Pulse radar for mm-precision in tank gauging

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The requirements of mm-precision in tank gauging under reference and application conditions are discussed. Decisive parameters of an overall concept (pulse radar, carrier frequency 6 GHz, phase evaluation, selection of antenna) are explained and their advantages illustrated.

1 Tank gauging with mm-precision

1.1 Application

Highly precise automated tank gauges (ATGs) are specifically employed in the storage of liquid hydrocarbons in the petrochemical industry. The API standard demands an accuracy of at least 3 mm (1/8”) across the whole measuring range for operating those systems installed having custody transfer approval [1]. Manufacturers of such tank gauging systems have to provide a certificate that proves an accuracy of at least 1 mm (1/6”) to a reference with an accuracy of at least 0.5 mm (1/32”).

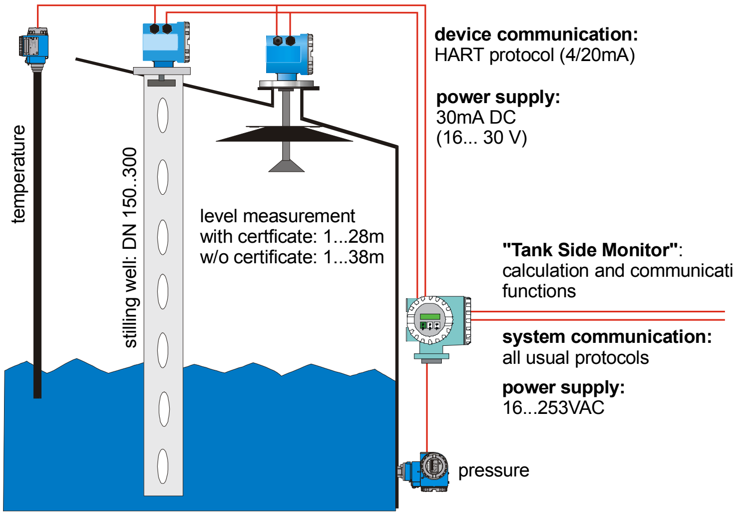


figure 1: Tank gauging system

Level measurement is usually computed together with pressure and temperature values to determine the total quantity of product in a given tank (figure 1). It is obvious that, in view of the high demands on precision, corrections also have to be made in level measurement due to the position of the temperature and pressure-dependent reference points as well as to the thermal and hydrostatic tank expansion.

The calculations described may be usefully solved using an evaluation and communication system that is separated from the actual level measurement, called a “tank-side monitor” as shown in figure 1. This enables the user to freely select the measurement methods and systems to be employed. Furthermore, all communication protocols of the particular control system may be operated at the common interface of the “evaluation system”.

1.2 “Accuracy” of the pulse time-of-flight methods

The “accuracy” of a measuring system is considered to be the reproducible maximum deviation of a sequence of measured values - covering the whole measuring range - from specific reference values. According to OIML R 85 [2], the difference between two measured points must also be within the maximum deviation (under reference conditions 0.02% or 2 mm in case of differences below 10 m).

Contrary to the long-standing dispute among manufacturers of radar level systems that those based on the Frequency Modulated Continuous Wave (*FMCW*) method and those based on the *pulse method* are both able to guarantee an accuracy of 1 mm over a wide temperature range under *reference conditions*.

In the case of the FMCW method, however, a relatively expensive temperature stabilisation of the oscillator must be carried out or an internal reference section installed. Continuous self-calibration is usually required. The pulse method differs insofar that: using a patented procedure [3], the time of flight may be returned directly to a temperature-stable quartz oscillator (cf. section 2.2).

The accuracy of radar level measurement instruments may considerably deviate in *applications* from that under reference conditions. The main reason for this is that the tank itself forms part of the sensor system. The interaction of the microwaves with the tank and its baffles determines, to a large extent, the accuracy that can be achieved (figure 2).

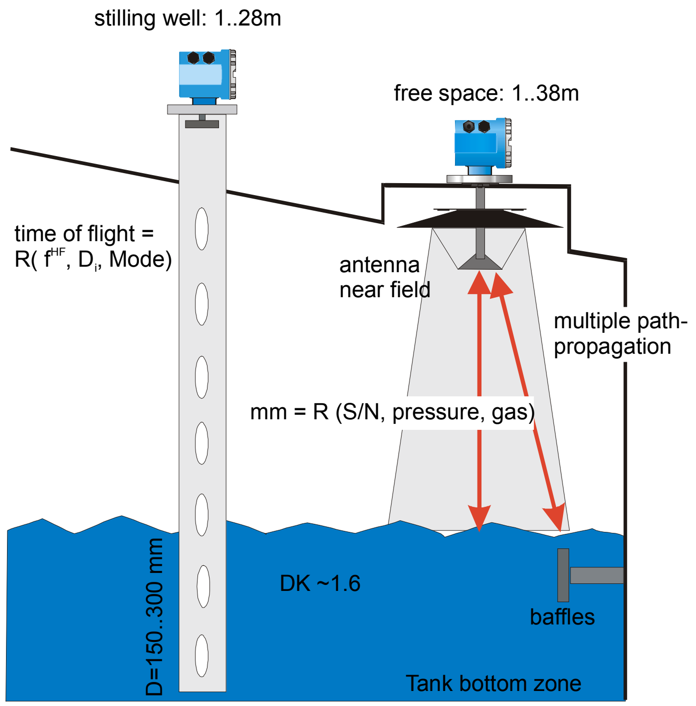


figure 2: Variables influencing application accuracy

Different factors that influence “free field” and “stilling well” can be identified where purely stationary obstacles may be assumed to be present in storage applications:

Free field:

- Impedance skips within the instrument / in the antenna coupling
- Impedance skips within the nozzle
- Interference reflections due to baffles
- Multiple reflections via wall, tank lid or tank bottom (the latter ones particularly in the case of the small dielectric constant of the product to be measured)

Stilling well as above but in addition:

- Time-of-flight changes in the electromagnetic wave with regard to the diameter of the stilling well / build-up within the stilling well, frequency-dependent propagation speed as well as modes having different propagation speeds.
- Mode changes of the electromagnetic wave with inconsistencies (antenna transition, slots, tank connections, ...) within the stilling well

Compared with mechanical tank gauging systems, radar systems offer the advantage that non-linearities with hystereses and “levelling out” of the sensors in contact with the product (floats, displacers) are not present. It is thus possible to trace the level very accurately during the filling and draining operations. Additional cost-savings for the user of “non-contact” instead of “mechanical” measurement methods have been described in detail [4], [5].

2 Modern mm pulse radar technology

2.1 The pulse time-of-flight method

In the pulse time-of-flight method, electromagnetic pulses of a defined (carrier) frequency and band width are transmitted by the measuring system and received after being reflected from the product surface. The time of flight of the pulse Δt - from the antenna to the product and back to the receiver – determines the distance D between the measuring system and the product surface (figure 2):

$$D = \Delta t * c / 2 \tag{1}$$

Determining this time of flight Δt using quartz-controlled timing is therefore unaffected by temperature and is briefly described below.

The carrier frequency may be transposed from the GHz range (high frequency, HF) to the kHz range (intermediate frequency, IF) via sequential scanning of the reflected signals, figure 3.

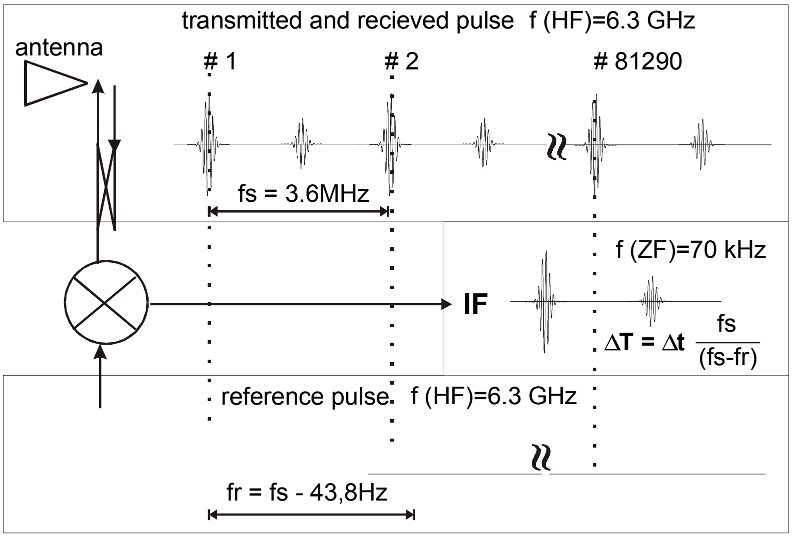


figure 3: Diagram of scanning procedure

Using an extended time factor, the time of flight of the pulses λt is linked to the time of flight of the pulses of the interim frequency λT. This is derived from:

$$\Delta T = \frac{fs}{\Delta f} \bullet \Delta t \tag{2}$$

ΔT can be determined from the product of the echo counter n_s and the scanning rate of the A/D converter τ_s and Δf can be replaced by its reciprocal value τ_Δ:

$$n_s \bullet \tau_s = f_s \bullet \tau_\Delta \bullet \Delta t \tag{3}$$

τ_Δ is measured with a counter having the same quartz time basis as the A/D converter controlling the interim frequency. τ_Δ can also be written using n_Δ (counter value) and τ_s (scanning rate of the A/D converter):

$$n_s \bullet \tau_s = f_s \bullet n_\Delta \bullet \tau_s \bullet \Delta t \tag{4}$$

This equation may now be solved for Δt:

$$\Delta t = \frac{n_s}{n_\Delta} \bullet \frac{1}{f_s} \tag{5}$$

The frequency of the quartz controlling the rate of repetition of the transmitted pulse as well as the evaluation of the two counters of n_s and τ_Δ is thus the only electronic variable in time-of-flight measurement, figure 4.

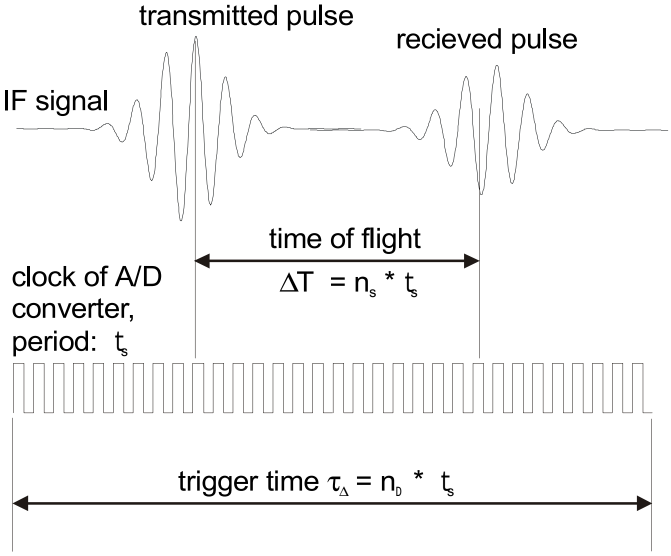


figure 4: Return of quartz-based time measurement

This quartz has been specified with a maximum change in frequency of 10 ppm for the total temperature range appropriate for custody transfer (-20°C to +60°C).

The scanning rate of the A/D converter must be chosen at a high enough level to achieve a suitable evaluation of the counters of n_s and τ_Δ. Employing the additional phase evaluation described below, the time of flight can now be measured with sufficient accuracy.

2.2. Phase evaluation of reflected signals

The band width of the carrier frequency is a decisive factor for achieving the accuracy inherent in all radar methods; a band width of 1.6 GHz can already reach a precision of 3 mm under ideal conditions, with the amplitude evaluation ("envelope curve evaluation") of the scanned reflected signals described above.

However, in order to guarantee an accuracy of 1 mm demanded for operation, a phase evaluation of the interim frequency signal relative to a reference oscillator is required. The algorithm for this is known as IQ demodulation. [5]

The phase of the interim frequency can define the distance to a target object with an ambiguity of N wave lengths. With respect to the level, the ambiguity doubles to multiples of N/2 wave lengths or λ/4, in which λ is the length of the electromagnetic wave.

The amplitude evaluation of the envelop curve therefore demands at least an absolute accuracy of λ/4.

max. allowable error “envelope curve evaluation” = $\lambda/4$ (6)

An accuracy of the “envelope curve evaluation” of 12 mm is required when using 6 GHz pulses.

This explains the application advantage when using 6 GHz pulses since the demands on the accuracy of the envelope curve evaluation increase with increasing carrier frequency. Because of multipath propagation of the electromagnetic waves or of interfering reflections, typical errors amount to 10 mm so that using 10 GHz pulses can lead to considerable problems.

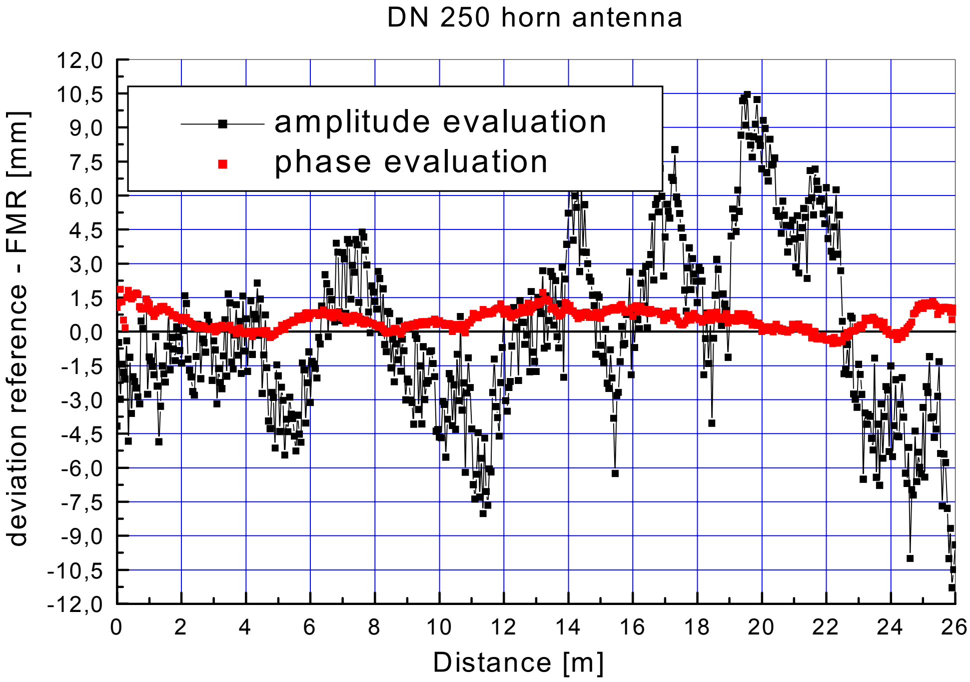


figure 5: Comparison of measured errors due to the effects of the wall (multipath propagation). In pure amplitude evaluation, measured errors of 10 mm occur, in measurement with an additional phase evaluation to achieve an accuracy of 1 mm is achieved (6 GHz, DN 250 horn antenna, distance from the wall is 600 mm).

Figure 5 clearly shows that the phase evaluation reduces the magnitude of the error by a factor of approximately 10. The test shows the level gauge mounted close to the wall (10” horn antenna, 600 mm from the wall). Measurement with a carrier frequency of 10 GHz would not be successful in this case because the envelope curve cannot be evaluated to the required minimum accuracy of $\lambda/4$ = 6mm.

2.3 Advantages of mm-pulse radar technology

Apart from the advantage of pulse radar technology already described, which does not require temperature stabilisation, there are further positive generic features, cf. table 6.

The FMCW method supplies power to the oscillating systems for approximately half the operating time. Pulse systems, however, are operated intermittently with the oscillators working only approximately 1/400th of the operating time.

The reduced power consumption to only 320 mW of the mm-pulse systems has been used for developing cost-effective “2-wire” systems with two standard 4-20 mA signal wires. The intrinsically safe versions for hazardous areas offer a further advantage: the housings may be opened on site without the need of workshop manipulation. By using standard 24 V power supplies fed by e.g. DCS systems, the customer also has reduced wiring costs. Finally, pulse systems as described here offer a high degree of operational safety because no “mains on the roof” of the tanks is required.

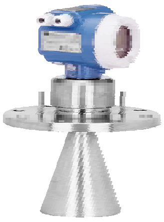
Since pulse systems consist of approximately 30% fewer components than FMCW systems, there is less weight and, above all, there is a more favourable MTBF.

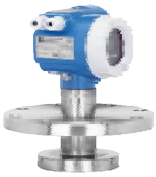
3 Fully-comprehensive systems

3.1 System concept

A fully-comprehensive concept of radar systems is of critical importance for industrial operation. Because of the wide range of application conditions, the instruments must be flexible as far as antennae, process connections, explosion protection classes and many other items are concerned. A special feature of the *Micropilot S* line from Endress+Hauser is, for example, that all systems offer a gas-tight gland for the antenna. This “second line of defence” is of great significance for users handling highly toxic or diffusive products.

However, in order to minimise maintenance costs, users demand uniform systems with respect to spare parts and operation, integration into existing control and communication systems and the use of standard tools. The system shown in Table 1 is integrated into a comprehensive concept which has also served in the development of radar systems for a “standard application” by the same manufacturer. All radar systems may be installed, analysed and documented using the same “Time-of-Flight” PC-based operating software tool. This is available at no extra cost.





Micropilot	**FMR 530**	**FMR 531**	**FMR 532**	**FMR 533**
Temperature	-40°C...200°C	-40°C...150°C	-40°C...150°C	-40°C...200°C
Pressure	64 bar	40 bar	40 bar	16 bar
Measuring range	38 m	20 m	38 m	38 m
Material	1.4571	PTFE	1.4435	1.4435
Sealing	Kalrez, Viton	No O-ring	HBNR, Viton	No O-ring
Option among other items	Suitable for custody transfer	...	Suitable for custody transfer	Suitable for custody transfer
Assembly	Free field / stilling well	Free field	Stilling well	Free field

Table 1: Specifications of Micropilot S - types

Features (**USPs**):

- low weight: “one man can carry two instruments”
- flexible mounting distance to wall using patented algorithms
- operation on site by menu-driven, alphanumeric display
- scalable, price-flexible systems: true stand-alone versions and additional “tank-side monitor” for custody transfer applications
- 24V DC power supply – “no mains on the roof”
- intrinsically safe versions – open housing during operation
- second line of defence due to gas-tight gland
- commissioning and documentation by a uniform “Time of Flight” tool

3.2 Free-field applications

“Free-field applications”, i.e. those tank installations in which microwaves may be freely emitted into the interior of the tank, are suitable for highly accurate applications, especially with versions having a parabolic antenna. The best possible radiation cone may be achieved with a large aperture.

It is also preferable to use 6 GHz pulses with regard to the absorption bands of water, ammonia and oxygen. At frequencies around 10 GHz, these low atomic weight compounds absorb a considerable part of the energy because of the pressure broadening of their rotational spectra.

Although free-field planar antennae usually have to be installed very close to the wall of the tank, parabolic antennae enable the distance to the wall to be freely chosen. Because of the patented compensation of multipath propagation integrated into the software, installations close to the wall also ensure high measuring accuracy.

3.3 Applications in stilling wells

Uneven surfaces inside the pipes (welding seams, build-up, tapered pipes, etc. (cf. Section1.1) may lead to interference in applications in stilling wells if the flux lines of the electromagnetic waves are oriented at random. In order to prevent this, a special planar antenna has been developed that generates a dynamically balanced orientation of the magnetic flux lines so that the electric flux lines do not touch the wall (TE01 mode), fig. 7.

figure 6: Planar antenna of FMR 532 generating TE01 modes for applications in stilling wells.

4. Summary

Pulse radar systems with a carrier frequency of 6 GHz and an additional phase evaluation offer the user cost-saving advantages. Not only does this ensure a high degree of measurement reliability their relatively low installation and maintenance costs are due to the technical principles described in this article.

Abbreviations

A/D	analogue / digital
c	speed of electromagnetic pulses
f_s	rate of repetition of the sending oscillator
f_r	rate of repetition of the reference oscillator
Δf	difference in rates of repetition of sending and receiving oscillators = $1/\tau_\Delta = f_s - f_r$
D	distance
FMCW	Frequency Modulated Continuous Wave
HF	high frequency (signal)
n_s	difference of the counter values determining the position of the reference echo and the target echo
n_Δ	value of the counter measuring the difference in repetition rates of sending and receiving pulses Δf
N	natural integer
MTBF	Mean Time Between Failure
ΔT	time of flight in units of interim frequency
Δt	time of flight in units of absolute time
τ_s	scanning interval of the A/D converter of the interim frequency
τ_Δ	time of synchronisation between sending and receiving oscillator
IF	interim frequency (signal)

Literature

[1] American Petroleum Institute (API): Measurement Standards. Section 3: Tank gauging. 6th draft of the proposed second edition, August 1999.

[2] OIML R 85 , table 1, automatic level gauges for measuring the level of liquids in fixed storage. Paris, 1998.

[3] EP 0355 537 A1

[4] Heim, M.: Auf höchstem Niveau. Verfahrenstechnik INTERKAMA Report 1999, Vereinigte Fachverlag GmbH, Mainz, Oct. 1999.

[5] Dressler, Th.; Trilling, U.: Instandhaltung in der prozeßnahen Technik – Cost of Ownership. VDI Berichte Nr. 1282, Düsseldorf, VDI, 1996.

[6] Ludloff, A.: Handbuch Radar und Radar Signalverarbeitung. Kapitel 5: Grundlagen der Filterung von Radarsignalen. Vieweg Verlag, 1993

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