Ultrasonic Ranging in Air – Impact of Sensor and System Design Elements on the Attainable Accuracy

Herbert F. Schweinzer[1,#] and Georg Kaniak[1]

1 Institute of Electrodynamics, Microwave and Circuit Engineering, Vienna University of Technology, Gusshausstrasse 25, A-1040 Vienna, Austria
Herbert F. Schweinzer / E-mail: herbert.schweinzer@emce.tuwien.ac.at, TEL: +43-1-58801-35440, FAX: +43-1-58801-35499

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Ultrasonic ranging in air is known as easy and cheap technique with limited accuracy. Its industrial application mostly demands a well-defined arrangement of measurement tools to guarantee correct results. On the other hand some advantages of applying ultrasound as e.g. working in dark, foggy and dusty environment creates a vital interest in this technology. There is a need of generic ultrasonic sensing and of using the potential of attainable accuracy which is exceeding significantly the common use. On base of scientific work of years, this paper tries to give an overview over the various sensor and system design elements and over techniques which can be included in setting up a generic ultrasonic system with high accuracy. Two realized systems shortly show applications of these elements: An ultrasonic sensor system for scene analysis which enables to create a picture of the environment on base of its movement, and an ultrasonic locating system which delivers device positions with high accuracy.

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1. Introduction

Ultrasonic (US) ranging in air is a frequently used method to gain information on distance, position and orientation of objects. Offering cost efficient solutions for that task, numerous techniques are applied mostly for industrial and professional applications. Additionally, some environmental conditions as e.g. dust, fog and darkness encourage the use of ultrasound which can be well applied in such situations. However, US ranging systems often suffer from low accuracy which significantly reduces the applicability in critical cases.

The design of US sensor systems is depending on various parameters: cost and technology of transducers, especially bandwidth; matching to air impedance and maximum measurement range; active measurement between US transmitter and receiver or passive signal echoing of objects back to a transmitting and receiving transducer; measurement protocols; signal processing algorithms. Besides different functional characteristics alternatives have their specific implication on the accuracy which can be realized. The main approach for attaining a high accuracy of ranging is using broadband signals and sophisticated signal processing in time or frequency domain. However, based on a precise time measurement the accuracy primarily depends on the knowledge of the speed of ultrasound in air which is influenced by different environmental parameters, e.g. temperature, humidity and motions of the air. A general provision for these parameters can be achieved by reference distances which allow correcting each measurement. Influences of dynamic changes depend on the measurement protocol and can be reduced by calculating mean values. By these means and based on a measurement resolution of <0.1mm, an accuracy of ±0.1mm can be reached for distance measurements. After discussing the impacts on the measurement accuracy the paper will shortly demonstrate methods used by two US systems which were investigated at the EMCE: a US distance and angle sensor, and an US locating system (“Indoor GPS”).

2. Aspects of US Ranging

2.1 Application of Ultrasound in air

Because of significant influence of environmental parameters on US signal propagation, mainly of wind, the outdoor use of ultrasound is dedicated to specific applications. Car parking aids and collision detection systems are well-known and typically short-range. Special Continuous-Tone-Frequency-Modulated (CTFM) signaling enables the operating of automatic lawn mowers which are recognizing trees and enables also aids for an effective orientation of blind persons [1].

Indoor US sensors are mainly used as ranging tools with manual operation or included in an automated industrial system. Some preconditions are often used: only the first echo is evaluated in complex environment which responds to the US signal with lots of echoes. However, a measurement of the sequence of echoes is possible (refer to chapter 4.2). Further, distance measurement demands a Line-of-Sight (LoS) condition.

2.2 Types of measurement

Basically, the distance *T*–*R* between Transmitter *T* and Receiver *R* is determined by a Time-of-Flight (ToF) measurement using the knowledge of the US speed in air and demanding a given LoS condition. The result is a mean value over the signal travel path which can be influenced by wind and temperature changes. An alternative are Time-of-Arrival (ToA) measurements of multiple signals which enables calculating the Time-Difference-of-Arrival (TDoA) of pairs of arrival times.

2.3 Transducer types

An important transducer feature is the bandwidth. A narrowband transducer has an explicit resonant behavior which creates a long transient oscillation. Thus, broadband transducers allow transmitting short signals which enables high accuracy of time measurements.

A second point is the signal energy: the measurement range is primarily influenced by the Signal/Noise Ratio (SNR). To get high signal energy the transmitter matching to air impedance is important.

Different technologies of US transducers are applied. The piezoceramic type is often used because it is robust, cheap and well-suited for industrial use. However, it has a significant resonant behavior (narrowband) and a bad matching to air impedance. Electrostatic transducers are also frequently used. They are broadband and have a good sound power, but they are only medium robust and therefore not often used in industrial environment. Foil transducers offer a high bandwidth. However, they can be easily damaged and reach only low sound power. Two types are sometimes used: PVDF (polyvinylidenfluorid) foils and Ferroelectret foils which are under investigation.

The radiation pattern of a transducer typically features a main lobe where the maximum signal amplitude is transmitted. Side lobes are neighboring to the main lobe. Transmitting via a side lobe is characterized by reduced signal amplitude and a phase shift with respect to the main lobe (Fig. 1). The width of the lobes is frequency dependent. If transmitting parts of the signal via side lobes, phase shifts result in the effect that broadband signals are changed and therefore not recognized. If the changed signal shapes are stored comparisons with the actual signal deliver the angle of transmission.

2.4 Signal processing and accuracy of ToA/ToF measurement

The basic method used to detect a received signal is applying a trigger level. The resulting uncertainty is quantized with the wave-length (full or half) and is depending on signal amplitude and rise time. Precise signal detection for high accuracy of ToA/ToF measurement requires more sophisticated techniques [2][3].

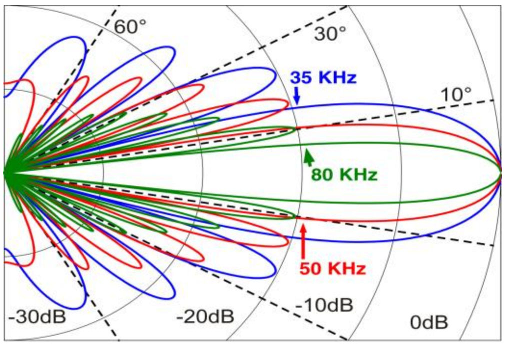

Fig. 1 Frequency dependent radiation pattern (piston membrane)

The use of narrow signal bandwidth applying e.g. highly resonant piezoceramic transducers implies a variety of problems. For more accurate signal detection the signal has to be frequency modulated within some time (in the range of much ms). Long signals increase the probability of signal overlapping while additionally the capability to separate overlapping signals of small bandwidth is reduced.

Applying coded signals using a broad bandwidth can overcome these problems. Depending on the available bandwidth short signal (≤ 1 ms) can be used. Also the separation capability of overlapping signals increases with the bandwidth. Utilizing correlative echo detection a high accuracy (<1mm) in ToF estimation can be reached.

2.5 Signal coding

A basic type of coding are sinus signals with rising or falling frequency, so called chirps, often inspired by the echo-location of bats where some species use similar signal types. Pseudorandom noise (PN) codes offer a more general approach to broadband coding [4][5]. Especially several orthogonal signals can be used for simultaneous transmitting which reduces problems with multiple access interference (MAI) [6].

Coded signals are mostly well adapted to suppress noise. The minimum level of the SNR which allows proper signal detection depends on the effort of signal detection. Signal disturbances in the used frequency range are similar to multiple signal access. Among others, an effective suppression depends on the amplitude ratio of signal and disturbance.

Inter signal interference (ISI) by echoes and multipath signal propagation is frequently occurring. It is mostly resulting in a partially signal overlapping with a time delayed signal copy. The signals can be separated if the delay exceeds a minimum value. Under this delay value the stronger signal dominates or the both signals are melted to a single differently shaped signal. The impact of the signal amplitude is called "Near-Far problem". This is a condition in which a strong signal captures a receiver making it impossible for the receiver to detect a weaker signal.

If transmitter and/or receiver of a ranging system are moving with enlarged speed, the Doppler effect becomes operative. Since received frequencies are shifted by a certain value the signal coding is changed. Knowing the transducer speed the Doppler effect can be compensated.

3. Sensor and System Components

3.1 Sensor design elements

The use of the same transducer for transmitting and receiving is very common, as it reduces costs. However, severe disadvantages arise from this approach. First the minimum distance of a reflector is increased as simultaneous transmitting and receiving is usually not possible. Further the effect of the directional characteristic of the transducer occurs twice, squaring the effect of the directivity. This leads to an undefined angle range where broadband signals can also be received in some parts of side lobes.

Using a transmitter and separated receiver(s) yields some advantages. Besides the fact that the distance to the reflecting object can be short, the use of separated receivers opens additional possibilities as relatively cheap receiving elements are now available that are almost omnidirectional. Therefore, the detection area is well-defined and increases if also signals transmitted via the side lobes are evaluated. As direction dependent phase shifts can be recognized by such a system this effect may be used to limit the detection area to a well defined main lobe, but also to accurately detect side lobe signals [7][8][9]. Also multiple omnidirectional receivers can be used for direction estimation by evaluating the time difference of arrival.

3.2 System components

Two types of system components are used: "passive" and "active" sensors. Passive sensors are only receiving while active sensors are additionally initiating US signals themselves. Passive sensors receiving US signals are able to detect random US signal sources anywhere. This sensor is containing some receivers (1 to n microphones) and is able to realize a Direction-of-Arrival (DoA) estimation if using three or more receivers. Passive sensors can perform ToF measurements if a fast start signal of the US emitting unit is available via a fast link e.g. RF, IR, or cable connection.

Active sensors allow measurements of received echoes of self-transmitted US signals. The sensor contains both transmitters (1 or more) and receivers (1 to n microphones). This approach includes the classic echolocation process for obstacle avoidance and scene analysis in robotics. The echo returns to the sensor from objects that have a surface normal pointing towards the sensor for specular reflectors or from diffuse reflecting objects. The reflectivity depends on the geometry of objects. Besides concave focusing reflectors, specular planes provide the best reflectivity. As the starting time of the transmission is known, ToF measurements can be straight applied in such a system. Direction estimation can be done by using three or more receivers. However depending on the spacing of the receivers different reflection points occurs for each receiver assuming specular reflections.

4. System types

4.1 Distance measurement

Three system types can be distinguished. The so called "A-B measurement" (transmitter A, receiver B) is used for distance measurement between two well-defined points. An external start signal is necessary. The measurement can be influenced significantly by wind.

Further, an echo measurement uses the ToF measurement of a transmitted and reflected signal to estimate the distance of the reflecting object. An external start signal is not required. The influence of wind is reduced due to the alternating influence for the two signal paths to and from the object.

An "active reflection" system represents an enhancement of the A-B measurement. The receiver B responds to the transmitted signal from A with a response signal after a well defined time delay. The influence of passive reflectors near the signal path can be eliminated by different signal coding. The influence of wind is reduced.

4.2 Scene analysis

Scene analysis deals with the recognition of object position, orientation, size and shape by US echo measurements. The methods connected to scene analysis are mainly used in the field of robotics for map building, path planning and collision avoidance [10]. The low speed of sound in air as well as the specular environment in indoor situations inhibits active scanning techniques. Desired is to evaluate multiple echoes after each US signal shot in a broad angle range. Sensor movement generates a trace of reflection points on objects that can be used to determine shape and position. Full 3D data of reflection point's positions requires ToF and DoA measurements. Frequently overlapping of echoes demands a good echo separation capability of the signal processing. Also the correspondence problem of assigning echoes detected on different receiver channels to the corresponding object has to be considered [11].

4.3 Local Positioning System (LPS)

Local positioning systems are based on A-B measurements using ToF or ToA information and trilateration or pseudo-trilateration algorithms for determinig the 3D position of a device. For trilateration at least three ToF measurements are needed, for pseudo-trilateration at least four TDoA measurements are needed. Other possible approaches are triangulation systems using at least three DoA measurements.

5. Critical physical influences

Imperative for ultrasonic distance measurements is the existence of a LoS connection between transmitter and receiver for A-B measurements or transmitter-reflector-receiver for reflectory measurements. Already small objects in the signal path can cause diffraction effects. In specular environments multipath propagation via one or more reflectors is likely to occur. Detecting multipath propagations is a challenge and demands additional information.

The reflectivity of objects depends on their geometry and surface conditions. But also the directional characteristic of the transducer reduces the amplitude at higher angles of transmission. Thus, at long distances or high angles only good reflectors will be detectable.

The air temperature has a strong influence on the speed of sound; so good temperature compensation is important [12]. For moving objects additional Doppler shifts of the frequencies occur and have to be taken into account.

6. Design Criteria and Attainable Accuracy

6.1 Compensation of temperature influence

Temperature compensation is imperative if accuracies in the distance measurement in the range of millimeters or below shall be reached. The common method is to measure the temperature at the sensor and to assume a homogenous temperature distribution in the measurement area. However, small scale temperature changes and air turbulence can still cause problems.

A better way, although not applicable in all situations, is the use of a reference reflector or a reference receiver in a well known distance,

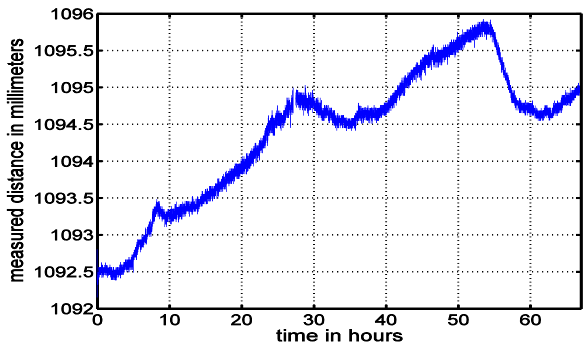

Fig. 2 Raw data of long time distance measurement

preferably close to the object to be measured. The advantage is that the speed of sound can be adjusted for each single measurement resulting in a high accuracy around ±0.1mm. By averaging of several measurements the reachable accuracy can be further improved.

Figure 2 shows distance values for a long time measurement (over three days) under room conditions for a assumed fixed speed of sound without temperature compensation. The temperature changes between day and night are clearly visible. Additionally to the measured object in about 1094mm distance a reference reflector was placed about half the way at 500mm. Figure 3 shows the same data corrected with a reference measurement for each single measurement.

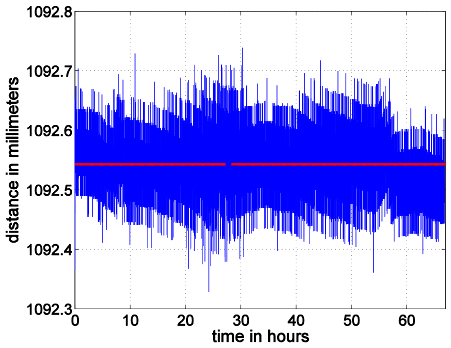

Fig 3 Temperature compensated by reference measurement

6.2 Suppressing influence of object shape

As mentioned the object geometry has a strong influence on the reflectivity. Signal processing methods that suppress the amplitude influence contribute to the general applicability of the sensor. A good option is the use of a polarity quantization of the signals. Together with correlative signal detection of broadband signals amplitude independence can be reached over a wide range. This method omits realizing a big dynamic amplitude range which would be needed for analog signal processing.

For multi-receiver systems the object geometry causes different more or less spaced reflection points on a single object. This effect results in systematic distance deviations of the distance measurements. The error decreases with decreasing receiver spacing. So it can be reduced by a compact sensor design, however for the price of a less resolution of the direction estimation caused by the lower resolution of the DoA measurement [13].

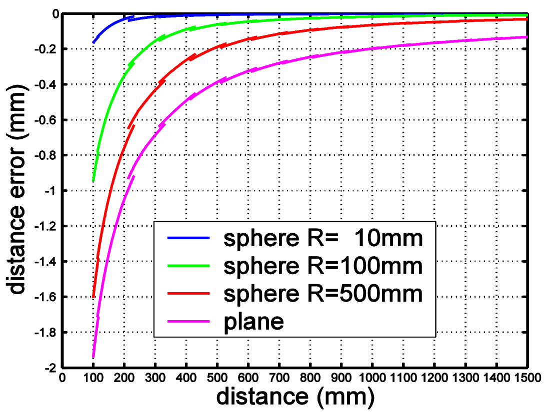

Fig. 4 Object dependent distance error for a receiver pair spaced 80mm with transmitter in the center; object radius R

Figure 4 shows the distance error for a 'binaural' two receiver configuration often used for scene analysis tasks. The distance error decreases with rising distance of the object. So it is important to choose a receiver spacing that is appropriate for the desired distance range.

Figure 5 displays a further advantage of a compact sensor design: The signal paths of parallel channels are close together and therefore a common impact of disturbances on all channels is likely. Thus, differences of channel signals as used for DoA estimation suppress these disturbances.

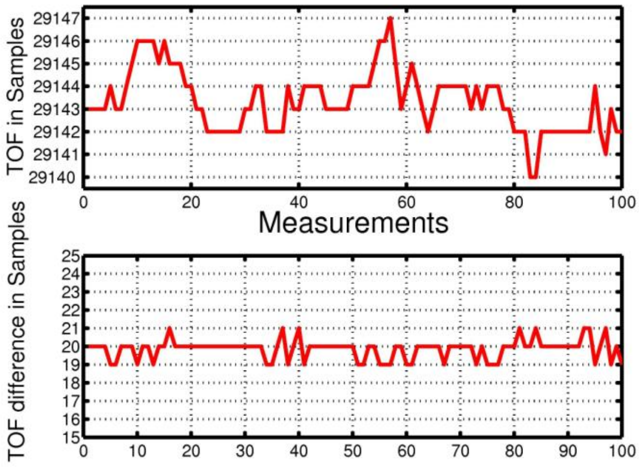

Fig. 5 Suppression of common-mode ToF errors in the difference of two receiver channels of a compact sensor design

6.3 Redundancy of measurement

The use of more receivers or transmitters than necessary can provide additional information to deal with ambiguities. So for LPS systems multi-lateration can be used instead of tri-lateration. Also possible linearization of the equations systems by additional information can enhance the calculation. For scene analysis the use of more than three receivers also can contribute to resolve signal overlaps or to detect erroneous measurements.

Redundancy is a main method for recognizing artefacts. Artefacts are objects measured in certain positions which, however, do not exist. A reason for that can be multipath signal propagations where the signal is reflected by several objects (minimum 2) before returning to the receivers. In that case both ToF and DoA estimations are wrong. This wrong measurement is often combined with a right LoS measurement. However, in case of missing LoS artifacts can also be the only measurement results.

7. Example "Active sensor for scene analysis"

Exemplary for multi-receiver systems based on reflective pulse-echo measurements is the system presented in [13]. The DoA measurement at two receiver pairs arranged as a cross with the transmitter in the center gives two direction angles. The configuration is shown in figure 6. By additionally evaluating the ToF the 3D position of a reflection point in a specular environment can be estimated.

Utilizing sensor movement, the traces of reflection points on the object surfaces can be measured and object geometries can be determined to establish a 3D model of the scene. The compact sensor design with the transmitter-receiver distance a=40mm allows an estimation of the reflection point that is independent from the object geometry, as the object dependent error may be neglected.

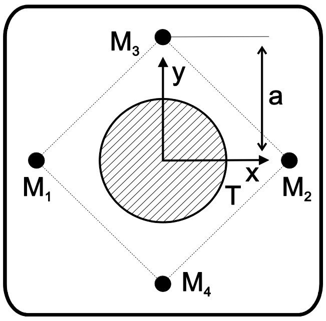

Fig. 6 Configuration of a four-receiver system

Additionally the use of broadband signals with correlative echo detection allows accurate distance measurements, while the implemented polarity quantization provides amplitude independence. Figure 7 shows the result for a scene measurement of the system. The sensor was moved along a linear robot axis. The sensor positions in the foreground are marked red. In the background the measured reflection points on different objects are displayed. In the back is a plane reflector; a cylindrical object and an edge reflector (rod with diameter 10mm) are positioned before the plane. The objects are fitted to the point cloud of reflection points. Note that not all boundaries of the objects can be determined by this measurement. Impacts of an object margin are visible for the plane, as the reflection points moved towards the end of the plan that acted as additional edge reflector. Moreover, the plane reflector was not completely flat but had a slightly convex shape.

8. Example "Locating System LOSNUS"

LOSNUS (Locating of Sensor Nodes with UltraSound) is a LPS developed at the EMCE which is actually in a test state [14][15]. Locating is performed by means of a permanently installed infrastructure consisting from minimum 5 US transmitters per room which are installed near the ceiling of each room. Located devices are equipped with US receivers. They have to store received US signals and pass them eventually after preprocessing to a locating server. This server holds all the necessary information to compute device locations and transmits the locations back to the devices. Data communications are done via the wireless sensor network (WSN) ZigBee.

LPS are mostly used for path tracking of mobile devices. However, if permanently installed and cyclically operating, LPS can

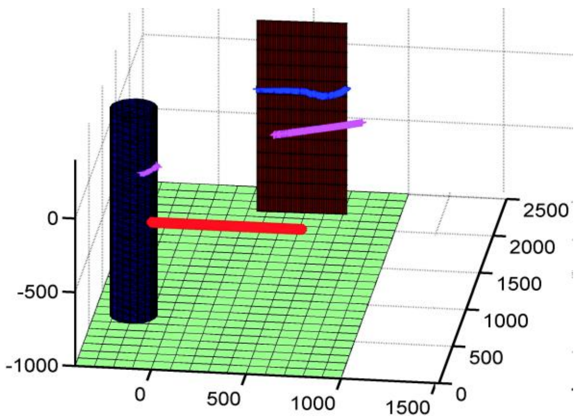

Fig. 7 Scene with three objects measured with moved (red line) four-receiver system. Axes are scaled in millimeters

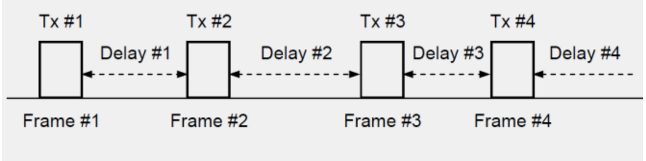

Fig. 8. Signal sequence: Ensures non-overlapping reception of LoS signals which simplifies the design of the broadcast locating system.

additionally support supervising of static devices. Thus, *LOSNUS* is directed at locating of static sensor or actuator devices with the following goals: high accuracy of measured device location (deviation about 1cm) which enables application of closely placed sensors, e.g. sensor arrays; further, cyclically repeating of locating for detecting dislocating or malfunction of sensor devices; automatic integration of newly installed sensor/actuator nodes in a WSN; utilizing device locations which are limited to the room boarders by using US locating for enhanced network security.

The crucial point in the context of this paper is gaining a high accuracy of locations which is depending on different attributes of ranging and on the locating method and algorithm. *LOSNUS* is based on performing several A-B measurements for locating a device. The transmitted signal frames are broadband and individually coded to identify the transmitters. They are sent in a sequence with short delays which prevent the overlapping of LoS signals of different transmitters at any receiver position (see Fig. 8).

An important aspect of receiver construction is limiting the effort to a minimal extent. Thus, received locating signals are 1-bit converted (polarity conversion) and sampled with 1 MS/s which allows using a synchronous serial port of a microcontroller for signal reception. This sample rate delivers a resolution of ToAs with ±0.3mm. Also the choice of TDoA as locating method reduces the receiver effort because any construction for receiving a start signal can be omitted. However, TDoA locating delivers a reduced accuracy (about a factor 5 [16]) which is moreover depending on the geometric position of a receiver. Therefore, only an average value of about 1cm deviation of the position can be given.

Considering a homogeneous temperature distribution in the room, this influence can be easily handled because of the static character of the devices. Only at the initial starting of locating a reference device with known position helps improving the accuracy. Some time later every static device can play the same role and therefore random changes of temperature or influence of air flow (open window or door) can be recognized and considered.

Significant influence on the requested accuracy has the missing synchronism of transmitter clock and local device clocks. Using delay

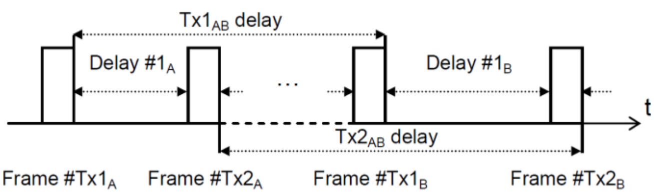

Fig. 9. A calibration of receiver clocks makes use of transmitters which send two frames with different transmitter coding. The different coding is indicated by the frame index A and B. The delay between the two frames is clearly defined by the transmitter clock and will be adjusted to the same value of the respective ToAs of each receiver which delivers local correction factors.

times in a protocol has the disadvantage that based on their local clocks transmitter and receivers consider different delays (this effect is also occurring at "active reflection" systems). In *LOSNUS* a method of calibrating receiver clocks is used which is based on repeated transmitting of parts of the sequence or of the complete one (see Fig. 9). The signals are differently coded when transmitted again and will be received and stored by the receivers. In calculating a devices location the location server detects a repetitive sensing of the same transmitter. Knowing the delay time a calibration of the receiver clock can be done with the assumption that the ToF between transmitter and receiver has remained constant.

9. Conclusions

This paper summarizes sensor and system design elements which are frequently applied in various combinations for setting up US measurement systems. The impact of specific design elements on the performance of systems is discussed. Based on this analysis our goal is designing generic measuring systems with high accuracy. This goal can be reached by employing techniques which reduce the complexity of influences on measurements. Two application systems are shortly described which are using the presented techniques. Our work is still ongoing concentrated to improvements of techniques which have shown their value in principle but have to be adapted for practical use, e.g. signal transmission via transducer side lobes.

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