

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

In the context of a Six-Port radar the distance d of a target can be evaluated with knowledge of the used transmission frequency f_{RF} and determining the phase of the complex vector $\underline{z}$

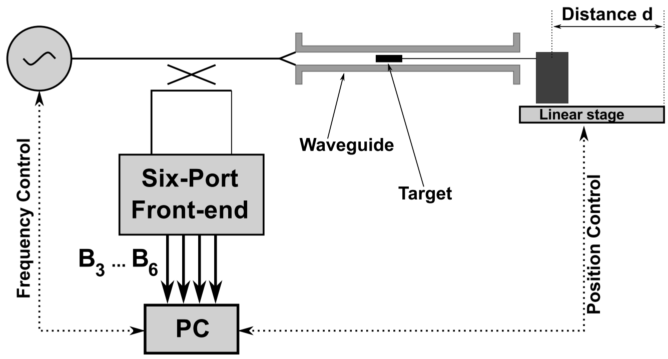

Fig. 1. Measurement setup for waveguide based distance evaluation.

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

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 [5]. Calculating the difference between the two phase responses, an absolute, coarse distance d_{coarse} can be evaluated

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

After 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 rage of d_{max}

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

A further problem arises if the measurement takes place in an enclosed system, e.g. to detect the position of a reflecting target within a waveguide, because the dispersion has to be considered. Due to the field propagation within a waveguide structure, the wavelength of a transmitted signal λ_w within the waveguide depends on the cut-off frequency of the used

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TABLE I

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

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

mode and the free space wavelength $\lambda_0 = \frac{c}{f}$ of the transmitted signal

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

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

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

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

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

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

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

A few examples of possible unambigous ranges at free space propagation as well as within the waveguide are provided in Table I.

III. NOISE LIMITATIONS

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 low bandwidths 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 at the second step.

Fig. 2 shows the simulation results of the system using different frequency spacings f_B from 1 MHz to 2.4 GHz at different noise levels 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 a unambiguous range of 50 cm, this means an overall SNR of lower than approximately 40 dB. To achieve reliable measurements in ranges higher 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.

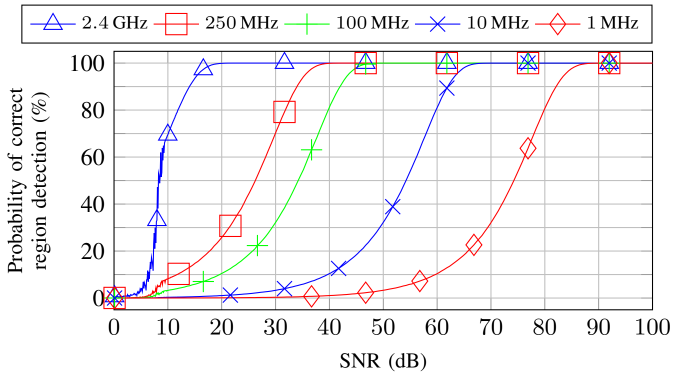

Fig. 2. Simulation results of the usability of the dual tone setup with the influence of additive white gaussian noise.

The shown considerations are only based on noise effects. Additional errors caused for example by multiple target scenarious or non-linearities have to be taken into account separately.

IV. TIMING CONSIDERATIONS

The proposed system has the capability of very high measuring rates, because there is neither a time consuming algorithm, nor long acquisition times for an accurate fast fourier transformation needed. The mainly time consuming parts for the Six-Port radar are settling time of the PLL between the frequencies, digitizing the values, and calculating 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.

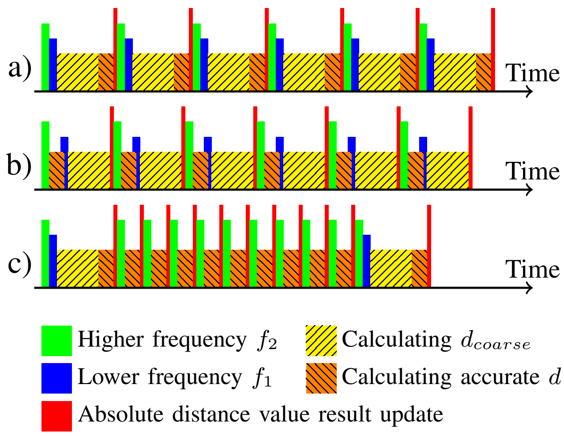

Fig. 3. Different measurement timings for the proposed system.

Nevertheless, this system is capable of high speed measurement value update rates. In Fig. 3 the 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 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 only seldom, for example only at the initialization of the system, and just following the phase jumps by remembering the old distance values. In measurement scenarios where no mechanical target jumps are possible, like in the here described waveguide system, 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 into trouble using the dual tone concept.

V. Measurement Results

For concept validation an *Agilent E8267D* signal generator was used as synthesizer to obtain the two accurate frequencies f_1 and f_2. The target is positioned by a *PiMicos* linear stage. This stage can move over 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 measurement setup for distance evaluation inside a waveguide is shown in Fig. 1. The Six-Port front-end is connected by a coaxial-to-waveguide adapter to the waveguide. The used waveguide has a length of 1 m and the measurements were performed in the middle of the structure. For the waveguide system all measurements were performed over the entire length of the stage of 15 cm to provide realistic results.

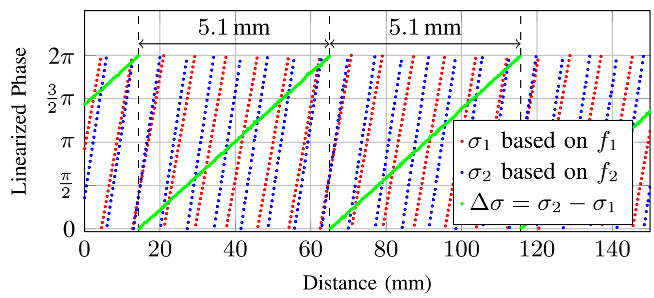

Fig. 4. Linearized phases for waveguide measurements at 24 GHz and a frequency spacing of $f_1 - f_2 = 2.4$ GHz.

Fig. 4 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, having a spacing of 5.1 cm, corresponding to the value in Table I. From these phase responses it is possible to detect the ambiguity period of the phase measurement for a single frequency and thus an accurate distance information. The results are plotted in Fig. 5 for the first ambiguity period, i.e. the interval from about 15 mm to 65 mm. Because of the high accuracy of the system, the error calculated with respect to the reference system is directly shown. The first plot shows the coarse distance evaluation results for the beat frequency without any compensation or offset correction. The small gain error is compensated in the second plot, while in the third plot 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 [6]. The error is below ±25 µm exceeding the accuracy for FMCW, e.g. shown in [7], where a bandwidth of 1 GHz is used achieving a maximum error of 150 µm.

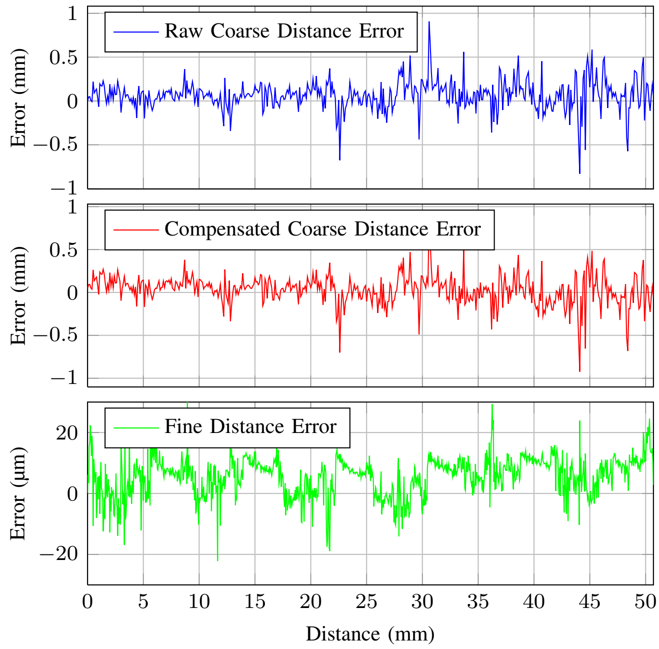

Fig. 5. Waveguide based distance measurements at a frequency spacing of 2.4 GHz within the first ambiguity period of the beat frequency.

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 unambigous range of approximately 50 cm, although the measurement is limited by the stage to only 15 cm. The results are shown in Fig. 6. Caused by the smaller bandwidth this measurement has significantly higher errors at the coarse distance detection. In the first plot 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 could have different influences, for example an erroneous calculation of λ_w.

Nevertheless, these linear errors can easily be removed and the resulting compensated coarse distance error is below a quarter of the value of the single tone wavelengths. There-

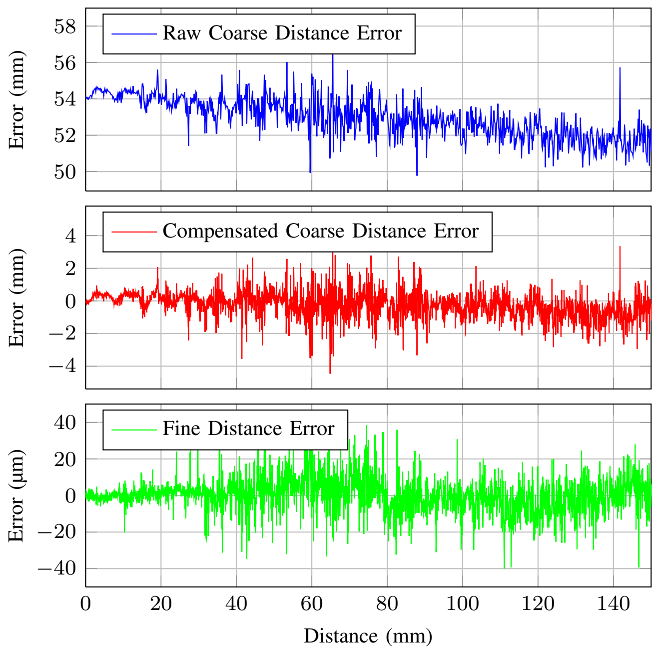

Fig. 6. Waveguide based distance measurement with ISM conform bandwidth of 250 MHz.

fore, a fine distance evaluation based on the single phases is possible. The results of this evaluation are shown at the bottom plot in Fig. 6. Here, the error is higher than for the first measurement, but still over the whole distance range below ±40 µm. The high noise, especially in the mid range, is probably caused by mechanical friction between the slider in the waveguide used as target and the wall of the waveguide because the error is significantly lower at the beginning of the waveguide within the first distance values.

For a better comparison with other systems, Fig. 7 and Fig. 8 show a statistical analysis of the coarse distance error and the overall error, respectively. On the left a histogram of the achieved error is plotted, while the right side 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. In this measurement this was achieved for more than 99.9 % of all measurements.

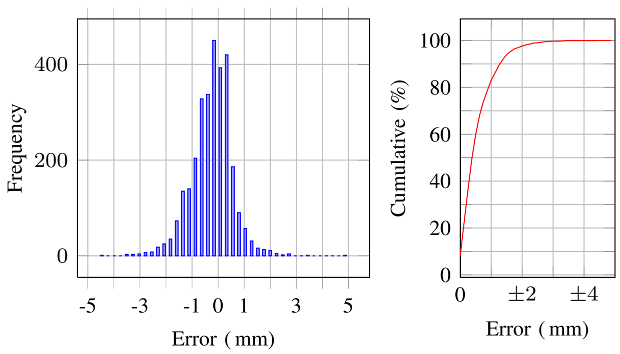

Fig. 7. Histogram of coarse distance detection ($f_B = 250$ MHz).

The statistical analysis of the fine distance evalution is shown in Fig. 8. The cumulative frequency of measurements yielding an error lower then ±35 µm is more than 99.73 %, i.e. within the 3σ range. More than 75 % of the measurement errors are even lower than ±10 µm.

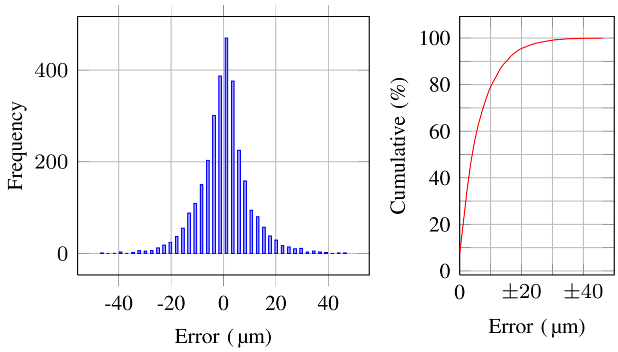

Fig. 8. Histogram of fine distance detection ($f_B = 250$ MHz).

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 accurate distance calculation within the waveguide setup shows an error of only ±35 µm (3σ) while providing an absolute, unambiguous measuring range of about 50 cm at an ISM conform frequency spacing of 250 MHz. 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, "A correlation-based method for precise radar distance measurements in dispersive waveguides," in *Radar Conference, 2009. EuRAD 2009. European*, 2009, pp. 302–305.

[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] 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.

[5] 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.

[6] 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.

[7] 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.