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# A Correlation-Based Method for Precise Radar Distance Measurements in Dispersive Waveguides

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**Abstract**—This contribution deals with guided radar distance measurements in the field of industrial tank level control. The aim is to achieve a submillimeter gauging accuracy even when conducting the measurement within a highly dispersive environment of large and thus overmoded cylindrical waveguides. Normally multimode propagation causes a decrease in measurement precision. Therefore, the effects of intermodal dispersion are fundamentally reviewed and based on these results, a correlation-based signal processing method is presented. The method is able to exploit the otherwise parasitic dispersion effects to enhance the measurement precision even in constellation with a simple waveguide transition or antenna, respectively. Measurement results in a frequency range of 8.5 to 10.5 GHz are provided for two different kinds of waveguide transitions proving the capability of the method.

**Index Terms**—Radar distance measurement, level measurement, radar signal processing, correlation, overmoded circular waveguides, multimode waveguides, intermodal dispersion.

## I. INTRODUCTION

In process instrumentation industry, radar techniques are commonly applied for high-precision distance measurements in free-space applications, e.g. for tank level probing of liquids [1]. In this contribution, however, the measurement is conducted in large tank-mounted metal tubes, often called still pipes or stilling wells, acting as overmoded circular waveguides, as sketched in Fig. 1. In this case the waveguide's feeding section, represented by the utilized antenna or by the respective transition between the mono-moded fed waveguide and the overmoded metal tube, often leads to the excitation and consequently the propagation of higher order modes within the system. To explain the consequences of this matter, Fig. 1 highlights two cases of different waveguide transitions applied in a tank system.

On the left hand side a long conical horn is used, providing a smooth transition between the different waveguide diameters, which thus leads to a quite mode-preserving transmission of the used fundamental mode  $H_{11}$  to the overmoded waveguide. Obtained from a commercial 3D FIT field simulator (CST MICROWAVE STUDIO, Vers. 2009), the electric field distribution of the sole fundamental mode in this case, propagating as a gaussian pulse in time domain (20% fractional bandwidth), is depicted within the left tube as a snap-shot for one point of time. Due to the large tube diameter the mode-inherent (chromatic) dispersion of the  $H_{11}$  mode plays an inferior role [2], so the measurement device is able to receive an almost

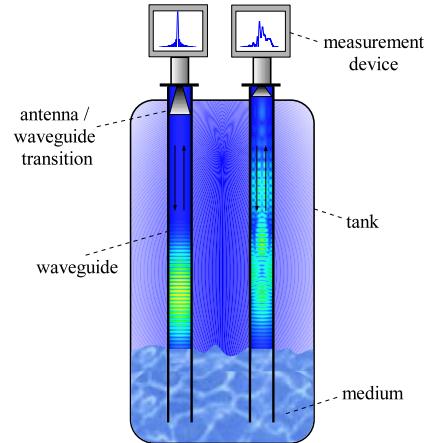


Figure 1. Guided radar distance measurement in an industrial tank environment conducted with two different waveguide transitions

undistorted pulse returning from the surface of the medium. The metal tube on the right hand side is equipped with a shorter conical horn, representative for on the one hand intentionally simple and on the other hand more compact and thus less cost-intensive transitions, which are often requested by industry. As a result, a multitude of modes is excited due to the horn's precipitous flare angles, which thus propagates within the metal tube. Hence, because of the different propagation velocities of each mode's signal portion, the planar phase fronts of the pulse are distorted in comparison to the left hand side. Furthermore the signal energy is more and more spread within the metal tube with increasing propagation distance. This leads to nonlinear phase distortions in frequency domain and to a deteriorated pulse shape in time domain, respectively. Due to this effect the gauging accuracy is significantly decreased, when using conventional free-space optimized signal processing, like pulse-based barycenter computation in time domain [3]. To sum up, retaining conventional signal processing demands for significant effort for the waveguide transition to avoid spurious mode excitation, especially when complying with compact geometrical constraints [4]. Therefore, this contribution deals with a different approach to achieve the desired submillimeter measurement precision. To understand how the method works, initially the influences of multimode propagation, i.e. the two dominating effects of intermodal dispersion and their resultant pulse shape distortion

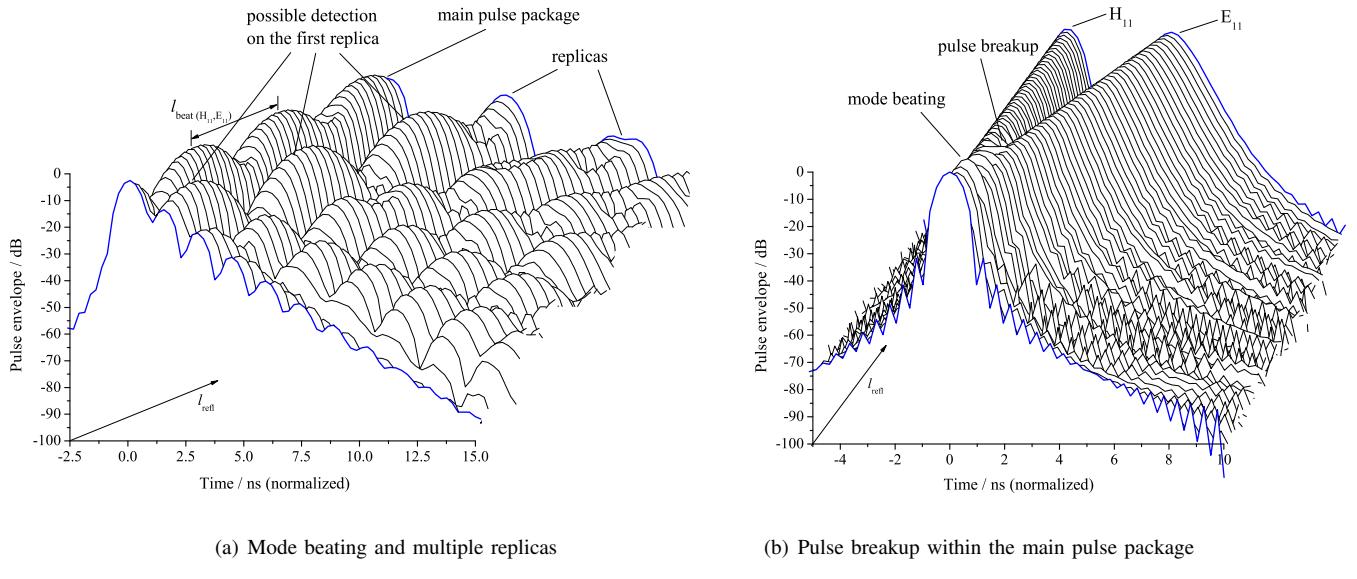


Figure 2. The dominating effects of intermodal dispersion

are described in detail in Sec. II. Subsequently in Sec. III the core of the proposed measurement method is introduced as an alternative correlation-based signal processing algorithm, exploiting the multimode signal distortion. Finally in Sec. IV measurement results indicate the capability of the proposed method.

## II. EFFECTS OF INTERMODAL DISPERSION

In this section the basic effects of multimode propagation on pulse shape deformation are investigated. Based on the theoretical fundament of analytical waveguide equations accounting for the mode-dependent propagation behavior inside the metal tube, a MATLAB-based waveguide simulator is utilized in conjunction with an analytical model of a waveguide transition to synthesize multimode propagation scenarios [2]. Exemplarily, a scenario with only one parasitic mode  $E_{11}$  with a transmission level of  $-3$  dB for the scattering parameter  $|S_{2(E_{11}),1(H_{11})}|$  is assumed. For this case various impulse response envelopes, each with a normalized time axis with the main pulse package at  $0$  ns, are depicted in Fig. 2(a) for an increasing reflector distance in the interval of  $l_{\text{ref}} = [0.2 \dots 0.7 \text{ m}]$ . The curves are obtained from the inverse Fourier transform of the system's reflection coefficient in the frequency domain with a bandwidth from  $8.5$  to  $10.5$  GHz for an inner tube diameter of  $d_{\text{sp}} = 80$  mm. As a basic principle, waveguide transitions, when supposed to be loss-free multi-port devices featuring independent ports for each excited mode, cannot be matched for every single port, if multimode excitation is present [2]. As a result, mode-dependent multiple reflection cycles arise inside the tube, that generate pulse replicas, which may exceed the peak amplitudes of the first main reflection pulse. This evolves from a phenomenon comparable to the "mode beating" effect known from the theory of optical transmission lines [5]. Consequently, a conventional barycentric processing algorithm could unlatch due to wrong detection on pulse maxima of replicas.

An oscillating amplitude can be observed here for each pulse

package due to constructive or destructive interferences between the different modes' signal portions, caused by phase differences due to unequal round trip times for the metal tube, after converting back to the fundamental mode in the monomoded feeding section of the transition. Possible constellations for erroneous detection on the first pulse replica are marked. The period length of the oscillation or the distance between two reflector positions  $l_{\text{ref}}$  with maximal amplitudes, respectively, is approximated by the beat length (compare [6]):

$$l_{\text{beat}}(H_{11},E_{11}) = \frac{\pi}{\beta_{H_{11}} - \beta_{E_{11}}} . \quad (1)$$

The variable  $\beta$  denotes here for the phase constant of the particular mode at the center frequency.

Concerning again the one parasitic mode scenario, Fig. 2(b) depicts the impulse response envelopes for a larger reflector interval of  $l_{\text{ref}} = [0 \dots 5 \text{ m}]$ , whereas pulse replicas are explicitly excluded for illustration purposes.

Evidently, with the present spurious  $E_{11}$  mode, the obtained package consists of two pulses, whereas the  $E_{11}$  pulse is delayed, owing to its higher cut-off frequency and consequently its lower propagation velocity. This leads to a temporal walk-off between the different modes' signal portions, causing a barycenter distortion of the pulse package. Finally the walk-off results in a pulse breakup with increasing reflector distance  $l_{\text{ref}}$  [7]. Hence, for large reflector distances also the intensity of the interferences and thus the beating of the pulse package amplitude decreases. Additionally, the shape of the separated  $E_{11}$  pulse becomes more and more deformed due to its increased chromatic dispersion in comparison to the fundamental mode.

## III. A CORRELATION-BASED SIGNAL PROCESSING ALGORITHM

Being aware of the intermodal dispersion effects, a different approach for a correlation-based signal processing algorithm is derived in this section. As a paradigm shift, the observed dispersion effects are now exploited instead of being usually

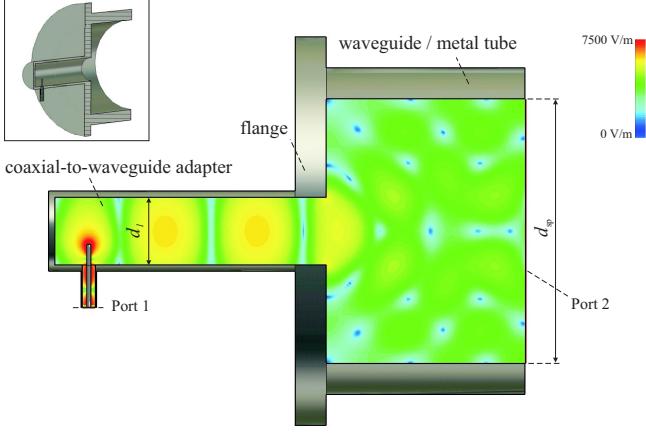


Figure 3. Electric field inside the stepped transition (E-plane)

considered as parasitic. Accordingly, the idea of the proposed algorithm is to evaluate the shape of multimode-distorted impulse responses, whose energy is spread in time domain in a unique way being unambiguously associated with every distinct reflector distance. In this case the analytically describable environment in the metal tube is utilized to generate synthetic reference signals for various reflector distances representing varying medium levels. The developed simulation model rebuilds the measurement setup incorporating a metal tube with a movable plane sliding short [4]. The simulated reference signals are compared with measured signals, under the use of a waveguide transition with an intentionally strong excitation of higher order modes.

The excitation of a variety of higher order modes is quite easy to achieve, e.g. with a simple stepped waveguide transition as used here. Fig. 3 depicts the waveguide transition as a 3D FIT model with its electric field distribution. The transition with a diameter step from the feeding waveguide with  $d_1 = 22$  mm to the overmoded tube diameter of  $d_{sp} = 84.9$  mm basically excites the modes  $H_{11}$ ,  $E_{11}$ ,  $H_{12}$ ,  $E_{12}$ ,  $H_{13}$  with excitation levels  $|S_{2(\text{Mode } x),1(\text{TEM}/H_{11})}|$  of about  $-5$  dB to  $-10$  dB, if propagable. This order of magnitudes leads to massive measurement accuracy deteriorations with an error of partially  $e > 1$  m in the observed interval of  $l_{refl} = [0 \dots 1.229]$  m] in case of conventional barycentric signal processing.

Correlation-based algorithms are often used for echo detection in radar applications, where a measured signal is correlated with the transmitted signal, being equivalent to matched filtering [8]. In this case, the measured signal or the complex envelope of the impulse response  $g_{ce,meas}(t)$ , respectively, is rather correlated with a table of simulated reference complex envelopes  $g_{ce}(t, l_{refl,tab})$  for every feasible reflector distance  $l_{refl,tab}$  in a desired step width  $\Delta l_{refl,tab}$ , specified here without loss of generality in a continuous time notation. This is equivalent to the application of various appropriate matched filters for each  $l_{refl,tab}$ . Moreover, reference signals could also be taken from reference measurements with variable distances, incorporating e.g. a sliding short.

The cross-correlation function  $R(\sigma, l_{refl,tab})$ , as a quantity for similarity between two functions or rather two energy signals

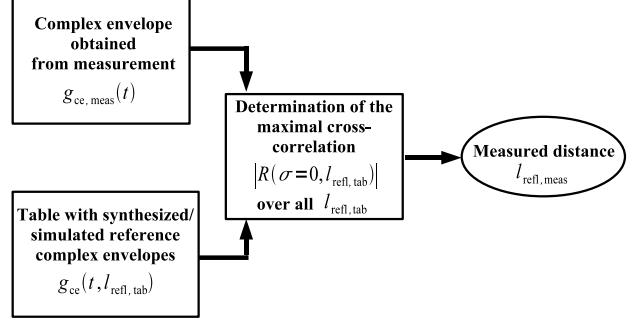


Figure 4. Block diagram of the correlation-based method

here, is defined in accordance to [9], as follows:

$$R(\sigma, l_{refl,tab}) = \int_{-\infty}^{+\infty} g_{ce}(t + \sigma, l_{refl,tab}) \cdot g_{ce,meas}^*(t) dt . \quad (2)$$

Furthermore, each complex envelope is normalized here to a signal energy of unity before performing the calculation. At the global maximum of the magnitude of  $R(\sigma, l_{refl,tab})$  over all  $l_{refl,tab}$  the particular reference distance  $l_{refl,tab}$  is chosen as the measured distance  $l_{refl,meas}$ . In case of an excitation port of the simulation coinciding with the calibration plane in the measurement, maximal similarity is expected for the quasi-autocorrelation, i.e. when the distance  $l_{refl,tab}$  from the reference table matches with the actual reflector distance  $l_{refl}$  in the setup. For this reason the global maximum of  $|R(\sigma, l_{refl,tab})| \forall l_{refl,tab}$  is anticipated to be at  $\sigma = 0$ , rendering possible to avoid the calculation of the entire correlation function.

Accordingly, the measured distance  $l_{refl,meas}$  is defined as

$$l_{refl,meas} = \left\{ l_{refl,tab} \in \{0, \Delta l_{refl,tab}, \dots, 1.229 \text{ m}\} \mid \dots \right. \\ \left. \dots |R(\sigma = 0, l_{refl,tab})| \text{ maximal} \right\} , \quad (3)$$

whereas the procedure is summarized in Fig. 4 as a block diagram. Moreover, to clarify the idea of the proposed method, in Fig. 5 a comparison is made between a measured envelope  $|g_{ce,meas}(t)|$  and a simulated reference one  $|g_{ce}(t, l_{refl,tab})|$  for a distance of  $l_{refl} = l_{refl,tab} = 1.229$  m, which is the maximal length available in the measurement setup. The measurement was conducted with a manufactured prototype of the stepped transition (Fig. 7(a)). A good agreement between both curves exists, which underlines the realistic simulation of the measurement setup. Fig. 6 depicts the absolute values of the cross-correlation function  $|R(\sigma = 0, l_{refl,tab})|$  at an exemplary reflector distance in the setup of  $l_{refl} = 0.6$  m for measurements with the stepped transition and additionally with a mechanically more complex mode-preserving one (Fig. 7(b)), avoiding multimode propagation as introduced in [4]. The correlation is conducted for all reference distances  $l_{refl,tab} = [0 \dots 1.229]$  m]. Thus, for a reference distance  $l_{refl,tab}$  matching with the actual distance  $l_{refl}$ , correlation is high and the theoretical maximum

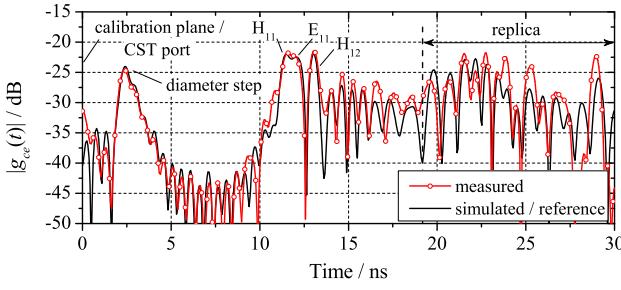


Figure 5. Measured and simulated envelopes for  $l_{\text{refl}} = l_{\text{refl,tab}} = 1.229 \text{ m}$

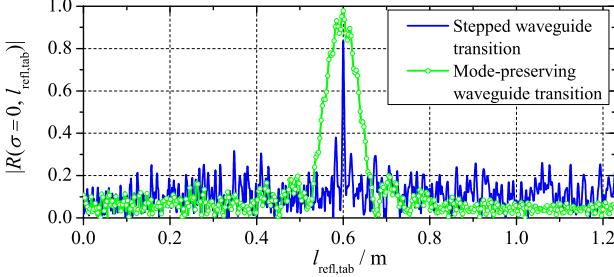


Figure 6.  $|R(\sigma = 0, l_{\text{refl,tab}})|$  at  $l_{\text{refl}} = 0.6 \text{ m}$  for two different transitions

of  $|R(\sigma = 0, l_{\text{refl,tab}})| = 1$  (owing to the energy normalization) is almost reached. The maximal value for the stepped transition is slightly lower because deviations between simulation and measurement setup carry more weight in case of multimode propagation due to signal portions cycling through the system more often. Moreover, the obtained peak in case of this transition is narrower, i.e. correlation with adjacent reference signals in the region of the adequate one declines faster than in case of the mode-preserving transition, which improves the measurement accuracy, if  $\Delta l_{\text{refl,tab}}$  is chosen sufficiently small.

#### IV. MEASUREMENT RESULTS

To verify the capability of the proposed correlation-based method, the resulting measurement error for both transitions is depicted in Fig. 8, whereas a step width of  $\Delta l_{\text{refl,tab}} = 0.2 \text{ mm}$  for the reference table was used. This leads to an error curve resolution of  $0.1 \text{ mm}$ . In case of the mode-preserving transition the curve exhibits a slightly stronger oscillating progression than the stepped one, whereas a marginally inclining progression for both transitions is present, which is attributed to manufacturing tolerances, e.g. concerning the tube diameter. As desired, in both cases a continuous submillimeter accuracy over the total measurement range can be maintained. The measurement results therefore indicate, that despite the multimode propagation a submillimeter accuracy can be achieved, when waveguide transition and signal processing algorithm harmonize.

#### V. CONCLUSIONS

Parasitic intermodal dispersion is revealed as the main distortion effect of guided radar distance measurements conducted in large overmoded metal tubes, if conventional free-space optimized signal processing is applied. This contribution reviews the multimode propagation effects within the waveguide to derive a solution for overcoming the drawbacks of this

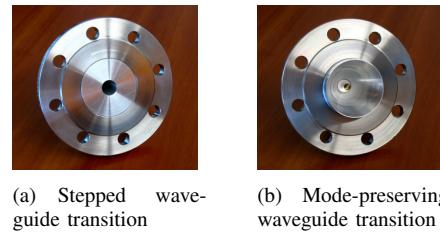


Figure 7. Fabricated waveguide transitions

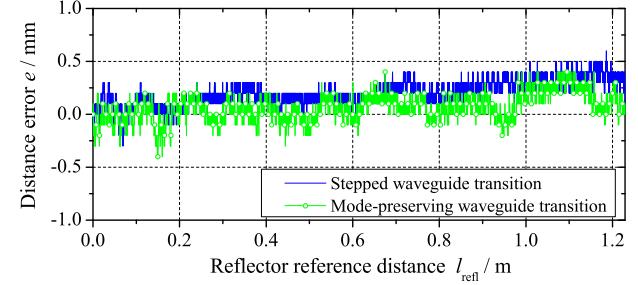


Figure 8. Measurement results for correlation-based signal processing

scenario. An alternative correlation-based processing method is proposed, offering more degrees of freedom and even simplification in the design of metal tube applied waveguide transitions. In this way it is shown that multimode propagation can be exploited to achieve the desired submillimeter accuracy. Consequently, the trade-off between the complexity of the signal processing algorithm and thus its computing intensity on the one hand and on the other hand the expenditure for the waveguide transition is clarified. The accomplished submillimeter precision is validated by measurements.

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