APPLICATION NOTE I

Radar Sensing and Detection of Moving and Stationary Objects

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Radar Sensing and Detection of Moving and Stationary Objects

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1. Introduction

1.1 Description of mission

Radar technology is more and more used to detect both, moving and stationary objects. In the meantime radar technology lost its reputation of being excellent but also expensive at the same time, since radar sensors are manufactured today in large quantities offering attractive prices. This application note shall facilitate the introduction to this technology and provide a certain background to the reader, to quickly get to a relevant radar solution while presenting and understanding the basics for the design of such a system.

The buzzword **"RADAR"** stands for **RA**dio **D**etection **A**nd **R**anging, which means not only the detection of objects, but also the evaluation of certain object parameters at the same time. Having initially started out from mainly defense-oriented applications, in the meantime a variety of commercial and industrial applications have popped up.

The task given can be described as:

- detect an object in general or in other words prove its presence
- in case of a stationary object, define its instantaneous position (range, angle)
- in case of a moving object,
    - evaluate and measure its movement (velocity, direction of motion)
    - clock and track the permanently changing position

For manifold reasons the usage of high-frequency electromagnetic waves, so-called *MICROWAVES* seem to offer attractive solutions, since

- the objects to be detected (human beings, animals, vehicles, machine parts, paper sheets etc.) are somehow structured , that the used wavelength of the radar wave is within the same dimension or below, in order to provide sufficient resolution.
- these frequency ranges are ideally suited to build directional antennas with well-defined patterns to accurately locate an object.

1.2 Radar frequency ranges and regulations

It is very obvious that a user of radar techniques must not transmit electromagnetic energy somewhere and somehow within the densely populated electromagnetic spectrum. Therefore certain frequency ranges have been allocated for such applications.
The situation of admitted frequency ranges and especially the provided bandwidth is on the move right at this moment. Additional to international recommendations (like from CEPT) also domestic regulations exist, like for instance in Germany issued by the RegTP in Mainz.

The allocated frequencies for Germany are as follows:

2.400 ... 2483,5 MHz	9.200 ... 9.500 GHz
13.40 ... 14,00 GHz	24,00 ... 24,25 GHz
61,00 ... 61,50 GHz	122 ... 123 GHz
244 ... 246 GHz	

On top of that the 77 GHz band has been reserved almost all over Europe and USA for automotive applications.

Beside the frequencies and bandwidths the transmitted power is also regulated. The maximum radiated peak power is defined as

- a maximum of 100 mW or +20 dBm for frequencies above 10 GHz
- a maximum of 25 mW or +14 dBm for frequencies below 10 GHz .

⇒ Just to remember the conversion of mW to dBm:

P in dBm = 10 log P in mW

example:	1 mW	equivalent	0 dBm
	2 mW		+3 dBm
	5 mW		+7 dBm
	10 mW		+10 dBm
	100 mW		+20 dBm
	0,1 mW		-10 dBm
	usw.		

Please note the **peak power** being the relevant power value, calculated as the so-called **EIRP**.

What does **EIRP** mean?

EIRP stands for **E**quivalent **I**sotropic **R**adiated **P**ower, which means the power in reference to the power transmitted by an omnidirectional isotropic radiator. Or in other words, it is not sufficient just to know about the maximum available power of a transmitter at the output connector. The additional gain of a directional antenna must be known and added as well.

For example:
In case a transmitter is capable to generate 5mW (+7dBm) of power at the antenna connector, the antenna gain by focussing must not exceed 13 dB (+7dBm + 13 dB = +20 dBm), in order not to exceed the limit of +20 dBm.

A few words regarding **peak power**:

In many situations in our life highest available power is anticipated and appreciated. But not really, when it comes to the transmission of Microwave power!

In contrary to the understanding of some users the certification authorities just care for peak power only and definitely not for average power! That means nobody can cheat these authorities for instance by pulsing the transmitter. The auditor will want to know if your device can be pulsed and if yes, what is the range of your "duty cycle" (ON/OFF ratio). With this value the auditor will calculate back to the transmitted peak power.

All that together does not mean, that a user may presume the existence of a European- or even worldwide common understanding and common regulations. For instance in UK the 24 GHz range is limited to 24.150... 24.250 GHz. Different regulations apply in the USA and Japan regarding permitted transmitter power. The relevant measured value in USA for instance is field strength in V/m versus power in Europe.

This means that the manufacturing OEM better takes care to find out in which countries he plans to market his product and what regulations apply therefore.

As a matter of fact the 2 bands 2.4 and 24 GHz are worldwide allocated ISM frequencies (with the exception of Japan, who may adjust soon). Since the 2.4 GHz band might be polluted in the near future by other services and users (microwave ovens, Bluethooth etc.) and the relatively low frequency (wavelength 12 cm or 4.7 inches) does not allow much flexibility regarding directional antenna patterns, the 24 GHz band definitely has the beauty and advantage of a lower wavelength application like small antenna solutions and higher permitted EIRP power. On the other side worse propagation properties for 24 GHz versus 2.4 GHz must be considered.

Certification in Europe:
In order to avoid charges for the operation of individual sensors a generic certification is desirable. A certification received in Germany helps and dimishes the process in different European countries.

InnoSenT has acquired experience in preparing the documentation and receiving the final certification either for a standard product or a customized product.

1.3 Comparison of radar technology in relation to other technologies

The techniques competing with radar technology are infrared and ultra-sound techniques. An infrared sensor differs from a radar sensor basically by the fact that it detects preferably lateral and sideward motions, since they change the temperature pattern. However it is relatively insensitive to motions directly towards or away from the sensor, while the radar sensor is blind to real orthogonal motions, however extremely sensitive to radial motions.

Ultrasound technology is limited to short distances (<1.5m) and suffers from sensitivity to environmental impacts and the necessity of the transducer having direct access to the required propagation medium “air“, which enforces the visibility of such a detector.

The following table explains the advantages and disadvantages of the individual techniques based on the mechanisms and physics of energy generation and propagation.

technology	advantage	disadvantage
infrared sensing	▪ detects othogonal and tangential motions at best ▪ large detection angle in both, horizontal and vertical direction possible ▪ inexpensive in simpliest version	▪ blind or almost blind to radial motions ▪ sensitive to environmental influences like rain, wind, dust, fast changes in temperature ▪ impossible to be mounted invisibly, high-quality and complex covers/radoms required (shaping and material) ▪ just presence detection, no information available about velocity, direction of motion and range of an object

technology (continued)	advantage	disadvantage
ultrasound sensing	▪ very low cost ▪ triangulation possible ▪ accurate range information in close range	▪ very limited range (<1m) ▪ sensitive to environmental influences like noise, wind, fast changes in temperature ▪ sensor always visible ▪ no information about velocity and direction of motion
radar sensing	▪ detects radial motions at best ▪ relatively insensitive to environmental influences (rain, snow, dust, fast temperature changes) ▪ penetrates non-metallic materials ▪ simple and low-cost radom materials ▪ very flexible regarding antenna pattern ▪ identification of direction of motion ▪ range measurement and/or coarse range classification	▪ limited angle of detection ▪ orthogonal or tangential motions to be detected badly or not at all ▪ higher cost than infrared or ultrasound ▪ prejudice from end-users against "radiation"

From this summary it becomes evident that radar technology has got significant advantages over other techniques regarding functionality while being slightly higher in cost.

2. Radar principles

2.1 Physical basics – radar equation

2.1.1 Reflexion

Microwaves behave similar to light because of their short wavelength (i.e. 12mm or 4.7 inches at 24 GHz), which means, effects like scattering, diffraction, reflexion, divergence, interference etc. do exist. Many characteristics of a radar system have to be understood under this consideration.

In case of a radar application someone expects a transmitted electromagnetic wave being scattered that way, that at least a certain portion of this energy will be reflected back to the point of transmission.

Analyzing the receive signal strength after reflexion by an object, the mathematical description looks as follows, called the "radar equation"

$$\frac{P_E}{P_S} = \frac{g^2 \cdot \lambda^2 \cdot \sigma}{(4\pi)^3 \cdot D^4} \qquad (1)$$

It means:

P_e	receive signal power
P_s	transmitted power
l	wavelength of transmitted signal (e.g. 12 mm at 24 GHz)
σ	radar cross section of an object
D	distance between radar sensor and object

Two facts are of significant importance, without going further into detail:

The receive signal power is

- reverse proportional to the 4.power of range or vice versa, the range of a radar changes with the 4.root of the transmitter power
- directly proportional to the radar cross section of an object.

The *radar cross section* of an object is *frequency dependent* and amounts at 24 GHz for

a human being	abt.	0.5 m²
a Coke can		0.5 m²
an automobile depending on angle of arrival		1 – 5 m²
a metal sheet of 1m²		a few 100 m²

In other words a human being is a pretty bad radar target compared with a piece of metal. The properties of different materials become more evident, since we discuss the penetration of material in the next chapter.

2.2.1 Penetration of material

The fact, that microwave energy penetrates materials more or less, is very much appreciated, if you want to hide a radar transmitter behind a cover (radome), in order to let the radar become invisible and insensitive to environmental conditions.

Microwaves penetrate:

metal	not at all, full reflexion
water	almost not at all, full absorption
chemical foams	very well, very little attenuation
clothing	dry – well wet – losses up to 20 dB
rain	well – but up to 6 dB attenuation
plastic	very well – 0.5 to 3 dB loss with optimized thickness and correct spacing
human being	not really, but fraction, absorption and reflexion
wood	dry – good wet – losses up to 10 dB
ice	up to 10 dB attenuation

As a summary all absorbing materials, of course, do have a small radar cross section, because they generate some sort of reflexion just because of the unmatched change in material, while most of the energy is absorbed.
As an example microwaves are not suited to track submarines or to communicate with them, since water behaves as a perfect absorber. In this case for communication long waves are used and for detection the sonar principle (reflexion of sound waves) is applied.

2.2 Selection of radar principles

Radar principles can be devided into two big groups:

- CW (continuous wave) radars and
- pulse radars.

The decision for one of the principles is of course depending on the application.
It is of importance, which parameter shall be measured <u>primarily</u>

- presence and motion or
- range

2.2.1 Detection of moving objects: CW-radar – Doppler principle

2.2.1.1 Basic elements

The CW-Doppler radar is the simplest and most efficient solution in cases where the detection of moving object is the only and outstanding task. It utilizes the Doppler effect, which describes all sorts of wave generators and says the following:
Wave fronts, transmitted by a wave generator (sound, microwaves, light etc.) hit a moving target. Depending on the direction of the motion of this object, the wave fronts are either "compressed" or "diluted", which finally means a shift in frequency. The signal, shifted in frequency and reflected, is subtracted from the unchanged transmit signal in a relatively simple mixer (for experts called "homodyne" mixing) and results in a sinusoidal intermediate frequency (IF). It doesn't matter whether the sensor moves relatively to the object or the object moves relatively to the sensor.

As a matter of fact only the component of the velocity vector pointing parallel to the direct connection sensor-object can be calculated. The mathematical formula looks as follows:

$$f_D = 2 f_0 \cdot \frac{v}{c_0} \cdot \cos\alpha \qquad (2)$$

It means:

It means:	f_D	Doppler- or differential frequency
	f_0	transmit frequency of the radar
	v	magnitude of velocity of the moving object
	c_0	velocity of light
	a	angle between the actual direction of motion and the connecting line sensor-object

Selecting 24 GHz as transmit frequency, the following rule of thumb applies:

$$f_D = 44 \frac{Hz}{km/h} \cdot \cos\alpha \qquad (3) \qquad \left(\text{or } f_D = 71 \frac{Hz}{miles/h} \cdot \cos\alpha\right)$$

With this formula the expected Doppler frequency can easily be calculated as well as the passband of the following IF-amplifier can be predicted.
For instance it makes no sense to design the upper frequency limit of the signal conditioning part of a unit detecting human beings as higher than 300 Hz, since this corresponds to a speed of 6.8 km/h of a (pretty fast) pedestrian. On the other hand, when using radar sensors to check the speed of German (!) car drivers on a motorway ("Autobahn"), the amplifier got to have an upper frequency limit of at least 10 kHz corresponding to 220 km/h.
As a summary the speed of an object can be evaluated by measuring the Doppler frequency (in an analog system by counting the zero crossings or in digital system by FFT), while considering the angle of the motion vector.

Attention please:
In the very rare case of a perfect circular motion of the object around the sensor, the angle becomes 0°, which causes the cos and therefore the Doppler frequency to go to zero. This specific motion won't be detected by this type of radar! However this object would have to move along this circle with absolute perfection, which seems to be pretty unlikely for a realistically "spread object".

The mostly well-known, but also unpopular example of such applications is the police radar, which for this specific reason has to be adjusted precisely under a certain constant angle towards the road lane and therefore the direction of the cars to be clocked.
Signal conditioning will be described in chapters further on in this note.

2.2.1.2 Identification of direction of motion

Radar sensors implement the big advantage to provide the information about the direction of a motion (leaving or approaching) simply by utilizing two mixer circuits, which are spaced by a quarter wave length, called an I(n phase)/Q(uadrature phase) mixer.
In many applications predictable actions or processes got to take place before the sensor triggers an alarm or a certain function like a door opener just to open when somebody approaches or for sanitary equipment to flush water just after leaving a water faucet or an urinal. Depending on what signal is leading by 90° phase, the object gets identified as leaving or approaching.

2.2.2 Detection of stationary objects

2.2.2.1 Pulse radar

In case the measurement of the position and therefore the distance of a moving or a stationary object is of major importance, the pulse radar is the obvious solution.

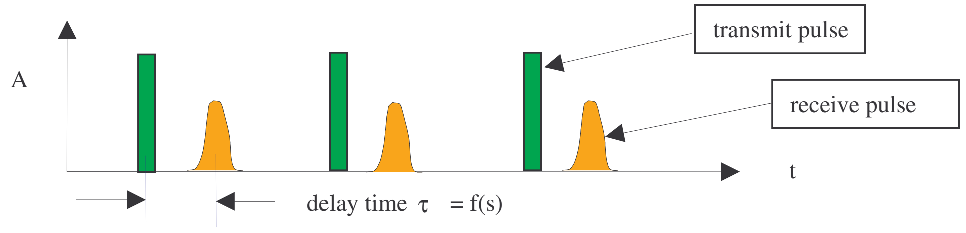

Fig. 1: Time-dependent shape of transmit and receive signal of a pulse radar

Simply enough the time delay is measured generated by transmitting a short pulse and clocking the reception of the reflected pulse. Since the pulse package travels by speed of light and covering the distance sensor-object twice, for instance a pulse gets delayed by 6 nsec for an object distance of 1m. From there it is obvious what the issues of such pulse techniques are:
In order to have good resolution, especially for objects in close distance, those pulses got to be very short, which requires enormous bandwidth, which is very much disliked by the certification authorities or even just not allowed.

In general this approach evaluates the distance or range of objects primarily. Velocity information can only be obtained by the timely derivation ds/dt taken from a plurality of measured distance values.

2.2.2.2 The FMCW radar for distance measurement only

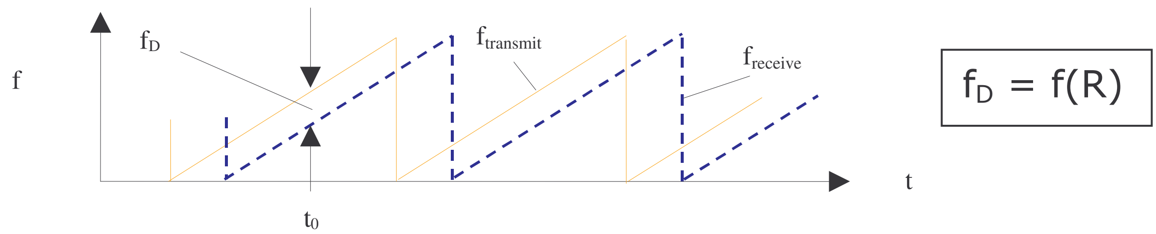

Fig. 2: Time-dependent shape of transmit and receive signal of a FMCW radar with sawtooth modulation scheme

The **FMCW**-(**F**requency-**M**odulated-**C**ontinuous-**W**ave) radar represents a different approach to detect stationary objects. Contrary to the pulse approach a permanent electromagnetic wave is continuously transmitted, whose frequency however changes as a function of time. In the same way the transmitted signal suffers from a time delay so that the reflected and therefore delayed transmit signal and the instantaneous transmit signal show slightly different instantaneous frequency values, since the transmit frequency has moved on in the meantime. The simplest change of frequency over time is a sawtooth function as depicted in fig. 2.

The following formula describes the dependence from distance:

$$R = \frac{c_0}{2} \cdot T \cdot \frac{f_D}{\Delta f} \qquad (4)$$

It means:

	f_D	differential frequency
	Δf	frequency deviation
	T	sawtooth repetition time period
	R	distance of a reflecting object
	c_0	speed of light

Related to the 24 GHz band, where at best 250 GHz bandwidth and therefore frequency deviation are allowed, it becomes obvious that a simple processing admits a minimal distance just down to about 2 to 3m. In case you want to get closer, pretty complex and fast DSP (digital signal processing) is required. On the other hand this radar has got a large zone of unambiguity, since the sawtooth repetition time T can be selected as high as required.

2.2.3 Simultaneous measurement of range and velocity

2.2.3.1 The FSK radar

Instead of changing the transmit frequency monotonously, as the FMCW radar does, it is possible to switch frequencies between 2 states with a few MHz or a few 10 MHz difference. By analyzing the phase difference of a receive signal while switching, the instantantaneous distance can be investigated, while the Doppler shift obtains (as described under 2.1.1.1) the velocity onformation. It is recommended to either store the signal shapes and compare them or to feed them to the input of a phase detector for phase discrimination.

Distance information can be extracted from the following equation

$$R = \frac{(\phi_1 - \phi_2) \cdot c_0}{2 \cdot (F_1 - F_2)} \qquad (5)$$

It means:

	F_1 und F_2	the two discrete transmit frequencies
	c_0	speed of light
	Φ_1 und Φ_2	the phase difference of the received IF signals at the mixer outputs (in radian)
	R	the range or distance

2.2.3.2 The FMCW radar with triangle modulation scheme

From a mathematical point of view the calculation of velocity and distance of an object means the solution of an equation system with two unknowns. In order to get plain solutions, two different equations are required.
We have identified, that the movement of a target shifts the receive signal frequency down- or upwards, while the distance of a target shifts the signal parallel to the time axis because of a resulting time delay. It seems logical to combine both effects by selecting the shape of the transmit frequency that way, that after reception speed and range can definitively be extracted, not necessarily in a first step, but certainly by a simple additional mathematical operation.

This opportunity is simply offered by a triangle modulation scheme.

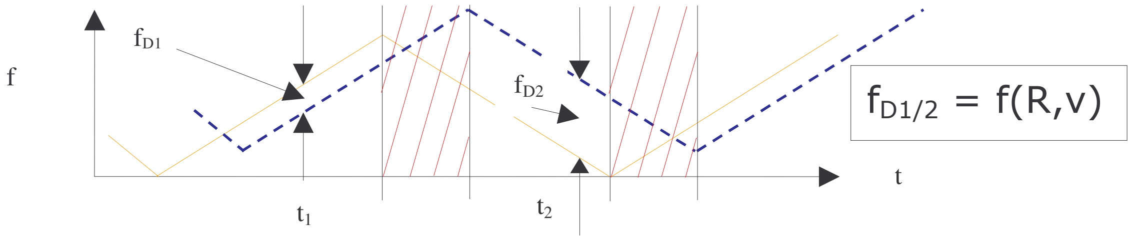

Fig. 3: Time-dependent shape of transmit and receive signal of a FMCW radar with triangle modulation scheme

In the upward ramp region, the additional frequency shift by motion and therefore Doppler effect and the range-dependent delay effect get subtracted by each other. In the downward ramp region those effects add to each other.

$$f_{D1} = f_{Doppler} - f_{delay} \qquad (6)$$
$$f_{D2} = f_{Doppler} + f_{delay} \qquad (7)$$

It means:

f_{D1} differential frequency at mixer output in the upward branch, measured value

f_{D2} differential frequency at mixer output in the downward branch, measured value

$f_{Doppler}$ frequency shift by Doppler effect, caused by object motion,

see (2) ($f_D = 2 f_0 \cdot \frac{v}{c_0} \cdot \cos\alpha$ (2))

f_{delay} frequency shift by delay effect of the transmit signal, caused by range between object and sensor see (4)

$$f_{delay} = 2R \cdot \frac{\Delta f}{(c_0 \cdot T)} \qquad (5)$$

Assuming an ideal and perfectly linear frequency change or chirp in triangular shape, for both, the increasing and the decreasing part of the triangular function certain time intervals exist with a perfectly constant differential frequency. This facilitates the processing considerably. After evaluating the resulting differential frequencies, equations (6) and (7) have to be subtracted and added to compute v and R.

Processing the differential frequencies requires some attention, since the red hatched region in fig. 3 cannot be used and should be blanked out because of the unsteadiness of the signal wave forms.

3. Proposals of solutions with commercially available radar sensors

3.1 Principal schematic of a radar sensor

All radar principles discussed in this note can be realized with a relatively simple and classic radar front-end approach. The receiver part mixes the received signal down to IF-frequency "Zero" or at least close to zero. Frequency conversion techniques as used in classic superhet receivers, where the receive signal gets converted into an intermediate frequency range of a few 10 MHz are not used in our cases. Of course this means that those types of radar sensors got a limited dynamic range (because of the relatively high 1/f-close-to-carrier noise). How-ever it has to be seen as a compromise between a complex solution and an affordable economic approach.

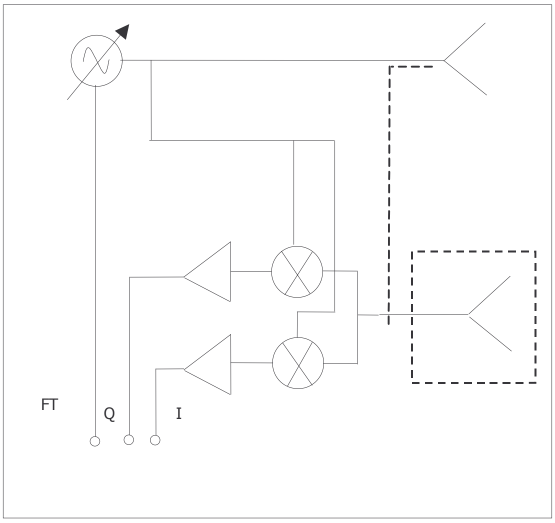

Fig. 4: Schematic of an InnoSenT radar frontend with separate transmit/receive antennas, common transmit/receive antenna as dotted line

The usage of separate transmit/receive antennas is recommended, since it provides highest sensitivity and increased mixer isolation (is specifically required in FMCW radars, see later on). In case space is limited and only available for one common antenna (for instance a narrow antenna pattern requires a large antenna area), the receiver antenna might be dropped (see dotted area), however the receive signal requires decoupling from the common transmit/receive path. Logically this results in a deteriorated sensitivity, since the receive signal is fed into both, the receive and partly into the transmit path, where it gets lost.

InnoSenT offer planar antenna solutions only, which are impressive just by its thickness or depth. Individual radiators or resonators are rectangular arrangements and are called patch(es). By combining columns and rows, antenna pattern can be designed and predicted precisely. The required area to shape an antenna pattern (aperture) is similar to the front opening of a horn antenna, while the depth is significantly smaller (see more about antennas in chapter 4).

It makes sense to integrate a low frequency amplifier right at the mixer output. This leads to 3 major advantages:

- mixer outputs are decoupled, whole sensor is insensitive to static discharge by persons or equipment during assembly – a major issue of sensors of older technology, where direct access to the mixer diodes was possible
- excellent shielding against interfering signals (EMC)

best possible match regarding gain, bandwidth and quality of following LF-amplifier stage, best achievable system noise figure.

3.2 Detection of moving objects

3.2.1 Motion detector to sense persons

InnoSenT offer both, standard catalog products and customized front-end approaches.

For instance the catalog item **IPS24-2-4-2-154** contains a front-end according to fig. 4 with the following characteristics:

- typical motion detector to sense moving individuals in a distance up to 10 or 12 m
- integrated transmit/receive antennas with 4 x 2 patch approach and corresponding 40 x 30° antenna pattern
- fixed frequency oscillator in the 24 GHz ISM band
- dual channel Schottky diode mixer with so-called I/Q outputs for identification of direction of motion
- integrated LF-pre-amplifier with 20 dB gain and a few kHz bandwidth
- ENABLE input, in order to pulse the sensor for current reduction and/or amplitude modulation

After connecting the sensor to a +5V supply and grounding the ENABLE input, the movements of a hand can be monitored, when connecting the outputs to the inputs of a scope. The generated low frequency signals will reach an amplitude of a few 10 mV's. With a permanent and monotonous movement in one direction the 90° phase shift, while one signal is leading, can be observed.

The current consumption of such a sensor with a state-of-the-art PHEMT-oscillator is typically about 40 mA including the pre-amplifier stages and therefore significantly lower than for formerly used GUNN device-based sensors. It is possible to even lower this current consumption, when applying a pulse signal with TTL levels to the ENABLE input. In this case the current decreases by the ON/OFF-ratio of the ENABLE drive signal. The user should pay attention to possible signal ringing at the mixer output, while for faster pulsing a sample & hold circuitry is required (see paragraph 3.2.3).

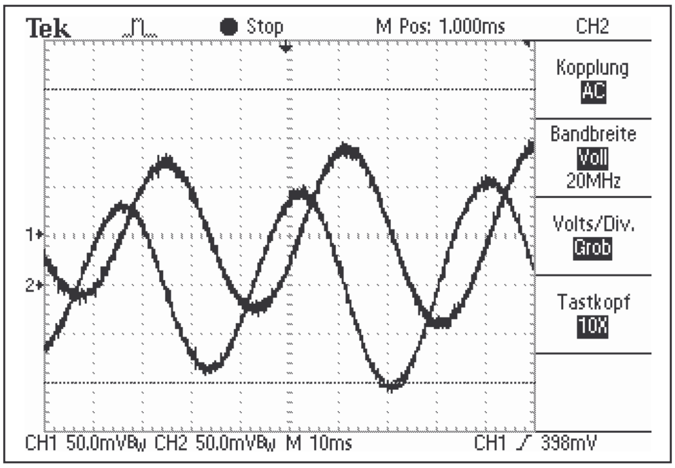

Fig. 5: Typical scope shot of the 2 I/Q outputs of a radar sensor from a monotonously moved target

The ENABLE port can, of course, be used for amplitude modulation (100% modulation depth). The highest modulation or pulse frequency applied to the ENABLE port is about 20 kHz.

3.2.2 Vehicle detection

This application is different in such way that detecting vehicles mostly handles objects with higher velocities, which

- provide higher radar cross sections, which improves the system sensitivity, but complicates the separation of different separate targets
- let objects appear in defined areas and ranges.

This leads to the fact that

- measured Doppler frequencies are higher and therefore require a pre-amplifier bandwidth up to 20 kHz (at 24 GHz)
- narrow beam antennas can be used and
- larger distances have to be bridged.

A typical example for such a device is **InnoSenT's sensor IPS24-2-8-4-144**.

According to the available datasheet by its 8 x 4 patch antenna with a 13 x 25° beam width it is capable of detecting car in a distance of 100m with velocities up to 250 km/h or 155 miles/h. This sensor can be pulsed as well.

Despite of its narrow beam, the total thickness of the sensor is 11mm (0.43 inches), which is never achievable with a horn antenna for instance

3.2.3 Additional circuitry of a sensor

Pre-amplification

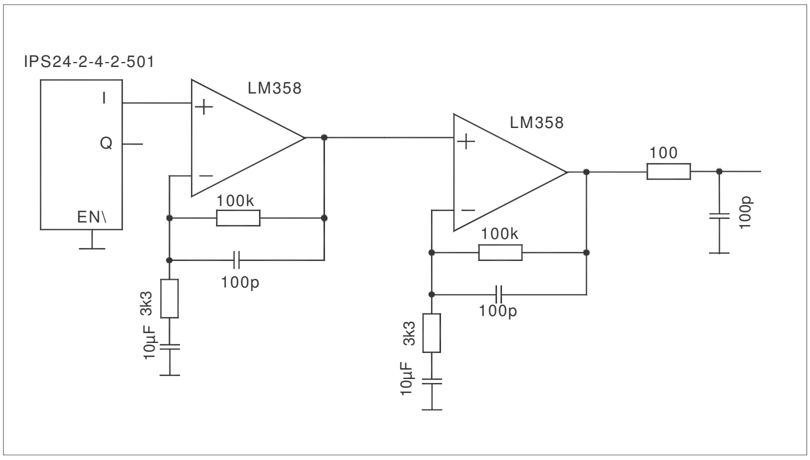

Fig. 6: proposal for pre-amplifier circuitry for one channel, 60 dB of gain, 30 kHz bandwidth

In order to process the detected signal, the user has to add further amplification stages outside the sensor. Op-amp based circuits are ideally suited, which should be band-limited in order not to unnecessarily add noise.
As a rule of thumb a total amplification is required (including the integrated sensor pre-amplifier) of 70 to 80 dB, if driving the signal into limitation should be avoided - except for a situation where the object is pretty close to the sensor (a few cm's or inches). Both, inverting and/or non-inverting amplifiers may be selected. To minimize the EMC sensitivity, low-ohmic resistors for the feedback path are recommended.
The voltage supply should be regulated (usually + 5V) and clean in order to avoid injection of FM noise.

Direction of movement detection

Another example is given for a circuitry which is able to distinguish between approaching and disappearing objects.

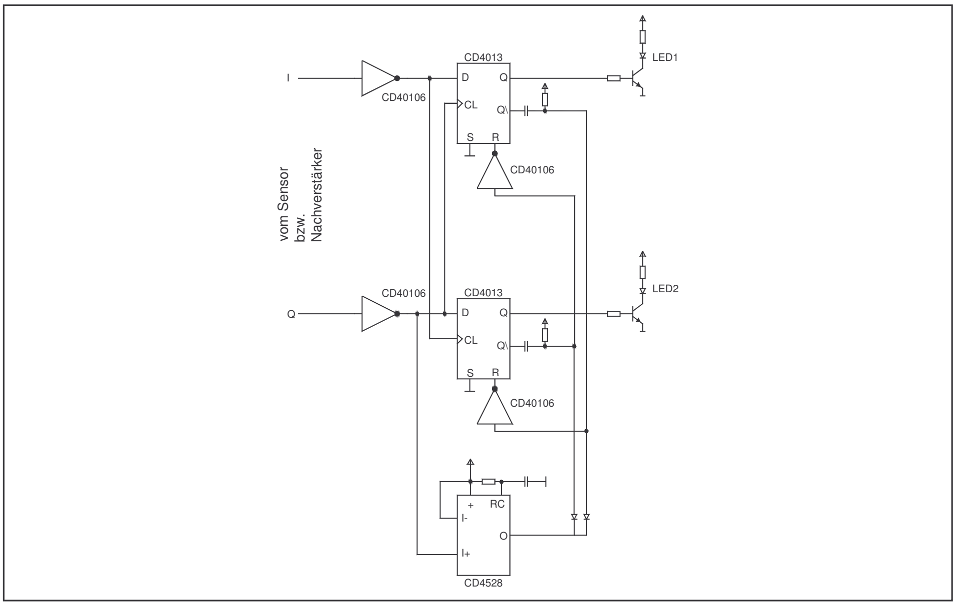

Fig. 7: proposal for a circuitry for direction of motion detection

The D-flip-flop (CD4013) which gets triggered at first, resets the second one. LED1 displays approaching or disappearing, while LED2 shows the complementary behaviour. The mono-flop (CD4528) shuts down the LED after a certain amount of time if the Doppler signal is missing.

Pulsing

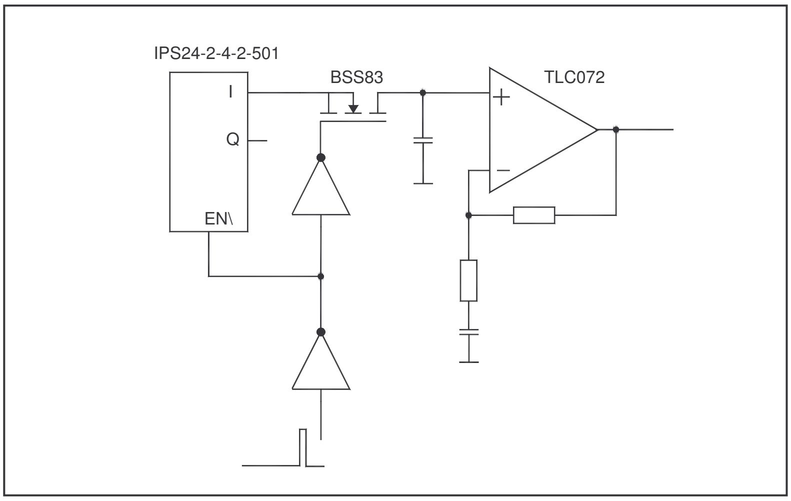

Fig. 8: pulsed radar sensor with sample & hold circuitry

In case a sensors operates in pulsed mode (EN\ input), it is recommended, to monitor the receive signal by a sample & hold circuit (see fig. 8).

The N-channel MOSFET BSS83 is very well suited as a sampler just because of its low feedback capacitance. For further amplification and buffering an op-amp with lowest input current (FET input) is required.

Due to the limited bandwidth of the internal pre-amplifier of the radar module the pulse length should stay below 10µsec. A sampling frequency of 10 kHz is rather typical.

It depends on the application, whether the detector is used as a presence detector or a speedometer, how complex the signal processing has to be done.

For a simple presence detection amplification/limitation of the signals and threshold comparison is sufficient, while a minimal number of periods should be required for an alarm in order to avoid interference and false alarms for instance at building installations by small animals or birds.

A velocity measurement is definitely possible with more or less technical effort.
Are you dealing with single individual objects, "zero-crossing-counting " of the Doppler signal might be sufficient. The longer the integration time is, the more accurate the results will be.

Multiple targets cannot be treated trivially anymore. In this case digital signal processing with A/D conversion and following FFT is required, since „zero-crossing-counting" won't work or would definitely lead to significant errors.

3.3 Detection of stationary objects

3.3.1 Operation of appropriate modules

Purely stationary objects can only be detected by CW radar modules when using the FMCW technique. For this approach the microwave oscillator got to be a VCO, which frequency can be swept periodically and monotonously. The simplest function over time is a linear chirp.

The **InnoSenT sensor IVS24-2-8-4-148** is a typical representative of a FMCW-capable module.

It includes
- a varactor-tunable transmit oscillator
- a 2 channel Schottky-diode receiver mixer with so-called I/Q outputs for detection of direction of motion
- integrated LF-pre-amplifier with 20 dB gain and 10 kHz bandwidth
- integrated separate transmit/receive antennas with 8x4 patch array (15x30° pattern)
- integrated microwave amplifier for lowest noise operation

In this case separate transmit/receive paths are mandatory in order to achieve best possible transmit/receive isolation (also see following paragraph).

3.3.2 External circuitry and signal conditioning

When driving the varactor, its internal circuitry has to be known and recognized

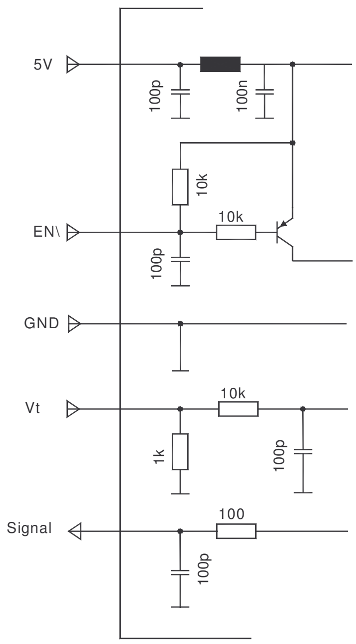

Fig. 9: Interface and internal circuitry of InnoSenT radar modules, espe cially of IVS24-2-8-4-148

The series resistor at the tuning input port (Vt) performs as a current limiter in case of any crisis like reverse biasing, while the parallel resistor improves the sensitivity regarding EMC. Both elements define the maximum modulation frequency together with the internal parallel capacitor.

The circuitry around the I/Q outputs is similar to the normal Doppler radar. The measured signal frequencies are located in the same bands as for a Doppler device.

By keeping the varactor voltage fixed, the module can be operated as a pure CW Doppler sensor, which gives the device the feature of a multimode sensor. It is important to recognize, that during FMCW operation the modulation sweep signal is detected at the receiver output and can be easily monitored on a scope screen. Now it becomes obvious why a good transmit/receive isolation is very advantageous. The worse the isolation, the more the modulation signal gets demodulated and processed.
In order to detect small objects, the desired signal has to be filtered out of the unwanted demodulated modulation signal. This explains, why the limit of a FMCW radar is reached whenever the modulation signal and the measured signal from an object get into the same magnitude frequency range. However this effect is a function of the frequency variation and modulation index of the FM signal. In the 24 GHz ISM band this maximum variation is 250 MHz (200 MHz is more realistic in order to keep a guard band to the band limits). From these facts it can be calculated that a 24 GHz FMCW radar cannot achieve resolution and closest distances of less than 1.5m or 5 feet. This parameter should not be mixed up with "accuracy", which can be driven down to mm's or tenth of an inch just by long integration periods.

4. Handling and mechanical aspects of radar modules

4.1 Precautions

As already mentioned earlier before the handling of InnoSenT radar modules is very simple and requires no precautions. A specific sensitivity against ESD does not exist. Both, the antenna parts and the interface connectors can be touched by individuals not being specifically well grounded.

4.2 Radom-materials and proposed dimensions

In normal operation a radar module is supposed to withstand tough environmental conditions. It is therefore recommended to mount it in a housing, while the antenna section must not be covered by metallic materials or layers. All sorts of plastic materials and foams are perfectly suited as long as they don't include any carbon content.

The following methods are **not suited** to protect and cover the antenna section:
- coverage with metal foils or even partly with metal parts
- spraying of the antenna structures with any kinds of paints or varnishes
- coverage with CFK laminates (conducting!)
- direct contact of plastic materials with the etched antenna structures (impact of higher dielectric constant on resonance frequency of the patches).

The following **suites very well**:
- coverage with plastic materials (ABS, PVC etc.) as long as they aren't in direct contact with the antenna patch structures and the correct thickness and spacing has been evaluated
- foams like Styropor and similar materials, whose relative dielectric constant is close to 1, they can even be mounted in direct contact with the antenna surface.

For 24 GHz the following rule of thumb can be used:
- thickness of the plastic material around 3mm or 0.12 inches
- air spacing to antenna surface similar, around 6mm or 0.24 inches

In other words in case a thicker plastic material than recommended is used, increased insertion loss must be taken into account and some impact on the antenna pattern is possible and likely. A varnish layer of black colour or "blackening" of the cover material with carbon particles should definitely be avoided.

In automotive applications mounting behind bumpers and therefore penetration of those bumpers is required, even in case of a metallic varnish version and existence of dirt, sludge and ice. In general metallic varnishes provide less insertion loss than usually expected (about 2 to 3 dB), while white varnish shows relatively high absorption (about 3 dB) due to its titaniumoxide content.

Coverage with ice and sludge causes additional attenuation up to 16 dB, which limits the longe range performance and the detection of objects with small radar cross section, however the radar won't stop working as for instance optical solution would do.

Finally some remarks should be made regarding the pattern of an antenna. Providing the figures in degrees for the width of an antenna pattern just says, that the transmitted or received energy has dropped at this point down to 50 percent of the maximum value. It does definitely not mean that beyond that point no transmission or reception is possible anymore. An object for instance with huge radar cross section (truck, metallic door) might very well compensate the loss by the antenna pattern and provide a significant radar signal. It is therefore not recommended to draw any conclusion on size and kind of a radar target without having range information available.

5. Summary and potential applications

More sophisticated radar principles and techniques, decreasing cost and the "all whether-proof" performance of radars encourage the end-user to select a radar sensor as his solution of his problem.

As a conclusion here is at least an attempt to list possible applications for radar sensing. This list does not claim to be complete, it shall raise questions and ideas, what's possible today using radar sensors.

Possibilities and applications for radar sensing techniques

➔ detection of human beings:
- door openers, option admission check
- sanitary applications: water taps, urinals
- intrusion alarm, inside and outside, optional with robots
- house installations: activation of light switches, video monitoring in case of a movement
- persons counting in super markets, sport events

➔ detection physically at the human being's body:
- sports applications: jogging, windsurfing, skiing
- permanent medical check

➔ detection of vehicles:
- wheel–based vehicles
    - traffic monitoring: vehicle counting, density measurement, classification of vehicles, speed enforcement (police radar)
    - distance measuring equipment: parking aid, stop-and-go-traffic radar, ACC, blind-spot-detection, pre-crash
    - safety tests: crash tests
    - rail vehicles
- trains: railway barrier check, platform surveillance, shunting aids

➔ detection at vehicle's body:
- all sorts of autonomous speed check like "true speed over ground" for applications with anticipated slippage
    - wheel-based vehicles: cars, tractors
    - rail vehicles: navigation
- distance radar: parking aid, stop-and-go-traffic radar, ACC, blind-spot-detection, pre-crash
- keyless entry/go

➔ machine control and monitoring
- printing machines
- conveyor belt monitoring

➔ gauging, level measurement
- in closed and/or open systems
- aggressive, melting and foaming media

➔ flow measurements
- speed
- contamination, sludge density.