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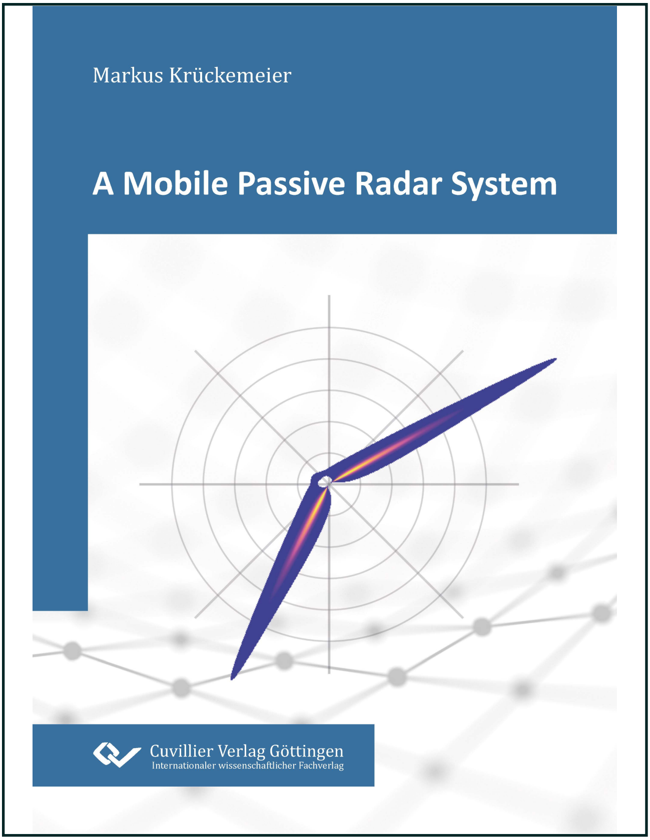
A Mobile Passive Radar System



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1. Introduction

Nowadays, the detection of distant objects by means of electromagnetic waves is usually described as radio detection and ranging (radar). The basic technique can be summarized relatively simply. One example for such a summary can be found in the radar handbook by Merill Skolnik [1]:

> *"Radar is an electromagnetic sensor for the detection and location of reflecting objects. Its operation can be summarized as follows:*
>
> - *The radar radiates electromagnetic energy from an antenna to propagate in space.*
> - *Some of the radiated energy is intercepted by a reflecting object, usually called a target, located at a distance from the radar.*
> - *The energy intercepted by the target is reradiated in many directions.*
> - *Some of the reradiated (echo) energy is returned to and received by the radar antenna.*
> - *After amplification by a receiver and with the aid of proper signal processing, a decision is made at the output of the receiver as to whether or not a target echo signal is present. At that time, the target location and possibly other information about the target is acquired."*

The technology goes back to the first fundamental experiments of Heinrich Hertz in 1886 [2]. He demonstrated the electromagnetic waves predicted 20 years earlier by James Clerk Maxwell and performed experiments on their reflection from metal plates - the first radar measurement. The first technical application of this effect followed with the "Telemobiloscope" of Christian Hülsmeyer, who demonstrated a device capable of detecting ships on the Rhine in Cologne in 1904 [3]. The first large-scale air surveillance radar, "Chain Home," was developed in the years before World War II by Robert Watson Watt and Arnold Wilkins. Their Davenport experiment in 1935 proved the technology could be used on a larger scale [4].

In addition to the classic areas in maritime and aviation surveillance, radar is nowadays used in a wide variety of applications: Weather radar systems are used to study the atmosphere, ground-based radar systems are used to monitor space debris, satellite-based radar systems are used for earth observation and to study other celestial bodies, ground penetrating radar systems are used in geology and archaeology, in the automotive sector radar sensors are used for driver assistance systems and many more examples of applications could be found. As diverse as the areas of application are, as diverse are the systems and challenges involved. The further development and improvement of radar is therefore still a topic of current research. The current reasearch topics start with the improvement of the underlying hardware, i.e. components such as signal sources, amplifiers, mixers, and antennas and also include questions about the backscattering properties of the potential targets. But, mainly they deal with the advancement of signal processing methods [5, 6].

In this thesis, a passive radar system designed for ground-based surveillance of airspace is presented. The concept of a passive radar is to use an illuminator of opportunity instead of transmitting a signal on its own. This principle was already used in the early days of radar. In fact, the already mentioned Davenport experiment of Wilkins used a public radio transmitter as the illuminator and therby classifies as a passive radar experiment.

However, further development of this technology was initially postponed in favor of the much easier-to-use monostatic radar systems, which transmit and receive from the same location[1]. It was not until the 1980s that passive detection came back into focus. Since the late 1990s and early 2000s, the first commercially available systems have been the Silent Sentry systems from Lockheed-Martin. These system were followed by other systems, such as the Homeland Alerter from Thales, the AULOS system from LEONARDO, a system from Airbus Defence and Space, and several other commercial systems [8, 9]. In parallel to these systems, a number of systems have also been developed for research purposes. Some examples are the PaRaDe system of the Warsaw University of Technology [10], various systems of the Fraunhofer Gesellschaft, such as Cora [11], or the software-defined multiband array passive radar (SMARP) system of the Italian national inter-university consortium for telecommunications (CNIT) [12]. When the research for this thesis was started, the supply of reference books on this research area in particular was still comparatively thin, however, in the meantime textbooks on this subject have been published. The first book on this topic was "An Introduction to Passive Radar" by Hugh D. Griffith in 2017 [9]. This was followed by the book "Signal Processing for Passive Bistatic Radar" by Mateusz Malanowski in 2019 [13]. These books describe many of the fundamentals used in this work in detail and are recommended as further reading.

The question, on which this thesis is based, resulted from the work with different projects around the detection of small aircraft, both manned and unmanned. E.g., an active frequency-modulated continuous wave (FMCW) radar system was developed for the detection of small air vehicles, which is also briefly described in the Appendix A. The first experiments in the field of digital beamforming and subsequent signal processing were carried out with this system.
The passive radar system described in this thesis was developed within the project: advanced low flying aircrafts detection and tracking (ALFA) [2]. This project was concerned with the detection of low-flying small aircraft or unmanned aerial vehicles (UAVs), which are frequently used for drug smuggling at the European southern border. ALFA relied on the combination of an active radar system, an electro-optical sensor, and the passive system described here. The measurements of these systems were merged via a sensor data fusion component. The system was additionally used as a passive radio detector, primarily for the detection of UAV. Although this type of use is not the subject of this thesis, it has been investigated and a short overview can be found in the Appendix D.

[1] Such monostatic radar systems are currently used for air traffic control. With the Ramet MSSR M10SR [7] as an example, here are a few key figures on the performance of such systems currently in use: maximum Range 256 NM, update rate 4 - 7.5 sec, angular mean square error 0.1 deg, range mean square error 60 m, altitude information None, detection probability 98 %

[2] The ALFA project has received funding from the European Union's Horizon 2020 programme under grant agreement No. 700002.

1.1. Contributions

The contribution of this work to the state of the art can be summarized in the following items:

- **SDR based Passive Detection System**
  As part of the ALFA [14] project, a combined system for passive detection and passive radar was built. The system includes a modular antenna system, receiver hardware and signal processing hardware. The system is used for further investigations within this thesis and represents the base for additional research in this area. The developed system is presented in Chapter 3.
- **Illuminator Locator**
  In Chapter 4.3, different methods for determining the illuminator position in bistatic passive radar systems are compared. The planar approximation (PA) method is introduced as an approach to improve the accuracy of iterative solution techniques. The method is compared with previous approaches and is found to be superior in the scenario studied.
- **PA based Tracking Algorithm**
  In Chapter 4.4, a tracking method is proposed that solves the fusion of measurements for track initialization with the PA method. The method can be used to determine targeted hypotheses for new tracks, reducing the effort required to find the right combinations of targets from different illuminators.
- **14 GHz Collision Avoidance Radar**
  Appendix 2.3 is an overview of the prototype of a 14 GHz FMCW collision avoidance radar that was developed as part of this thesis. Furthermore, exemplary results from student work are shown, in which signal processing and electronic beam steering for this system are demonstrated.

1.2. Organization of the Thesis

Following this introductory chapter, this dissertation is organized as follows:

Chapter 2 provides a selection of the important fundamentals of the radar systems used. The concept of radar is considered in general; the operation of FMCW radar, as well as the concept of passive radar are explained. The ambiguity function, which is relevant for both systems, is also introduced. In the field of antenna theory, beamforming and the modeling of antenna arrays are described. The explanations of the Kalman filter, as well as some nonlinear extensions of it conclude this chapter.

Chapter 3 describes the coherent receiver system that was developed as part of this thesis. The chapter starts with an overview of the used hardware, as well as the synchronization of the receive channels. In further sections, the antennas and the measurement of the noise figure of the system are described.

Chapter 4 describes the passive radar system developed in this thesis. The considerations for the selection of the illuminator system are described, as well as the complete signal processing. A separate section describes a method for determining transmitter positions using cooperative targets. Furthermore, in addition to the basic signal processing of the measured data, the fusion of this information by means of a tracking algorithm is described. This chapter concludes with the development of a model for the performance of the system.

Chapter 5 presents measurements performed with the developed system. The results of the system are compared with the model, as well as with independent reference data. The chapter concludes with a discussion of the results.

Chapter 6 summarizes the thesis and recommends future work.

Appendix A provides a brief overview of an active, FMCW radar system that was built early in this research. In the context of this work, it represents an experimentation platform on the basis of which initial experiments in signal processing were carried out.

Appendix B describes an alternative method for synchronizing the software-defined radio (SDR) channels in which only the common reference signal, which is distributed to all channels, is used and the local oscillator (LO) frequencies are generated with the internal phase-locked loops (PLLs). The limitations of this technique that led to its omission are also explained.

Appendix C is a compilation of measurement and simulation results for the characteristics of the amplifiers and antennas used.

Appendix D gives a brief outlook on the application of the system for the passive detection of radio signals. This technique is of high interest in the context of detection of smallest UAVs, but in the context of this thesis it is a proof of concept and functional verification of the developed hardware.

2. Fundamentals

This chapter covers a selection of the basics used in this work. They are intended to give the reader a brief overview on the topics and terminology used. If necessary, there are references to further literature given.

2.1. Radar Fundamentals

A radar system uses electromagnetic waves to detect distant objects by their reflection. The basic idea of a radar system can be explained as follows: An electromagnetic wave is radiated. After a certain propagation time t, the wave hits an object in a distance R where it is reflected and/or scattered [1]. After another time t, the reflected wave can be detected at the receiver. From the propagation time $2t$ of the signal and the known propagation speed c, the distance of the object can be determined.

The range of a radar system depends on whether the backscattered signal can still be detected at the receiver. To determine this, first the magnitude of the received power is described. Of course, this largely depends on the transmit power P_{I} with which the radar illuminates the target. Assuming that the power is distributed isotropically, i.e., spherically around the transmitter, the radiation density at distance R_1 is the power of the transmitter distributed over the surface of a sphere $4\pi R^2$.

Considering that the transmitter does not radiate the power isotropically but directed with an antenna, the directivity of the antenna can be understood as an increase of the transmitted power by the factor D in the direction of the radiated beam. With a real antenna, additional losses occur, which are described by the efficiency η. These quantities are summarized as the gain of the antenna $G_{\mathrm{I}} = \eta D$.

At the target, a certain part of the radiation density is reflected back in the direction of the receiver. Furthermore, directional effects and losses can also occur during this process. These effects are summarized as the effective aperture σ of the target, which is also referred to as the radar cross section (RCS). It is given in units of area.
Due to the various effects summarized in the RCS, it depends on the angle at which the target is illuminated and can vary greatly for different directions of incidence[2]. The radiation density at the target and the RCS σ can again be modeled as isotropically radiated power originating from the location of the target. On the way back to the receiver, the power is therefore again distributed on a spherical surface with the radius R_2. At the receiver the power density is then received with the effective antenna area A_{W}. This can be determined from the wavelength λ of the signal and the gain of the receiving antenna G_{R} [15, p.227] as

$$A_{\mathrm{W}} = \frac{\lambda^2}{4\pi} G_{\mathrm{R}}. \tag{2.1}$$

[1] Both terms are used synonymously. The exact physical process is not relevant for the purpose of this study.

[2] These effects result from the complex geometry of the targets and the materials used.

In summary, the power received at the radar is given by

$$P_{\mathrm{R}} = P_{\mathrm{I}} G_{\mathrm{I}} \cdot \frac{1}{4\pi R_1^2} \cdot \sigma \cdot \frac{1}{4\pi R_2^2} \cdot \frac{\lambda^2 G_{\mathrm{R}}}{4\pi}. \tag{2.2}$$

Assuming, that receiver and transmitter are in the same place[3] ($R = R_1 = R_2$), this expression can be reformulated into the so-called radar equation, which can be used to specify the maximum range of the radar as a function of the minimum signal power $P_{\mathrm{R,min}}$ that can be detected by the receiver, for a target defined by its RCS:

$$R_{\mathrm{max}} = \sqrt[4]{\frac{P_{\mathrm{I}} G_{\mathrm{I}} \sigma \lambda^2 G_{\mathrm{R}}}{(4\pi)^3 P_{\mathrm{R,min}}}}. \tag{2.3}$$

2.2. Topologies

An important aspect of the classification of radar systems is their topology. The most common are so-called monostatic radar systems. In a monostatic radar system is the transmitting and receiving units are located at the same site. In contrast, there are bistatic systems, where the transmitter and receiver are located at different sites, or multistatic systems, where multiple transmitters and/or receivers at different sites are used. An example of a bistatic topology is shown in Figure 2.1 for a passive radar system [1, 16]. The distance between illuminator **I** and observer **B** is defined as

$$R_{IB} = \|\vec{IB}\| \tag{2.4}$$

and is often referred to as the baseline. In addition, the distances between the illuminator **I** and the target **T**

$$R_T = \|\vec{IT}\| \tag{2.5}$$

as well as the distance between the receiver **B** and the target **T**

$$R_B = \|\vec{TB}\| \tag{2.6}$$

are also relevant.

2.3. FMCW Radar

Besides their topology, radar systems can also be distinguished by the type of illumination signal they use.

The signal shape is decisive for the information that can be obtained about a target. For example, in the early radar systems, only the distance to a target was determined. A simple pulsed signal was used for this purpose. With such a pulsed radar, the propagation time of a single pulse is measured for the round trip to the target. Such a system therefore provides information about the propagation time and thus about the distance to the target. For other radar systems, however, the information about the movement of an object is more relevant. As an example, an unmodulated continuous wave radar can resolve distances only in the range of a single wavelength by measuring the phase of the returned signal

[3] The scenario is therefore a monostatic one.

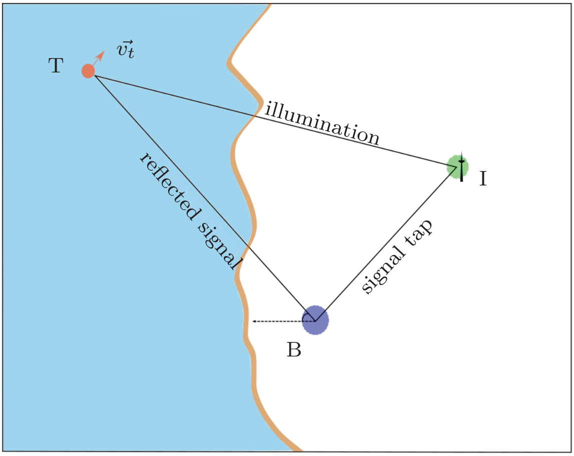

Figure 2.1.: Passive radar concept. A target T gets illuminated by an illuminator of opportunity at I. The observer B receives the direct signal from I and the reflected signal from T.

compared to the transmitted signal. This results in ambiguity of the received signal with a period of one wavelength. Therefore, these are usually unsuitable for distance measurement. However, from the phase shifts due to the Doppler effect, conclusions can be drawn about the radial velocity of the target. The Doppler shift results from the radial velocity v_r and the wavelength λ of the signal [15, p. 69]:

$$f_{\mathfrak{D}} = \frac{2v_r}{\lambda}. \tag{2.7}$$

One possibility to acquire both range and Doppler information of a target is the triangular **modulated** FMCW radar. The description of the FMCW radar is used here as a simple example of a (comparatively simple) modulated system and its evaluation for range and Doppler data. As the name implies, this is a radar in which the target is illuminated with a frequency modulated constant carrier. A good description, on which also the explanations shown here are based, can be found either in [15, p. 82 - 92] or in [17].

A simplified concept of such a radar is shown in Figure 2.2. The modulated radar signal is generated with a signal source and then split between the transmit antenna and a frequency mixer. At the mixer, the undelayed signal is used as the LO and mixed with the signal reflected at the target. The reflected signal is delayed by the signal propagation time. The Mixing of these signals results in the so-called beat frequency f_b. The relationship between the transmitted and the received signals is shown in Figure 2.3 for a distant, moving target. The transmitted signal is shown in blue; the received signal in green. The received signal is delayed by the propagation time and shifted in frequency by the Doppler effect. These shifts result in two distinct beat frequencies for the up- and the down-sweep. The difference

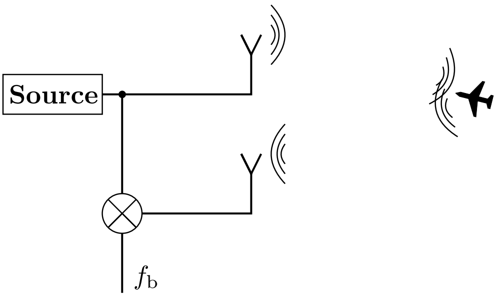

Figure 2.2.: Simplified diagam of an FMCW radar system. The generated radar signal is transmitted and reflected at the target. The delayed received signal is mixed with the signal from the source, resulting in the beat frequency f_b.

between the two is caused by the Doppler effect alone[4]. Therefore, the Doppler frequency of the target can be determined from the average difference between these two signals

$$f_{\mathfrak{D}} = \frac{f_{\mathrm{b,up}} - f_{\mathrm{b,dn}}}{2}. \tag{2.8}$$

The propagation time resulting from the target's distance also results in a beat frequency. If the target is stationary, this delay of the signal results in the same beat frequency for the up- and downsweep signal. However, the frequency shift from the Doppler effect is superimposed on this effect. The beat frequency is shifted by the same amount in each of the two sweeps, but in opposite directions in each case. Due to the equal but opposite shift, the frequency component resulting from the distance of the target $f_{\mathfrak{R}}$ can be determined as the average of the two signals:

$$f_{\mathfrak{R}} = \frac{f_{\mathrm{b,up}} + f_{\mathrm{b,dn}}}{2}. \tag{2.9}$$

Due to the time delay of the received signal, an ambiguous area is created between the ramps, in which the reflected signal of the last ramp is mixed with the signal of the new ramp. The size of this area depends on the distance of the target. Of course, this must be taken into account for signal processing, by not evaluating potentially ambiguous areas of the measurement. To identify these areas, the maximum range of the radar can be estimated with Equation (2.3). The propagation time of the signal for this range is then given by

$$\delta t_{\mathrm{ambigous}} = \frac{2R_{\mathrm{max}}}{c}. \tag{2.10}$$

The range resolution of an FMCW radar depends on the bandwidth B of the sweep used and is given by

$$\Delta\mathfrak{R} = \frac{c}{2B}. \tag{2.11}$$

In addition, when processing the signal from such an FMCW radar, a process gain is achieved, since the **correlated** energy of the target is integrated over the entire usable sweep duration and bandwidth, while the **uncorrelated** energy of the noise remains evenly

[4]The considerations here apply when an ideal, non-complex mixer is used.

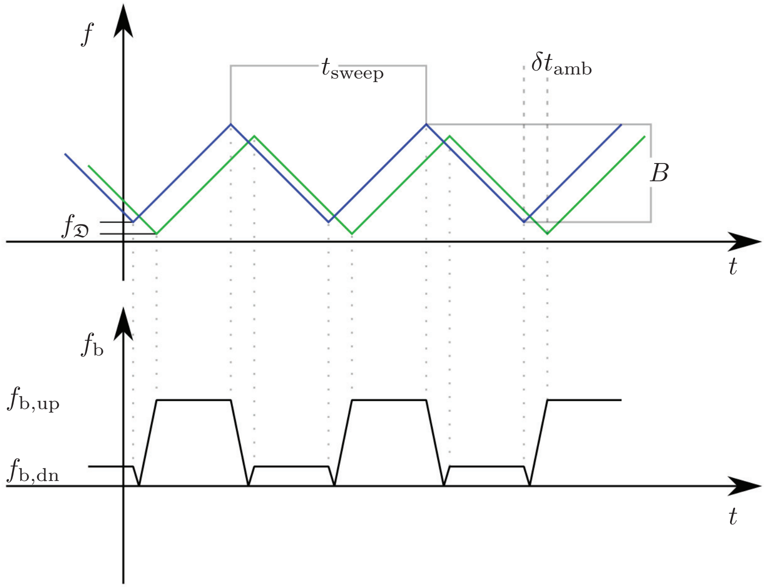

Figure 2.3.: Principle of a triangular modulated FMCW radar. The upper plot shows the frequency over time for the transmit signal (blue) and the receive signal (green) for a distant, moving target. The lower plot shows the beat frequency resulting from the complex mixing of these two signals.

distributed over the bandwidth. Thus, it can be calculated using the effectively used sweep bandwidth B_{eff} and the effective sweep time. Since upsweep and downsweep are evaluated separately, they must also be considered separately. The effective sweep time for the individual sweeps is therefore calculated as

$$t_{\mathrm{eff}} = \frac{t_{\mathrm{sweep}}}{2} - \delta t_{\mathrm{ambigous}}, \tag{2.12}$$

where t_{sweep} is the absolute time for upsweep and downsweep (compare figure 2.3). The process gain for the individual sweeps is then calculated with

$$G_{\mathrm{process}} = B_{\mathrm{eff}} \cdot t_{\mathrm{eff}}. \tag{2.13}$$

As already shown in Equation (2.3), the range depends on the minimum power the system can resolve $P_{\mathrm{R,min}}$. This power can be calculated depending on two parameters. The first is thermal noise, which can be described by

$$P_{\mathrm{N}} = k_{\mathrm{B}} T_0 B_{\mathrm{eff}}, \tag{2.14}$$

where $k_B \approx 1.38 \cdot 10^{-23}\,\frac{\mathrm{J}}{\mathrm{K}}$ is the Boltzmann constant and T_0 the equivalent noise temperature of the antenna. The second factor, which limits the detectable power, stems from additional noise contributions that arise in the system. These are described by the system's noise figure F.

With the process gain and the description of the noise, Equation (2.2) for the received power can be extended to get a relation between signal power and noise power. This eliminates the bandwidth from this equation, resulting in

$$\frac{P_\mathrm{R} G_\mathrm{process}}{P_\mathrm{N}} = P_\mathrm{I} G_\mathrm{I} \cdot \frac{1}{4\pi R_1^2} \cdot \sigma \cdot \frac{1}{4\pi R_2^2} \cdot \frac{\lambda^2 G_\mathrm{R}}{4\pi} \cdot \frac{t_\mathrm{eff}}{k_\mathrm{B} T_0} = \mathrm{SNR}. \tag{2.15}$$

This ratio is called the signal-to-noise ratio (SNR). It is an important measure in assessing signal quality, the larger this ratio is, the farther the wanted signal's power is above the noise.
Rearranging this expression for the range R yields a variant of the radar equation dependent on the system parameters

$$R = \sqrt[4]{\frac{P_\mathrm{I} G_\mathrm{I} \lambda^2 G_\mathrm{R} t_\mathrm{eff} \sigma}{\mathrm{SNR} (4\pi)^3 k_\mathrm{B} T_0 F}}, \tag{2.16}$$

with $R = R_1 = R_2$.

2.4. Passive Radar

A passive radar system uses an illuminator of opportuinty, which is not directly part of the system itself. Therefore, such systems usually have a bi-static topology; Figure 2.1 on page 7 shows an exemplary setup of such a system.
An independent transmitter **I** is used to illuminate the target **T**. The system's receiver **B**, located at another position, receives the reflected signal and the direct signal. By correlation with the transmitted signal (and its Doppler-shifted variations), the bi-static range $\mathfrak{R}$ and the bi-static Doppler shift $\mathfrak{D}$ is obtained. Unlike in mono-static topologies, $\mathfrak{R}$ does not directly express the distance to the target but the difference in path length between the direct line of sight (LOS) to the illuminator and the reflected signal. $\mathfrak{R}$ is calculated from the time difference of arrival between the reflected signal and the LOS signal tap. It is defined as [9]

$$\mathfrak{R} = \|\vec{BT}\| + \|\vec{TI}\| - \|\vec{BI}\|. \tag{2.17}$$

The bi-static Doppler frequency is calculated from the frequency shift resulting from the target's velocity $\vec{\boldsymbol{v}}$ and the center frequency of the illuminating signal f_I. The Doppler frequency $\mathfrak{D}$ for this scenario consists of the dot product of $\vec{\boldsymbol{v}}$ with the difference of the two radial components, one from the Illuminator **I** to the target **T** and one from the target to the observer **B**. It is defined by [18]

$$\mathfrak{D} = f_\mathrm{I} \cdot \left(\frac{\vec{v}}{c} \cdot \left(\frac{\vec{TB}}{\|\vec{TB}\|} - \frac{\vec{IT}}{\|\vec{IT}\|} \right) \right). \tag{2.18}$$

This equation is valid for $\|\vec{v}\| \ll c$.

The most crucial factor in assessing a radar system's performance is the SNR achievable for a given target. This results from the ratio of the received power P_R and the contributions