# 1 Introduction

Radar (radio detection and ranging) describes the very general principle of using electromagnetic waves to detect and, possibly, locate objects. This is done by transmitting electromagnetic waves, receiving an electromagnetic response, and comparing the two signals. Radar is already widely used in meteorology, aviation and seafaring. Recently, industrial applications like object tracking are also becoming commonplace

To explain the technical realization of radar, the radar waveform that is the easiest to depict is a short pulse. The pulse is radiated from the transmit antenna to propagate in the surrounding medium, e. g., air, as an electromagnetic wave. At every discontinuity in the medium, a fraction of the wave is reflected. Having a receiver at the same position as the transmitter, it is possible to detect the reflected energy. In the time $\tau$ between sending the pulse and receiving the echo, the pulse has traveled a distance of $2R$. Using the speed of light $c$, the distance between the radar and the discontinuity can be calculated as $R = c\tau/2$.

The pulse, however, is not the only waveform that can be used for distance measurements. In fact, any modulated signal can be used. If, however, a continuous signal is to be used, it is less clear how the transmission delay $\tau$ is to be determined since both the transmit and receive signal is continuously present at the receiver. As will be shown later in this dissertation, the cross-correlation between the transmitted and the received signal can be used to compress the continuous signals into pulses. The correlation approach can be used for any signal that has significant bandwidth and duration. This includes, for example, complex pulses that are not cosine shaped but modulated with a frequency ramp which includes continuous frequency ramps and even noise. For all these signals the correlation produces one pulse for every scatterer, allowing the delay to be determined precisely like it was for the pulsed radar. The distance can be calculated accordingly. The advantage of the continuous wave (CW) stimulus is that the energy is spread out over a longer time, hence a lower peak power is required to transmit the same energy and achieve the same range.

The requirement for effective correlation and impulse compression is to have a wide bandwidth signal with the stimulus power equally distributed over frequency. One class of signals that perfectly matches these characteristics is ‘white’ thermal noise. Using the correlation, it is possible to build a radar system using noise as stimulus. Both finding applications for noise radar and implementing suitable measurement systems are goals for this thesis. It will be shown that noise radars can be simplified by not using actual random noise, but synthetic signals that imitate the characteristics of natural noise processes. Maximum length sequences (M-sequences) are a family of binary signals that are particularly well suited for the practical implementation of a such a pseudo-noise radar.

Radar is, of course, not limited to simple distance measurements. What has been described here is a system that measures the impulse response of its environment either directly, by exciting it with a short pulse, or indirectly by using a wideband signal and compressing it into a pulse in post-processing. The impulse response function (IRF) is a very general way to fully describe the behavior of an linear, time-invariant (LTI) system. An LTI system can be anything that allows a signal to propagate, such as the air between two antennas or an electronic amplifier. The LTI assumption is valid, at least over a short time, when observing a natural environment. The same assumption can also be applied, at least as an approximation, to many electronic systems containing active components. The assumption of linearity is only acceptable over a limited range of input power and an amplifier, as mentioned above, is a good example of this limitation. A well-designed amplifier can be almost perfectly linear over a specified range of input signal amplitudes, yet quickly become highly nonlinear if the input exceeds the specification and the amplifier is driven into saturation.

For the radar ranging application, only strong peaks in the IRF that are indicating sharp discontinuities in the propagating medium are of interest. The same measurement can, of course, also be evaluated to provide more general insight into the properties of materials. Radar and material characterization are merely two different ways to view the same information.

Both the general concept of IRF measurements and the correlation of random signals to estimate the IRF do not only apply to electromagnetic waves. The approach is also in widespread use in acoustics to characterize loudspeakers, microphones and whole rooms. As John Vanderkooy put it in 1994:

> “MLS [maximum length sequence] systems are now popular for many system-identification tasks, perhaps because the excitation signal has good crest factor, is more pleasing to listen to (or endure), and excites systems more naturally.” [64]

Vanderkooy is writing about M-sequences or MLS that were briefly mentioned above in comparison with pulsed or frequency modulated stimuli. M-sequences are a group of time-discrete, two-valued sequences that have become immensely important in modern technology. They are periodic and can be reproduced at any time, only requiring the storage of a small number of coefficients. The sequences are sometimes referred to as pseudo noise (PN), emphasizing the characteristics shared with thermal noise. They are widely used in place of thermal noise in a correlating radar with no critical degradation of the correlation performance. Since they are periodic and the sequence is known, the transmit signal does not need to be sampled, effectively reducing the complexity of the radar system by half.

Much of the theory behind M-sequences was published in the 1950s and 1960s. The history of shift register sequences was outlined by Solomon W. Golomb in his classic book [20]. When this work was published in 1967, M-sequence theory had been around for a long time, yet the origins were far from clear:

> "It is hard to establish priorities as to who did what first. For example, E. N. Gilbert of the Bell Telephone Laboratories derived much of the linear theory a year or so earlier than either Zierler, Welch, or myself, but his memorandum had very limited distribution. Many other have derived the linear theory independently since that time, and doubtless others will continue to do so. Of course, the first investigation of linear recurrence relations modulo $p$ goes back as far as Lagrange, in the eighteenth century, and an excellent modern treatment was given (as purely mathematical exposition) by Marshall Hall in 1937." [20]

Remarkably, Golomb's book is relevant and widely cited even today. M-sequences have since become an integral part of our communication infrastructure, being used in Global Positioning System and in every mobile phone as spreading code [65]. M-sequences are also used as test patterns for radio channel measurements and in testing integrated circuits. However, the use of such sequences for radar has not been subject to as much attention until more recently.

Starting in 1997, a research group at the TU Ilmenau led by Dr.-Ing. Jürgen Sachs has been developing modern wideband radars using M-sequences [51]. From the early 2000s until today, they have focused on custom integrated solutions, pushing the achievable bandwidth to 10 GHz and beyond [50]. Apart from increasing the bandwidth, researchers are also focused on increasing carrier frequencies. Recently, for example, a 77 GHz PN Doppler radar integrated circuit (IC) has been published by the Kepler University in Linz, Austria [35].

For many applications these huge bandwidths and high frequencies are not required. A good example is ground penetrating radar (GPR), where the low-pass characteristic of soils limits the usable frequency range to about 1.5 GHz and below[1]. This whesis focuses on these medium bandwidth applications where a complete M-sequence radar can be implemented relying only on commercially available parts.

## 1.1 Organization of this Thesis

Before diving into the details of wideband circuit design, the remainder of this chapter introduces the theoretical basics that can be used to estimate the performance of any radar system. The most common radar waveforms are shown and similarities as well as differences are analyzed. In Chapter 2 the M-sequence is compared to traditional pulsed and frequency-modulated waveforms to show advantages as well as trade-offs. The central chapters, 4 to 6, then present one radar system each, covering very different applications that still have much in common.

Chapter 3 introduces the first building block of any radar system: the signal source. Four different implementations are introduced and guidelines are presented for choosing a suitable generator for a given application.

In the following chapters, three applications are introduced and three different radar topologies are developed to solve the particular measurement tasks. In Chapter 4 a close range distance measurement solution is presented. It uses the two-way time of flight of the pseudo noise signal to calculate distance. The prototype presented in this chapter implements the signal generation and analog front-end but signal acquisition and analysis is done using commercial measurement instruments.

Chapter 5 adds analog synchronization of two M-sequences to the basic radar hardware. The intent is to develop a wireless clocking and synchronization backbone that is prerequisite to a large-scale positioning system. It will be shown that an analog implementation of the synchronizing control loop provides a high level of precision that would be very difficult to achieve using commercial digital circuits.

Chapter 6 shows the development and testing of a ground penetrating radar system, an application that poses strong limitations on the usable bandwidth and frequency range. By using an field-programmable gate array (FPGA) for signal generation and processing, this radar system is able to integrate both the analog front-end and digital high-speed baseband, and does not rely on external measurement instruments.

## 1.2 Contributions

This work not only proposes but also demonstrates beneficial applications of the M-sequence in two different applications:

[1]See Chapter 6 for a more in-depth discussion.

**Positioning** Chapter 5 proposes a possible improvement on current industrial positioning systems. Positioning is commonly accomplished by taking multiple distance measurements between an object being located and a number of sensors at fixed positions. This can be accomplished by having the object transmit a characteristic signal and all sensors measure the time difference between this signal and a precise common time reference. Many current positioning systems rely on cabling to synchronize the numerous stationary nodes. This work proposes a wireless synchronization based on M-sequences. By using orthogonal sequences (code division multiple access) for synchronization and distance measurement to an object, the same ultra-wideband channel can be used for both functions. The large bandwidth ensures good resolution in dense multi-path environments while the ability to re-use the channel, and thus the transmitter and receiver hardware, simplifies the implementation and correspondence to conform to existing ultra wideband (UWB) regulation.

**Ground Penetrating Radar** A novel M-sequence GPR radar is demonstrated in Chapter 6. It is shown that an ultra-wideband transceiver can be implemented mostly in a modern FPGA, producing a compact and low-cost radar system. A complete GPR solution based on the new transceiver is shown and characterized. The prototype system has already shown detection capability on par with commercial systems. Even better results are expected for a fully optimized system with improved antennas.

Additionally, a number of technical solutions and even proven modules for generation and wideband sampling of M-sequences are presented in Chapter 3 and 6. These modules are available to quickly implement and characterize future radar concepts.

## 1.3 Radar Fundamentals

This section briefly introduces the characteristics and some theoretical approximations for classic pulse and frequency modulated radars. The characteristics mentioned here represent the benchmark to which the noise radars introduced in the following chapters are compared.

### 1.3.1 Pulsed Radar

Pulsed radar is the oldest and most widely used radar method. It uses short pulses that are transmitted at a fixed pulse repetition frequency (PRF) $f_p = \frac{1}{T_p}$. The pulses propagate from the antenna at the speed of light. Whenever they hit a discontinuity, a part of the pulse energy is scattered back toward the radar where it can be detected.

Since the transmitting and the receiving antenna are usually placed close together direct coupling between the antennas can be a problem. Strong coupling means that the receiver has to be able to handle pulses that are much larger than expected for a remote scatterer. If objects in close proximity to the radar itself are of no interest, the receiver can be turned off during the transmission or a transmit/receive switch can be used to isolate the receiver. This ensures almost perfect isolation between the transmitter and the receiver. The dynamic range that the receiver needs to handle is thus only defined by the size and distance of possible radar targets, it is not unnecessarily enlarged by the antenna coupling. This reduction in dynamic range is a substantial advantage of pulsed radars over CW radars that will be introduced later in this chapter.

The resolution capability $\Delta R$ of the radar depends on the pulse length $\tau$ since the pulse can be thought of as extending over a distance $c\tau$ in space, with $c$ being the speed of light [58].

$$\Delta R = \frac{c\tau}{2}$$

For cosine-shaped pulses, the bandwidth $B$ is controlled by the length of the pulse, $B\tau \approx 1$. Thus,

$$\Delta R = \frac{c}{2B}.$$

The maximum unambiguous range is limited by the PRF. The pulse has to make it to a remote target and back to the radar within $T_p$, hence

$$R_{\text{max}} = \frac{c}{2f_p} = \frac{cT_p}{2}. \tag{1.1}$$

In order to build a radar that combines a large range with good resolution, $\tau$ needs to be small and $T_p$ large. This means that the duty cycle $\tau/T_p$ of the radar is very low and the pulse power $P_t$ is much higher than the average power. $E = P_t\tau$ is the pulse energy.

$$P_{\text{av}} = P_t\frac{\tau}{T_p} = \frac{E}{T_p}$$

To investigate the influence of transmit power on the energetic range of the radar, the general radar range equation (1.2) can be used [58].

$$R_{\text{max}} = \left(\frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 S_{\text{min}}}\right)^{\frac{1}{4}} \tag{1.2}$$

$G$ is the gain of the antennas, receiver and transmitter antenna are assumed to have equal gain.

$\lambda = \frac{c}{f}$ is the wavelength at the center frequency.

$\sigma$ is the radar cross-section of the target.

$S_{\min}$ is the minimum detectable signal.

The ability of the receiver to discern a reflected signal from noise mostly depends on thermal noise in the receiver itself. This can be modeled by calculating the noise power in a given bandwidth $B$, $P_n = kT_0B$. The noise figure $F_n$ specifies how much the input signal-to-noise ratio deteriorates due to the receiver. Finally, noise is a statistical phenomenon so a significant power difference between the mean noise power and the incoming signal is needed for reliable detection (limited false alarm rate), this power difference is specified as minimum signal-to-noise ratio $\left(S/N\right)_{\min}$. A common requirement for $\left(S/N\right)_{\min}$ is 13 dB. Combining all aforementioned factors, an approximation for $S_{\min}$ can be found:

$$S_{\min} = kT_0BF_n\left(\frac{S}{N}\right)_{\min} \tag{1.3}$$

For a radar using unmodulated pulses satisfying $B = \frac{1}{\tau}$, combining (1.2) and (1.3) leads to

$$R_{\max} = \left(\frac{\overbrace{P_t\tau}^{E_t}G^2\lambda^2\sigma}{(4\pi)^3kT_0F_n\left(\frac{S}{N}\right)_{\min}}\right)^{\frac{1}{4}}. \tag{1.4}$$

It can be concluded from (1.4) that the overall energy $E_t$ contained in the pulse limits the achievable range, hence long pulses make achieving long range on a power budget easier. Increasing $\tau$ does however reduce the resolution $\frac{1}{\Delta R}$. To be able to use long pulses without compromising the resolution of the radar system, intra-pulse modulation can be used, for example, by using a longer pulse and modulating it with a frequency sweep. This allows the pulse width to be made independent of bandwidth, providing $B\tau \gg 1$. The receiver then has to use pulse compression to reduce the long pulse transmitted over the air, back to a shorter pulse with good spacial resolution.

If digital processing of the radar signals is desired, the receiver output has to be sampled while retaining the full bandwidth $B$ of the signal.

Stationary air surveillance radars commonly operate with peak powers in the megawatt range. Many examples of this have been listed by Skolnik [58]. Of course, the components required to handle large pulse powers are not readily available as small, low-cost electronics. The idea of compressing long pulses into shorter ones, however, can be taken to the extreme by continuously transmitting and receiving while using modulation to achieve any specified bandwidth. as the following sections will show, when radar systems are to be employed in large numbers continuous wave radars are often used.

### 1.3.2 Frequency Modulated Radar

Whenever the high pulse powers required by pulsed radar are a problem, CW radars are an alternative. Unmodulated carriers can be used for Doppler speed measurements or, by using the phase of the reflected signal, for interferometry. To be able to resolve multiple targets and to calculate the distance for every target, modulation of the continuous wave is required. This section will assume a linear frequency sweep as the most widely used modulation scheme for CW radars.

The great advantage of all CW radars over pulsed radars is the low peak to average power ratio $P_{\mathrm{av}} \approx P_t$. To achieve the same range as a pulsed radar, the peak power needed in a CW radar can be significantly lower, greatly relaxing the requirements on the power handling capability and linearity of the transmit chain, particularly the power amplifiers.

This advantage, however, does come with a price. Transmitter and receiver are continuously operating. Hence, direct coupling between transmitter and receiver becomes a problem. In monostatic radars, sharing one antenna for both transmitter and receiver, a circulator has to be used to separate outgoing and incoming signals. Circulators often achieve isolation of no better than $-20\,\mathrm{dB}$, making the direct coupling by far the strongest signal in the receiver and hence increasing the necessary dynamic range. To alleviate this problem, bistatic antenna setups are often used with CW radars. By using physically separate antennas, possibly with some kind of conductive barrier in between, better isolation is achievable at the cost of additional space required by the antennas. Simulations have shown that, by introducing a simple metal shield, in the frequency range around 15 GHz isolation of up to 60 dB is achievable between neighboring patch antennas. If, for example, a common radome for both antennas is added later, reflections will degrade the isolation.

An additional advantage of frequency modulated continuous wave (FMCW) radars is the small bandwidth required for digitizing and processing the receiver output. This is possible since the range information for this type of radar is a frequency difference, not a time difference.

Figure 1.1a shows the basic elements of a FMCW radar frontend. A linear frequency ramp $s(t)$ is transmitted. The signal is reflected from a remote target and the reflection reaches the receiver after a time delay $\tau$ as $s(t+\tau)$. In the receiver, the reflected signal is mixed with the transmit signal. Due to the delay $\tau$ and the continuous change of the transmit frequency there is a constant frequency difference between $s(t)$ and

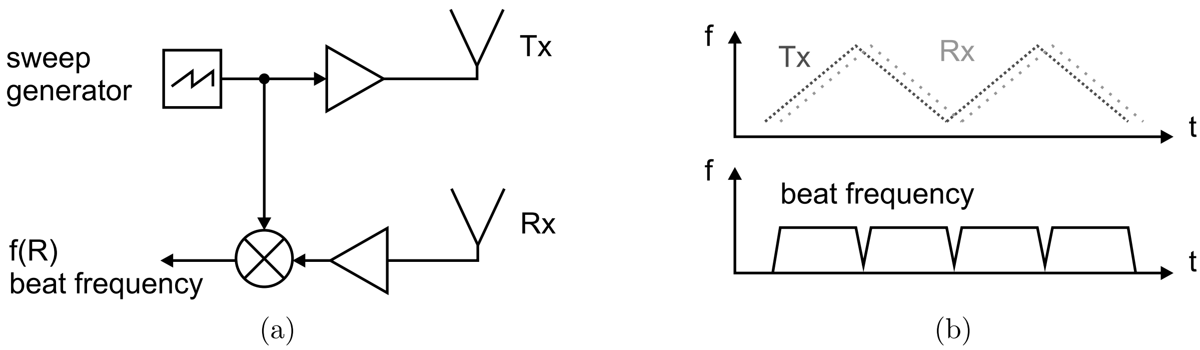


Figure 1.1: FMCW block diagram (a) and characteristic signals (b).

$s(t + \tau)$. The mixer output is this difference frequency $f_b$ that is commonly called beat frequency or pseudo-doppler frequency [25].

The beat frequency $f_b$ is directly proportional to the distance between the radar antenna and the target. The sweep bandwidth can be much larger than the range of the beat frequencies. See Jankiraman for a more detailed discussion of the beat frequencies [25].