TKK Dissertations 155
Espoo 2009

PULSED RADAR MEASUREMENTS AND RELATED EQUIPMENT

Doctoral Dissertation

Mikko Puranen

Helsinki University of Technology
Faculty of Electronics, Communications and Automation
Department of Signal Processing and Acoustics

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Dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Faculty of Electronics, Communications and Automation for public examination and debate in Auditorium S4 at Helsinki University of Technology (Espoo, Finland) on the 27th of March, 2009, at 12 noon.

Helsinki University of Technology
Faculty of Electronics, Communications and Automation
Department of Signal Processing and Acoustics

Teknillinen korkeakoulu
Elektroniikan, tietoliikenteen ja automaation tiedekunta
Signaalinkäsittelyn ja akustiikan laitos

Distribution:
Helsinki University of Technology
Faculty of Electronics, Communications and Automation
Department of Signal Processing and Acoustics
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P.O. Box 3000
FI - 02015 TKK
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ISBN 978-951-22-9803-7
ISBN 978-951-22-9804-4 (PDF)
ISSN 1795-2239
ISSN 1795-4584 (PDF)
URL: http://lib.tkk.fi/Diss/2009/isbn9789512298044/

TKK-DISS-2577

Picaset Oy
Helsinki 2009

ABSTRACT OF DOCTORAL DISSERTATION	HELSINKI UNIVERSITY OF TECHNOLOGY P. O. BOX 1000, FI-02015 TKK http://www.tkk.fi

Author Mikko Puranen

Name of the dissertation

Pulsed Radar Measurements and Related Equipment

Manuscript submitted June 13, 2008	Manuscript revised February 16, 2009
Date of the defence March 27, 2009	
☐ Monograph	☒ Article dissertation (summary + original articles)

Faculty	Faculty of Electronics, Communication and Automation
Department	Department of Signal Processing and Acoustics
Field of research	Measurement Science and Technology
Opponent(s)	Prof. Mike Underhill
Supervisor	Prof. Erkki Ikonen
Instructor	Prof. Pekka Eskelinen, Doc. Petri Kärhä

Abstract

The purpose of this thesis has been to develop novel methods for pulsed radar measurements, creating practical tools for verifying the operation of a modern pulsed radar, and to build working prototypes suitable for field use.

Very little information has been published in the radar field perhaps due to the military nature of many research projects. Methods and equipment are typically researched by different armed forces. In this thesis, some tools for frequency, power and waveform measurements are presented. Even the most modern commercial measuring instruments, however, are not capable of measuring a pulsed radar signal, mostly due to the short (even tens of nanoseconds) pulse length. The limitations of conventional measuring devices are discussed in the overview part of the thesis and also in Publications II and IV.

The first publication demonstrates a radar calibration system, based on a fiber-optic delay line. The idea to use an optical delay line for such a purpose is not new, but an operational setup has not been published previously. The calibrator provides a convenient method to use the radar's own signal for calibration. The optical link makes it possible to use long delays, even tens of microseconds, without significant signal attenuation.

Furthermore, two frequency measurement methods for short-term stability evaluation are presented. Both are based on a phase detector. The first setup has better frequency uncertainty, even 1.6 Hz, with a sampling speed of 10 000 s^{-1}. The other setup is used to detect frequency differences: A deviation of 200 kHz in the carrier frequency could be detected when the pulse length was 200 ns. This system outperforms the first one when short pulses are evaluated. The phase detector based setup itself is old and familiar technology, but the idea to use it in this application is one thing new.

Finally, two new instrumentation radars are also presented. They are used to measure the effects that terrain, weather, vegetation and seasonal changes have on radar clutter or signal propagation. A significant effort has been made by other scientists in developing mathematical models to be able to simulate the effects mentioned, but so far the only reliable method for creating clutter models is to collect data with a real radar. Such instrumentation radars have probably been developed earlier, but until now they have not been published.

Keywords Pulsed radar, radio frequency, power, frequency, waveform

ISBN (printed) 978-951-22-9803-7	ISSN (printed) 1795-2239
ISBN (pdf) 978-951-22-9804-4	ISSN (pdf) 1795-4584
Language English	Number of pages 72 p. + app. 31 p.

Publisher Helsinki University of Technology, Metrology Research Institute

Print distribution Helsinki University of Technology, Metrology Research Institute

☒ The dissertation can be read at http://lib.tkk.fi/Diss/2009/isbn9789512298044/

VÄITÖSKIRJAN TIIVISTELMÄ	TEKNILLINEN KORKEAKOULU PL 1000, 02015 TKK http://www.tkk.fi

Tekijä Mikko Puranen

Väitöskirjan nimi

Pulssitutkan mittaukset ja aiheeseen liittyvät laitteet

Käsikirjoituksen päivämäärä 13.6.2008	Korjatun käsikirjoituksen päivämäärä 16.2.2009
Väitöstilaisuuden ajankohta 27.3.2009	
☐ Monografia	☒ Yhdistelmäväitöskirja (yhteenveto + erillisartikkelit)

Tiedekunta	Elektroniikan, tietoliikenteen ja automaation tiedekunta
Laitos	Signaalinkäsittelyn ja akustiikan laitos
Tutkimusala	Mittaustekniikka
Vastaväittäjä(t)	Prof. Mike Underhill
Työn valvoja	Prof. Erkki Ikonen
Työn ohjaaja	Prof. Pekka Eskelinen ja dos. Petri Kärhä

Tiivistelmä

Tämän tutkimuksen tarkoituksena on ollut kehittää uusia menetelmiä pulssitutkamittauksiin. Tavoitteena oli luoda käytännöllisiä työkaluja nykyaikaisen pulssitutkan toiminnan varmistamiseen sekä rakentaa toimivia prototyyppejä, jotka ovat käyttökelpoisia myös kenttäolosuhteissa.

Tähän mennessä aiheesta on julkaistu hyvin vähän tietoa johtuen todennäköisesti tutkan sotilaallisesta luonteesta. Menetelmiä ja laitteita kehittävät tyypillisesti armeijat. Tässä opinnäytteessä esitetään joitakin työkaluja tutkan taajuuden, tehon ja aaltomuodon mittauksiin. Koska nykyaikaisimmatkaan mittalaitteet eivät pysty luotettavasti mittaamaan pulssitutkan signaalia, rakennettiin myös jonkin verran uusia laitteita. Perinteisten mittalaitteiden rajoituksia on käsitelty tämän opinnäytteen yhteenvedossa ja julkaisuissa II ja IV.

Ensimmäinen julkaisu esittelee toimivan tutkakalibrointijärjestelmän, joka perustuu optiseen viivelinjaan. Järjestelmän perusidea ei ole uusi, mutta vastaavaa toimivaa laitteistoa ei ole aiemmin julkaistu. Kalibraattori mahdollistaa helpon tavan käyttää tutkan omaa signaalia kalibroinnissa. Optinen viivelinja mahdollistaa jopa kymmenien mikrosekuntien viiveen ilman signaalin merkittävää vaimenemista.

Kaksi taajuusmittausmenetelmää lyhytaikaisen taajuusstabiiliuden mittauksiin on kehitetty. Kummatkin perustuvat vaihevertailijaan, toinen laitteisto tarjoaa paremman epävarmuuden, jopa 1,6 Hz, kun taas toinen laitteisto toimii nopeammalla näytteenottotaajuudella, jolloin voidaan tutkia jopa alle 200 ns pituisia pulsseja. Vaihevertailijaan perustuvat mittauslaitteistot eivät itsessään ole uusia, mutta vastaavia taajuusmittausjärjestelyitä tai niiden tuloksia ei ole aiemmin julkaistu.

Artikkeleissa esitellään kaksi instrumentointitutkaa, jotka rakennettiin tutkimuksen aikana. Niitä käytetään kasvillisuuden, sään, maaston ja vuodenaikojen vaihtelun aiheuttaman välkkeen ja signaalin etenemisominaisuuksien muutosten tarkkailuun. Monissa ansiokkaissa tutkimuksissa välkettä on mallinnettu tietokoneilla, mutta toistaiseksi ainoa luotettava menetelmä välkemallin luomiseksi on kerätä tarpeeksi mittaustuloksia ja rakentaa malli niiden pohjalta. Vastaavia tutkia on todennäköisesti kehitetty aiemminkin, mutta toistaiseksi ne eivät ole julkisia.

Asiasanat Pulssitutka, radiotaajuus, teho, taajuus, aaltomuoto

ISBN (painettu) 978-951-22-9803-7	ISSN (painettu) 1795-2239
ISBN (pdf) 978-951-22-9804-4	ISSN (pdf) 1795-4584
Kieli Englanti	Sivumäärä 72 s. + liitt. 31 s.

Julkaisija Teknillinen korkeakoulu, MIKES TKK Mittaustekniikka

Painetun väitöskirjan jakelu Teknillinen korkeakoulu, MIKES TKK Mittaustekniikka

☒ Luettavissa verkossa osoitteessa http://lib.tkk.fi/Diss/2009/isbn9789512298044/

Preface

The research described in this thesis has been carried out at the Metrology Research Institute (MRI), Department of Electrical and Communications Engineering and at the Institute of Digital Communications (IDC) of the Helsinki University of Technology during the years 2004 – 2008.

I wish to thank the former head of the department, professor Pekka Wallin, and professor Erkki Ikonen for providing me with an opportunity to pursue post graduate studies. Especially I want to thank professor Pekka Eskelinen, who introduced me to this amazingly interesting topic and gave me freedom to do things in my own way. Sometimes it was a successful and sometimes less so. Without his tireless efforts I would never have been at this point, writing a preface for my own doctoral thesis.

Special thanks go to docent Petri Kärhä, who has given really valuable advice throughout my time at the MRI. Mr. Markku Nieminen is also acknowledged for his support. Dr. Jukka Ruoskanen and major Heikki Heikkilä are acknowledged as the co-authors of the publications.

The preliminary examiners of the thesis, professor Pertti Silventoinen, Dr. Edgar Schmidhammer, and docent Olli-Pekka Lundén, are thanked for their efforts.

Emil Aaltonen Foundation is acknowledged for financial support.

I have thanked my parents and all my dear friends for their existence already in two theses. Well, thanks again!

Mikko Puranen

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5 Conclusions and discussion 63

References 65

List of Publications

This thesis consists of an overview section and the following publications which are referred to in the text by their Roman numerals.

I Mikko Puranen, Petri Kärhä and Pekka Eskelinen. Fiber-optic radar calibration. *IEEE Aerospace and Electronic Systems Magazine*, 20(9), pp. 30–33, 2005.

II Mikko Puranen and Pekka Eskelinen. Measurement of short-term frequency stability of controlled oscillators. *Proceedings of the 20th European Frequency and Time Forum (EFTF 2006)*, Braunschweig, Germany, pp. 76–79, 2006.

III Mikko Puranen and Pekka Eskelinen. Improved methods for frequency measurement of short radar pulses. *Proceedings of the 21st European Frequency and Time Forum (EFTF 2007)*, Geneva, Switzerland, pp. 970–973, 2007.

IV Mikko Puranen, Pekka Eskelinen and Jukka Ruoskanen. Practical uncertainty of pulse power measurements in Ka-band RCS instrumentation. *IEEE Antennas and Propagation Magazine*, 50(4), pp. 120–125, 2008.

V Mikko Puranen, Pekka Eskelinen, Jukka Ruoskanen and Heikki Heikkilä. Simple 3D millimetre clutter scanner for field measurements. *Proceedings of the International Radar Symposium (IRS 2006)*, Krakow, Poland, pp. 339–342, 2006.

VI Mikko Puranen and Pekka Eskelinen. A short-pulse Ka-band instrumentation radar for foliage attenuation measurements, *Review of Scientific Instruments*, 79(11), 106106, 3 pages, 2008.

Author’s contribution

The research work presented in this thesis has been carried out at the MRI and at the IDC during the years 2004–2008. The thesis consists of a short overview section and six publications that are listed on page 11. All publications are the results of group effort. The author, however, has prepared the manuscripts and contributed significantly with both hardware and measurements towards the scientific content of the papers. This is explained in detail as follows:

[P1] The author designed and built the calibration system, performed the measurements and prepared the manuscript.

[P2] The author designed and built the described setup, performed the measurements and prepared the manuscript.

[P3] The author designed and built the described setup, performed the measurements and prepared the manuscript.

[P4] The author performed the measurements and prepared the manuscript.

[P5] The author prepared the manuscript, designed and built the electronics of the control unit and analyzed the measurement data. The author took part in the RF-system design.

[P6] The author designed the pulse modulator of the radar, analyzed the data and prepared the manuscript.

List of symbols and abbreviations

Δf	Doppler frequency
Δf_{span}	Frequency span of a spectrum analyzer
λ	Wavelength
ϕ	Grazing angle
σ	Radar cross section
σ^0	Normalized clutter coefficient
τ	Pulse length
θ_B	Antenna beam width
θ_b	Azimuth beam width
A_r	Effective aperture area of the receiving antenna
B_{res}	Resolution bandwidth
C	Clutter level
c	Speed of light
d	Aperture dimension of an antenna
e_{lin}	Linearity error
F	Pattern propagation factor
f	Frequency
G_t	Gain of transmitting antenna
k_f	Constant

P_r	Returning power
P_t	Transmitted power
R	Range
R_r	Distance from the target to the receiver
R_t	Distance from the transmitter to the target
S	Signal level
T_{sweep}	Sweep time
v	Speed of the target
ACC	Adaptive cruise control
ADC	Analog to digital converter
AMES	Air Ministry Experimental Station
CH	Chain home
CHL	Chain home low
CW	Continuous wave
DAC	Digital-to-analog converter
DRO	Dielectric resonator oscillator
DUT	Device under test
EMI	Electromagnetic interference
FM	Frequency modulation
GEMA	Gesellschaft für elektroakustische und mechanische Apparate mbH
GPS	Global positioning system

IDC	Institute of Digital Communications
IF	Intermediate frequency
LO	Local oscillator
MiG	Mikoyan-Gurevich
MRI	Metrology Research Institute
PDB	Planar doped barrier, in PDB-diode
PEP	Peak envelope power
PPI	Plan position indicator
PRF	Pulse repetition frequency
RADAR	Radio detection and ranging
RAM	Radar absorbing material
RBW	Resolution bandwidth of a spectrum analyzer
RCS	Radar cross section
SAR	Synthetic Aperture Radar
SARH	Semi-active radar homing
SWR	Standing wave ratio
TKK	Teknillinen korkeakoulu, Helsinki University of Technology
TR	Transmit-receive, in TR-switch
UK	United Kingdom
USA	United States of America
WWII	World War II

Frequency bands as per IEEE standard 521-2002 and their typical uses

HF-band	3-30 MHz	Shortwave radio
VHF-band	30-300 MHz	TV, FM radio
UHF-band	300-1000 MHz	TV, mobile phones
L-band	1-2 GHz	Mobile phones, GPS (Global Positioning System)
S-band	2-4 GHz	Wireless networks, Bluetooth
C-band	4-8 GHz	Wireless networks, weather radars
X-band	8-12 GHz	Communication satellites, many different kind of radars
K_u-band	12-18 GHz	Broadcasting satellites
K-band	18-27 GHz	Absorption due to the water vapor from 18 to 26.5 GHz
K_a-band	27-40 GHz	Radars, communication satellites
V-band	40-75 GHz	Scientific research, experimental radars
W-band	75-110 GHz	Millimeter wave radar research

1 Introduction

Radar (abbr. Radio Detection And Ranging) is an invention over 100 years old. The first radar-like device was built by the German scientist, Christian Hülsmeyer, in the early years of the 20^{th} century. He patented his invention, which he called the *telemobiloscope*, in 1904, after he had demonstrated its capabilities in public. Hülsmeyer, born on Christmas day in 1881, was then only 22 years old. [1, 2]

The telemobiloscope was designed to detect metallic objects, like ships, in poor weather and thus to prevent collisions. Hülsmeyer's device did not, however, yet feature a display, but used a bell instead to notify the users of detected metallic objects. Furthermore, since it was quite awkward to read the azimuth direction from the antenna, Hülsmeyer later added a device called a *Kompass* to his telemobiloscope. It was a pointer which moved synchronously to the antenna. This can be considered as a predecessor of a plan position indicator (PPI).

Hülsmeyer was also interested in ranging. Since the pulsed radar could not yet be built, he patented a method, where the range could be calculated by altering the elevation angle of the telemobiloscope transmitter [3]. He did not, however, explain the method very clearly in the patent application.

After these early advancements, radar development halted for over two decades. During this period, radio frequency (RF) technology took steps forward in other fields. Vacuum tubes were introduced, and in 1926 Japanese scientists Shintaro Uda and Hidetsugu Yagi from the Tohoku Imperial University, Sendai, Japan, designed a directional antenna, which is today widely known as the *Yagi-antenna*, or sometimes also as the *Yagi-Uda*-antenna. During the 1930's, radar development was under way again, and independent efforts to improve the technology were made at least in Germany, the United Kingdom (UK), France, the United States of America (USA) and Russia. In October 1934, Rudolf Kühnold demonstrated his radar to the German Navy, an event which sparked the *Freya* project. It was a warning radar designed for the German army by the company called *Gesellschaft für elektroakustische und mechanische Apparate mbH* (GEMA). During World War II (WWII) over 1000 Freya stations were built. In GEMA, there was one department that designed and manufactured custom-made radar measuring instruments as separate devices or modules. [4, p. 135]

At the same time, the UK had its own warning radar project, called *Chain Home* (CH). Chain Home stations (Figure 1.1), or AMES (Air Ministry Experimental Station) type 1 stations, were designed for long range detection, while Chain Home Low (CHL) stations (AMES type 2), had shorter operating ranges but they could detect an aircraft flying at a lower altitude. In the National Physical Laboratory (NPL), UK, the first RF power standard was developed to meet the needs the users of radars had set. Power calibration ended, however, for some time, in 1960. [5, pp. 462–464]

Figure 1.1: Chain Home stations. [6, p. 87]

In the USA, the most notable institution at the beginning of the radar era was the Lincoln Laboratory of the Massachusetts Institute of Technology (MIT). It was and still is known for its strong focus on analyzing real-world data from the advanced electronic systems it develops and operates. This compels the laboratory to build hardware with capabilities exceeding those commercially available. [7, 8, 9]

The Second World War was the *Golden Age* of radar development, and the benefits that radar could provide became widely known throughout the world. At first, radars were used to detect hostile aircraft and ships, and the demand for better resolution and range added impetus to the research. [10, 11]

When the war was over, radars also began to find uses in civilian applications, such as air traffic control and weather monitoring. Until recent times, however, very little information regarding radar research has been published. This is understandable, because the topic still is very much military in nature.

1.1 Use of the pulsed radar

This thesis concentrates mainly on pulsed radars. A basic monostatic continuous wave (CW) radar, for example, cannot be used to measure the distance to the target. Nowadays, Hülsmeyer's proposal on the alternation of the elevation angle is obsolete. Without distance information, angular data also loses its meaning because targets appearing at a given direction will produce a signal chaos on the radar display on one arbitrary line. Today short RF pulses can be produced and their travelling time can be measured, so the distance to the target can be precisely calculated.

The first pulsed radars were used for military purposes. The CH radar operated in very high frequency (VHF) and short wave (SW) bands, and featured pulse lengths of 5 – 45 μs. It was fairly primitive system, because better technology was not easily available at the beginning of the war, and radars had to be simple to construct. Freya was more advanced; it operated at ca. 10 times higher frequency, the resolution was better – pulse length was 3 μs – and smaller antennas could be used. This was also a disadvantage, because part supplies became very limited. [2, 5, 6]

Today, pulsed radar is commonly used in all kinds of applications where the exact place of multiple targets should be known. Recently, radars have spread even into everyday applications, like automotive systems.

Radar is already employed in some cars where it is used, for example, to provide information for cruise control system so that the distance to the car driving ahead will not become dangerously short. Some manufacturers have further developed this idea and constructed a collision avoidance system, which detects targets approaching quickly in front of the car and applies brakes. [12, 13]

Pulsed radars have developed at a significant pace, but the motivation of this thesis is not the radar technology itself but rather the *measurement methods for pulsed radars*. Pulses are typically really short, even tens of nanoseconds, the power level may be low (e.g. -70 dBm), and the operating frequency may be far beyond the measurement range of the available equipment. One may face problems even with the most recent spectrum analyzers [14], as described in Publication IV. Quite recently, some promising oscilloscopes, like the Tektronix DSA8200 [15], have become available, with over 70 GHz bandwidth and 5 ps rise time. Unfortunately, these devices are – at least for the moment – far too bulky for field use.

To overcome these challenges, one has to apply the engineering skills of many fields, since in RF systems not only the electrical part but also the mechanical structure of the device plays an important role. New instruments have to be developed to aid measurements, and innovative ideas are required to expand the use of conventional measurement devices.

1.2 Contents of this thesis

This thesis begins with a short introduction to the radar world. In the second chapter, radar theory is briefly discussed. Topics covered include, for example, CW radar and pulsed radar. In the third chapter, the devices built at TKK during this research project are presented and reviewed. These are either separate fully functional systems, like the optical delay line, or devices used together with commercial measurement instruments. Chapter Four concentrates on pulsed radar measurements, being divided into three sections; frequency measurements, power measurements and waveform evaluation methods. The fifth chapter summarizes the topic, and discusses the findings.

Publications I–VI cover quite variable topics. Some concentrate on the measurements, and others on the hardware developed in the course of the research. The overview part of this thesis mostly covers measurements and related instruments which were necessary in the research work. Individual findings in the Publications I to VI are not repeated in the overview section of this thesis.

1.3 Contribution of the research

The thesis contains the following new scientific results:

- A novel measuring method for determining clutter characteristics of vegetation and landscape has been developed, where each resolution element is scanned individually. The narrow beamwidth of the antenna enhances the resolution, and the mechanics of the radar provides good positional repeatability. The performance of the method has been tested using a prototype radar.
- A new method to measure the attenuation caused by vegetation has been developed. The described method uses a short, 17 ns pulse, and a corner reflector. A prototype radar was used to evaluate the performance of the method.
- Methods to measure frequency changes during short pulses have been evaluated. A new frequency measurement method to observe short-term frequency stability

is developed. The demonstrated setup is based on a phase detector and a delay line. The frequency measurement uncertainty of the system is 1.6 Hz with 25 MHz center frequency and 100 000 s^{-1} sampling rate.

- The performance of conventional measuring instruments have been compared when measuring the power or the waveform of short RF pulses. A measuring receiver that exceeds the performance limits of such instruments has been developed and characterized.

1.4 Scope of the thesis

The research work reported here can be divided into two parts. The first is the development of two radar measurement methods: The clutter scanner provides data to evaluate the characteristics of landscape and nature, and the short-pulse radar is used for foliage attenuation measurements.

The second important part of this work is the research on new measurement instrumentation and methods, which were required for the development of the radars mentioned above. Since the radars are designed for long-term field use, reliability and performance had to be thoroughly tested during the development process. Due to the limitations of conventional measuring instruments, some new devices had to be developed during the period of research. Characteristics of certain commercial devices were compared and documented. The most significant result of the development of the measuring methods is the peak power and waveform measurement system for pulsed signals.

The frequency measurement setup for this research is based on a phase discriminator which is an old concept [16, Chapter 1.2.3.2.1]. To date, however, all publications have discussed the topic from a purely theoretical perspective.

The suitability of equipment for field use was a significant design criterion for the measuring methods. The term *field use*, in this case, means portability (weight, power consumption, power supply requirements), protection against difficult weather conditions, and durability in general. Military use typically means, that equipment will be transported from one place to another rather often, and the device itself has to be robust to withstand mechanical shocks and heavy handling. EMC compatibility is also an important issue, the measuring equipment must work reliably near, for example, an operating radar.

The reader should keep in mind that, for example, some new oscilloscopes can be used in radar measurements without any of the extra tricks discussed in this thesis, but they consume a lot of power and are large and heavy, limiting significantly their suitability for field use. [15]

The clutter scanner uses a novel method to gather information over a long time scale; it can be used even for months at a time. This is especially important in Finland, because during the four annual seasons, the clutter characteristics of the landscape vary significantly due to the growth of the vegetation. Data itself do not have scientific importance from the instrumentation point of view, so they are not published in this thesis apart from some examples. Also in [17, 18] clutter measurements are discussed. Clutter models have been developed, e.g. [19, 20], but simulating the effects caused by the vegetation and seasonal changes is extremely difficult.

The short-pulse radar demonstrated in publication VI is based on a rather simple pulse modulator. When used together with a frequency doubled dielectric resonator oscillator (DRO), it produces well-shaped, short 17 ns pulses. Although the hardware is simple, the end result was obtained by carefully tuning and optimizing the modulator-oscillator combination. The significance of the short pulse length is discussed in [21].

Short pulses have certainly been demonstrated earlier. In [22] a 300 ps pulse has been presented. The same authors also improved their design in [23], where the circuit is quite clever in its simplicity. The topic and the required hardware have also been discussed in [24, 25]. The notable achievement in our work is that we have been able to demonstrate a fully operational and mechanically compact device which provides reliable measurement results also in the true field conditions of the Finnish climate. Designing a convincing modulator, however, is merely the first step in building a working radar. Similar system for vegetation attenuation measurements has been demonstrated, for instance, in [26], but it is a lot bulkier and thus not comparable to our radar. Theory and some experiments have been presented also in [27].

The whole field of radar is still covered with some kind of a cloak of secrecy due to its military nature, and therefore very little information has been published. An important theme in this thesis is field use, and it is a topic that is not discussed at all in the most of the articles. I still want to mention one notable work, that is Jukka Ruoskanen's PhD thesis [28]. Dr. Ruoskanen discusses similar issues that are found in this thesis, but he has taken a more mathematical approach to the affairs and the focus there is on the phenomenological side of radar signals.

2 Radar theory

In this chapter, basic radar theory is discussed to provide the reader with some relevant information to further understand the presented research findings.

2.1 Radars in general

The very basic idea of radar is presented in Figure 2.1. The transmitted signal is reflected in many directions when hitting a target, and a part of this reflected signal hits the receiving antenna. The signal is then amplified, detected and indicated. The amplitude of the signal, or the observed size of the target, depends, among other things, on its radar cross section (RCS or σ).

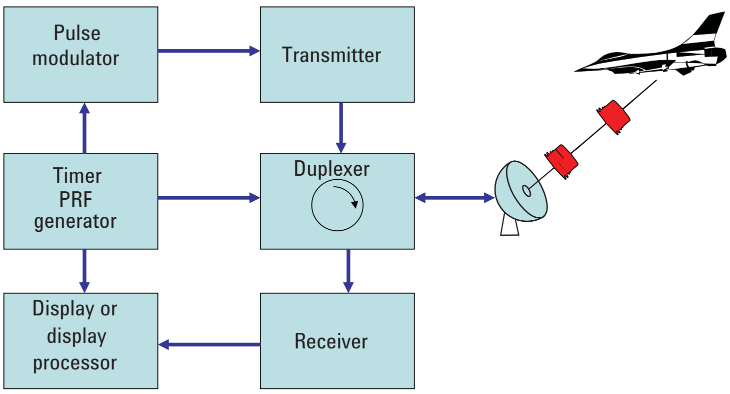

Figure 2.1: The basic working principle of a radar. RF signal is transmitted. When the signal hits the target, the signal is scattered and a part of it is received. The signal is amplified, detected and the target is shown on the display. The azimuth angle of the target is detected by monitoring the orientation of the antenna. The pulse modulator is also shown in this diagram. [29]

In military applications, the observability of a vehicle or a missile is a critical issue. Therefore, the RCS is designed to be as minimal as possible. Radar cross sections of some military vehicles are listed in [30]. Typical methods to reduce the RCS are special shapes, non-metallic parts, or coatings with radar absorbing material (RAM). The F-22 fighter (Figure 2.2), manufactured by Lockheed-Martin and Boeing, is a good example of a modern stealth vehicle. Every part of the aircraft, even the hinges and pilot helmets, have been optimized to minimize the RCS. [31, 32]

Figure 2.2: Lockheed-Martin/Boeing F-22 Raptor is a modern stealth fighter. Pay attention to the special shape of the aircraft and the hidden engine nozzles. Photo: Ian Heald.

The radar transmitter is typically a high-power RF oscillator, for instance, a magnetron or a synthesizer followed by cascaded amplifiers. If the same antenna is used for transmission and reception, a transmit-receive-switch (TR-switch, providing high isolation) must be used to prevent the high-power signal from destroying the front-end of the receiver.

The incoming signal is usually amplified by a low-noise amplifier (LNA) and then detected using a diode. The last parts in the signal path are signal processing devices and usually some kind of a display. Additional amplifiers and filters may also be used.

The radar equation describes the fundamental relation between the characteristics of the radar, the target, and the received signal. The power P_r returning to the receiving antenna is

$$P_r = \frac{P_t G_t A_r \sigma}{(4\pi)^2 R_t^2 R_r^2}\,, \tag{2.1}$$

where P_t is the transmitted power, G_t is the gain of the transmitting antenna, A_r is the effective aperture area of the receiving antenna, σ is the radar cross section, R_t is the distance from the transmitting antenna to the target and R_r is the distance from the target to the receiving antenna. [33, p. 1.6]

For monostatic radars, $R_t \equiv R_r$, but in bistatic and multistatic geometries, these distances may show large differences. In surveillance radars, we have to use as much transmitter power as practical because the distance range can exceed 500 km. Fire control and other short range systems can work with tens or hundreds of watts but they often give superior spatial resolution.

2.2 Continuous wave radar

Based on the waveform employed, there are basically two types of radars: continuous wave and pulsed radar. This thesis mainly discusses the latter, but in this section CW radar is briefly covered. In CW radar, a continuous signal is transmitted, and in the simplest case, only the presence of a target is detected.

A Doppler radar can provide speed information, and a frequency modulated (FM) CW-radar (FMCW) is able to measure the distance to the target. One should note that Doppler- and FM radars can also be pulsed radars. If the radar operates in a pure CW mode, the clear benefit comes from the narrow (theoretically zero) bandwidth which brings ultimate sensitivity in terms of thermal noise. The most significant limitation is that the CW radar is only able to track one target at a time. [34, p. 6]

The Doppler radar is most commonly used in traffic speed monitoring. If the target is moving, the frequency of the signal reflected from the target differs from the original due to the Doppler Effect. The change in frequency, Δf, is

$$\Delta f = \frac{vf}{c}, \tag{2.2}$$

where f is the transmitted frequency, v is the radial velocity of the target and c is the speed of light. The radar measures the change in frequency by mixing the transmitted signal and the received signal. Radar-based intrusion detection systems also typically rely on the Doppler principle. Even in this Doppler case, the receiver can be a very narrow band, perhaps only some tens of kilohertz and thus, the noise floor is not a problem.

In FMCW radar, the frequency of the transmitted signal is swept according to a predefined pattern. By comparing the frequencies of the transmitted and the received signals, the distance to the target can be measured. Frequency modulation is sometimes called chirping. [35, 36]

FMCW radar is also used in Adaptive Cruise Control (ACC) systems. It constantly measures distances to possible obstacles in front of the car and, if necessary, decelerates the car. In recent versions, an automatic braking feature has been added. [37, 12, 13]

Radars typically feature a mechanically scanning antenna. In cars, this kind of solution would be quite unusable, so in directional automotive radars, a phased array antenna is used. The removal of mechanical parts would be desirable also in conventional radars, but so far traditional antennas have been more popular. [38]

One interesting application of the CW radar is the semi-active radar homing (SARH) missile, such as the AIM-7 sparrow. The aircraft illuminates the target with a CW radar, and the missile follows the reflected signal. Most modern aircraft radars have a CW feature built-in for missile guidance purposes. [39]

2.3 Pulsed radar

In pulsed radars, short pulses are transmitted at selected intervals. By measuring the traveling time of the pulse, the distance to the target can be determined without frequency modulation. Also the size and the speed of the target can be measured. Some key specifications for pulsed radar are the pulse repetition frequency (PRF) and the pulse length (τ). The former depends mostly on the application; a low PRF extends the range of the radar, because the echo from the target must be received before the transmission of the next pulse. Usually, the PRF is so low that echoes from distant targets disappear in the background noise or clutter. A typical PRF is 0,1 – 10 kHz, the minimum range depending on the pulse length and the delay of the TR-switch. [40]

The pulse length is a factor that makes the measurements discussed in this thesis so challenging. In modern radars, the pulse length may be less than 100 ns. Short pulses are desirable, since they are a way to increase the range resolution. If the radar pulse is long, two targets near each other may look like a single large target, but with short pulses, separate targets may be seen (see Figure 2.3).

Shorter pulses provide also means to reduce surface and volume clutter levels. In an elementary case, a reduction of the pulse length by a factor of ten, for example from 1 μs to 100 ns, means 10 dB lower surface clutter. In [33, p. 1.10], signal-to-clutter ratio S/C is defined as

$$\frac{S}{C} = \frac{\sigma}{\sigma^0 R\theta_b(c\tau/2)\sec\phi}\,, \tag{2.3}$$

where σ^0 is the normalized clutter coefficient[1], R is the distance to the clutter patch, θ_b is the azimuth beam width, τ is the pulse length and ϕ is the grazing angle.

However, short pulses call for a wideband receiver in which the contribution of thermal noise cannot be neglected. In fact, there is an optimum value for which clutter and noise give equal limits for the maximum target range as was shown in [28].

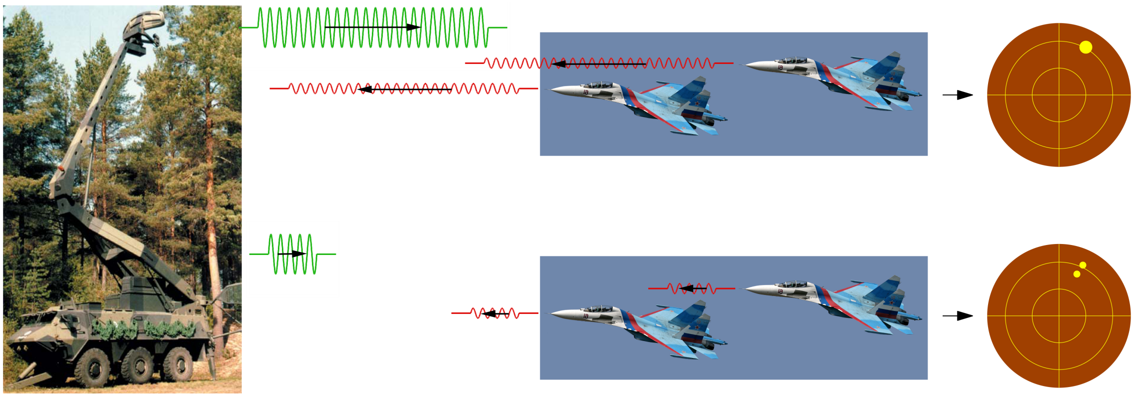

Figure 2.3: The range resolution of a pulsed radar depends on the pulse length. Two targets near each other may be indicated as single large target, because of the received echoes overlap. With shorter pulses, two separate targets can be seen on the plan position indicator (PPI) display. Photos: Finnish Defence Forces and Max Bryanski.

The beamwidth of the antenna defines the angular resolution. The beamwidth is related to the aperture dimension of the antenna (e.g. the diameter of the parabolic antenna) and to the signal wavelength. If an antenna has an aperture dimension d, and it's operating wavelength is λ, the beamwidth θ_B (in degrees) can be approximated by

[1] Clutter coefficient is the ratio of the clutter echo to the area illuminated by the radar.

$$\theta_B = \frac{65^\circ \cdot \lambda}{d}. \quad (2.4)$$

Better angular resolution can be achieved by shortening the wavelength, as can be seen in Equation 2.4. [41, p. 77]

A diagram of a non-coherent pulsed radar is presented in Figure 2.4. High power radar pulses are generated by a modulated oscillator, typically a magnetron. They are directed to an antenna via a circulator or a T-R switch. The received signal is amplified with a low noise amplifier (LNA) and down-converted to an intermediate frequency (IF). The IF-signal is amplified again, filtered with a band-pass filter and indicated with a detector diode. The final blocks are a signal processor and a display.

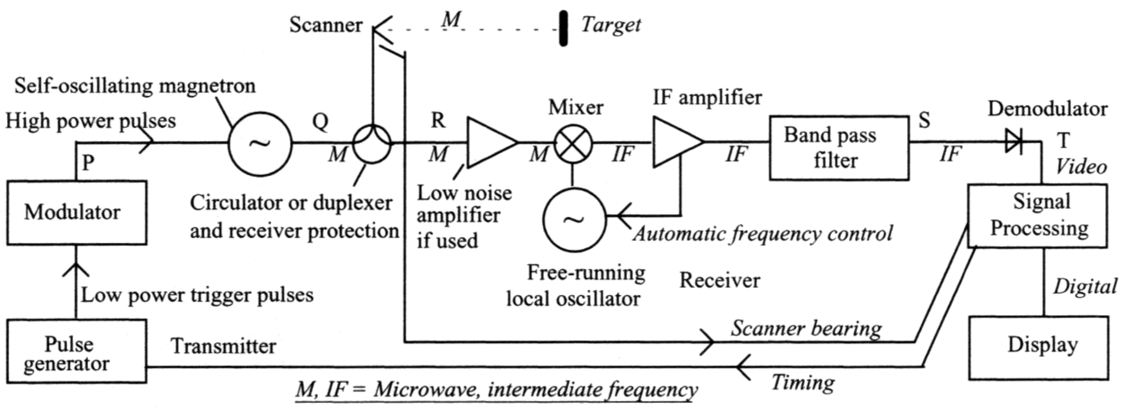

Figure 2.4: A block diagram of a non-coherent pulsed radar. The signal source is a pulse modulated magnetron. The signal is fed to the antenna via a circulator or a duplexer. The received signal is amplified, mixed to a lower frequency band and filtered. The final parts are the detector, the signal processing system and the display. [40]

The so-called ultra-short pulse radars have novel applications in automotive safety systems and intelligent transportation devices. They are typically short-range radars with transmission power of less than 100 mW. [42, 43]

2.4 Radar calibration

Radar calibration in this case means the calibration of the RCS and distance readout. Typically a radar can be calibrated by using reference targets, for example, corner reflectors. This method, however, does not necessarily provide accurate results due to certain factors that are not ideal, like disturbances in the atmosphere, mechanical misalignments or multipath propagation issues. An easy method to fix this problem would be to use an external radar transmitter which could be connected to the input of the radar to be calibrated. Some modern radars, however, are able to detect this kind of fake signals and thus cannot be calibrated this way. The radar's own signal must be used instead.

By delaying and attenuating the radar's signal in a controlled way, we can calibrate even the most complex devices. In the beginning of this research project, a fiber-optic radar calibrator was built, providing a convenient way to maintain the pulse shape, coherence and power, and still the delay may be long, even over 10 μs.

2.5 Instrumentation radars

The clutter scanner is discussed in Publication V. The RF-part of the radar is an example of a basic CW radar. The radar is used to scan one resolution cell at a time. It can be directed either manually, using an optical viewfinder, or it can be programmed for automatic scanning using a microcomputer. The positioning repeatability is 0.1 degrees in elevation and 0.3 degrees in azimuth and thus the effective resolution is ca. 0.3 degrees. This good level of resolution makes it possible to measure certain hotspots without the target getting smeared in the surrounding random variations during successive scan passes.

In Publication VI, a method for foliage attenuation measurements is described. A short-pulse radar and a reference target are used for the purpose. The requirements for dynamic range and clutter performance for such radar are discussed. The dynamic range of our instrument exceeds 37 dB, which enables us to record an attenuated response with the same settings as the unattenuated one. The effect of clutter is reduced by using an antenna with narrow beamwidth, ca. 1 degree, and employing an ultra-short, 17 ns pulse.

The radar is based on a dielectric resonator oscillator (DRO). The modulator is built around a fast bipolar transistor 2N2219A, which is driven by 74S-series logic gates. The trick is to create a suitable waveform that produces a well-shaped RF pulses. The 74S-series is not the fastest or the most modern logic family, but it is fast enough for this application, and the pulse shape is well suited for this application.

The length and voltage levels of the modulating pulse have to be adjustable to be able to optimize the pulse shape for each oscillator individually; two oscillators working in exactly the same way are rarely found. In our case, a 250 ns pulse was required to create the 17 ns radar pulse, because the oscillator needs some time to start oscillating. The higher voltage level of the modulating pulse was adjusted to achieve the highest possible output power without clipping. The lower voltage level had to be some tenths of a volt on the negative side to completely shut down the oscillator after the pulse was transmitted.

3 Task-specific measuring equipment

This chapter concentrates on the equipment built during the research projects. The radar calibrator is a working device in its own right, however most of the other technical gadgets were needed to enable us to measure radar signals with commercial measuring equipment that was available at the time of writing.

The video amplifier which was designed is a versatile high-gain amplifier which was used as a functional part in radars and for many other purposes during the measurements. The measuring receiver comes in particularly handy with pulsed power and waveform measurements, where a conventional power meter is useless. Microcontrollers are just briefly discussed in the overview part of this thesis, but they have provided the basic control and monitoring functions in both radars that were built during this research.

3.1 Calibration setup

The setup presented here is discussed more in Publication I. The calibration system has three main components: an optical transmitter, a fiber transmission line and an optical receiver. The design target was to create a delay system, which would be completely transparent to the radar. The block diagram of the suggested calibration setup is presented in Figure 3.1, including components of the fiber-optic delay line.

Signal conversion from electrical to optical and back causes an attenuation of ca. 35 dB, which can be compensated with an amplifier if considered necessary. The amplifier must have a linear frequency response in the operating region, and its noise figure should be low, since the power level of the signal may be really close to the noise floor. In our case, two low-noise amplifiers (LNA) with noise figures of 1.5 dB and 2.2 dB were used. LNAs

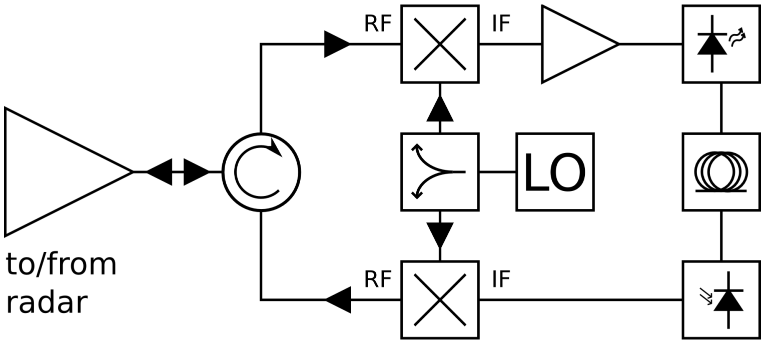

Figure 3.1: A block diagram of the calibration setup and a view of the fiber-optic delay line. An antenna is used for receiving and transmitting radar signal. A circulator is used to forward the received signal to a mixer. The IF signal is amplified, and laser diode is used to transmit the signal to the fiber-optic delay line. Photodiode receives the signal, then it is mixed back to RF, and fed to the antenna via the circulator.

typically cannot handle high input power, but the 10 dBm power limit of these amplifiers was suitable for the application.

The fiber-optic delay line has been employed for this purpose [44], but the work done for Publication I was the first time when the performance and the construction of a delay line for radar use were comprehensively explained. It should be noted that most articles discussing calibration methods cover imaging geographic synthetic aperture radars (SAR), but hardly any information has been published on calibration of pulsed military radars. [44, 45, 46, 47]

The main component of the transmitter is a fiber-coupled laser diode, which operates in the 1550 nm range. The diode has an RF input, whose impedance is matched to 50 Ω with an external resistor. No data was available on the input circuitry of the laser diode, so additional measurements would have been needed to be able to design a non-resistive matching circuit. In this case, however, the resistor was used for impedance matching, because the power loss caused by it was not a critical contributor to the overall performance of the system.

Since the laser requires a stable, interference-free operating current, the driver circuit must be designed carefully. The circuit used is based on the device presented in [48]. Fault tolerance is increased by implementing voltage and injection current monitoring and a soft-start by using a microcontroller. The transmitter includes a temperature controller, which is needed to prevent drifting of the output power and the wavelength.

The optical fiber is of standard single mode type. The length of the fiber can be altered to change the length of the delay; other characteristics of the system, for example, attenuation, do not significantly depend on the fiber length. The attenuation of a standard single mode fiber is ca. 0.2 dB/km at 1550 nm [49].

The optical receiver is a reverse-biased photodiode with a fiber connector. Impedance matching is implemented with an external resistor, which is also needed due to the DC-bias. The receiver is battery powered to reduce unwanted noise and interference. The casing is intact, and the seams are covered with copper tape. Since the power level at this point may be really low, careful mechanical and system design is needed to ensure high signal quality.

This calibrator is designed to operate at around the 1.8 GHz frequency. The frequency response of the system is measured with a CW-signal, and the measurement result is presented in Figure 3.2. The upper curve is measured without the amplifier, with -10 dBm input power. The lower curve demonstrates the performance with amplifiers, the input power in this case is -50 dBm. As can be seen, in this case the signal is amplified by 5 dB. Slight power level undulation is caused by the impedance mismatching. In this measurement, the delay is 3.2 μs, which equals the fiber length of ca. 960 m.

The usable bandwidth of the current calibrator setup is 300 MHz. Measurement result is presented in Figure 12 in Publication I. By improving the impedance matching circuit by, for example, employing impedance transformers, wider bandwidth could be obtained. This would also further improve the noise performance and remove the power loss caused by the matching resistors.

The maximum allowed input power of the laser – 4 dBm in this case – dictates the placement of the amplifiers. If allowed by the power limit, amplifiers should be used in front of the transmitter to maintain the best possible signal-to-noise ratio (SNR). In our experiment, the best solution was to separate the amplifiers, and to place one device on each side of the delay line system (see Figure 4 in Publication I).

3.2 Amplifier and receiver

A video amplifier and a measuring receiver were designed. The video amplifier is a high-gain wide-bandwidth amplifier used to amplify the output signal of the detector in radars. In such applications, special attention has to be paid to the rise time and noise performance, otherwise short low power pulses may not be detected.

In this research, two types of diode detectors, HP 8471D [51] (with option 103, positive polarity output) and HP 8473D [52] (with option 003, positive polarity output) were used. The detectors include a diode, an input matching circuit implemented with 50 Ω resistor, and an RF bypass capacitor. The electrical model of the detector is presented in Figure 3.3.

The typical video impedance R_v is 1.5 kΩ for both diodes. The bypass capacitance C_b of the 8471D is 6800 pF and that of the 8473D 30 pF. The rise time of the detector T_r can be approximated using equation

$$T_r = \frac{2.2 R_l R_v (C_l + C_b)}{R_l + R_v} , \tag{3.1}$$

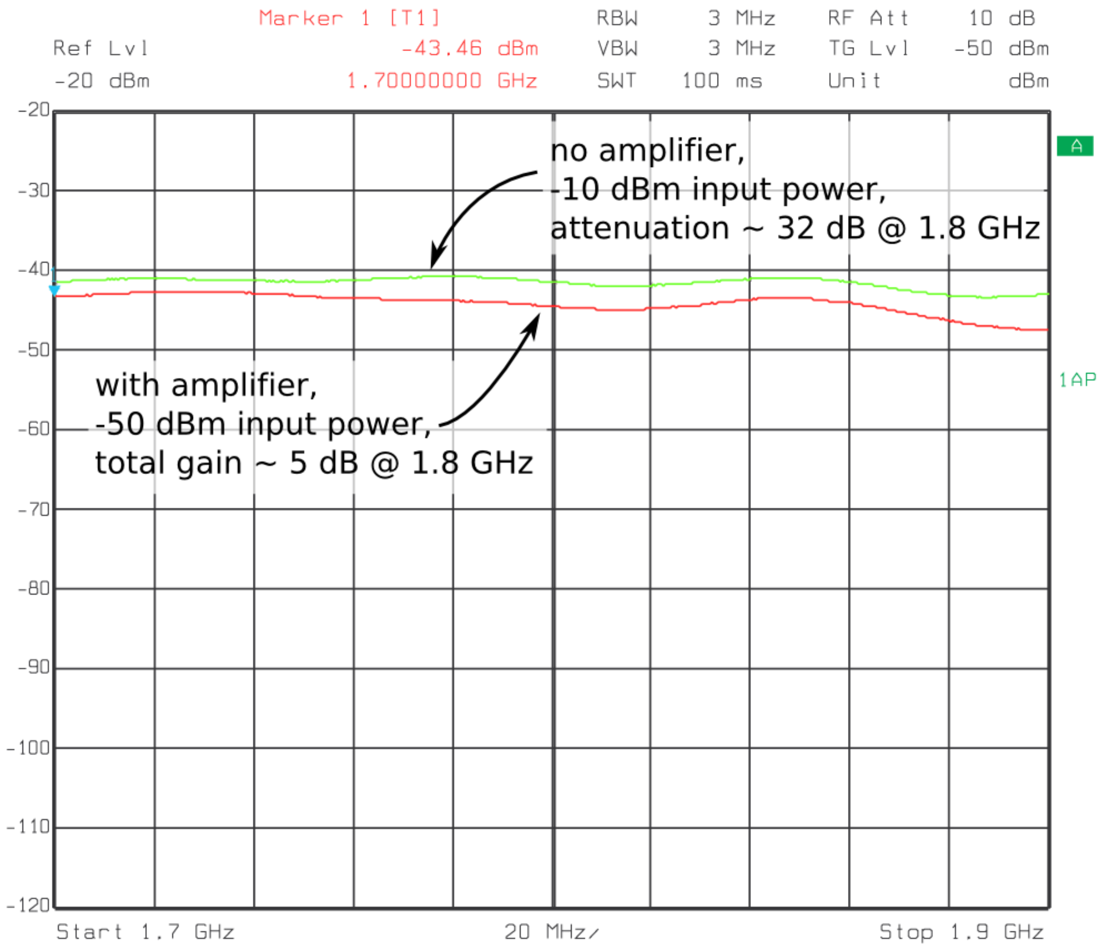

Figure 3.2: Frequency response of the calibrator measured using a CW signal. The upper curve is measured without amplifier, the input power was -10 dBm. The lower curve demonstrates amplifier performance with -50 dBm input power.

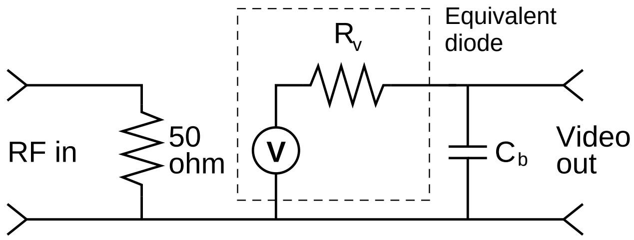

Figure 3.3: The electrical model of HP detector diodes. Input is matched to 50 Ω with a resistor. C_b is RF bypass capacitor, and R_v is video impedance. [50]

where R_l is load resistance and C_l load capacitance. The rise time can be reduced by using lower load resistance. The rather high video impedance, however, causes power loss, so the suitable load resistance depends on the application.

The video amplifier is a two-stage amplifier, with 50 Ω input and output impedances. The pre-amplifier has larger gain, while the second stage is used as a power amplifier which drives the load. In this design, the gain of the first stage is ca. 40 and that of the second stage 10. A schematic view of the video amplifier is shown in Figure 3.4.

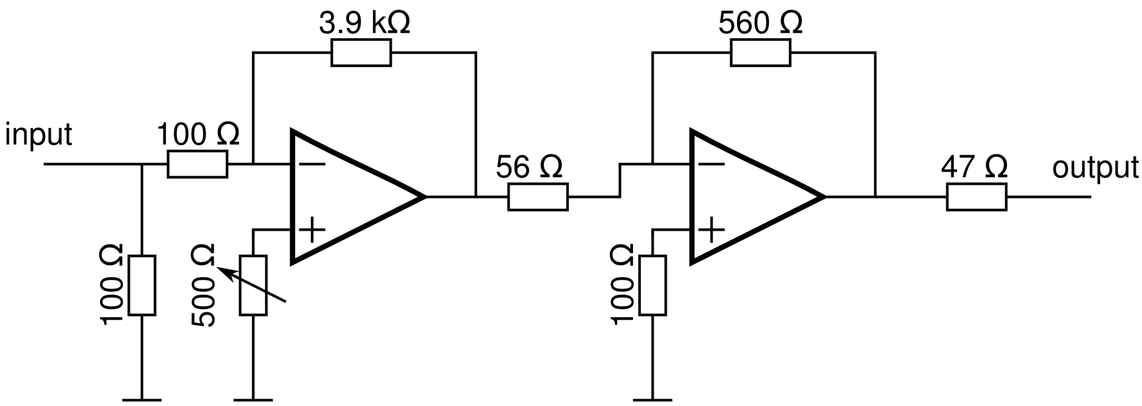

Figure 3.4: A schematic view of the video amplifier. Input matching is implemented with two 100 Ω resistors connected in parallel (virtual ground at negative input of the operational amplifier). Potentiometer and resistor at the positive inputs of the amplifiers are used to optimize offsets. A resistor is used also for output matching.

When dealing with such high gains, the compatibility of the amplifier circuits proved to be an issue. A typical problem is ringing which can be seen from Figure 3.5. The problem was solved by changing the type of the second stage operational amplifier. Sometimes, for unknown reasons, integrated circuits simply do not work well together when operating close to the performance limits. This behavior is very difficult to predict or simulate, and therefore has to be discovered in real life.

The performance of the fixed design with the new amplifier circuit is presented in Figure 3.6. The open loop gain is 390; measured output voltage drops to half due to the 50 Ω impedance matching. The rise and fall times are 25.5 ns and 26.8 ns respectively. The pulse shape is reproduced well. Also the offset may be an issue in sensitive applications such as this. In our design, an adjustable offset compensation resistor was required.

The mechanical design of the amplifiers proved to be also a significant contributor to the overall performance. This is mostly due to the quality of the grounding. By using surface mounted components, a large ground plane may be used. The complete amplifier is shown in Figure 3.7. The enclosure is specially dimensioned and machined for this circuit board. In this case, improvement in grounding further reduced noise and solved stability issues. [53]

The measuring receiver built during this research is used in power measurements and waveform evaluation. It is more versatile than a bare detector diode, and it is calibrated for lower measurement uncertainty. The receiver consists of a waveguide-to-coax adapter, a wideband detector diode (HP 8473D, 10 MHz–33 GHz), a video amplifier (which is discussed earlier in this thesis in Section 3.2), and a 400 MHz low-pass filter (Mini Circuits SLP-450 [54]). The usable bandwidth of the diode extends up to 40 GHz [52]. The input impedance of the amplifier is 50 Ω which provides a good combination of sensitivity and rise time, as mentioned previously [50, 52]. The block diagram of the receiver can be seen in Figure 3.8

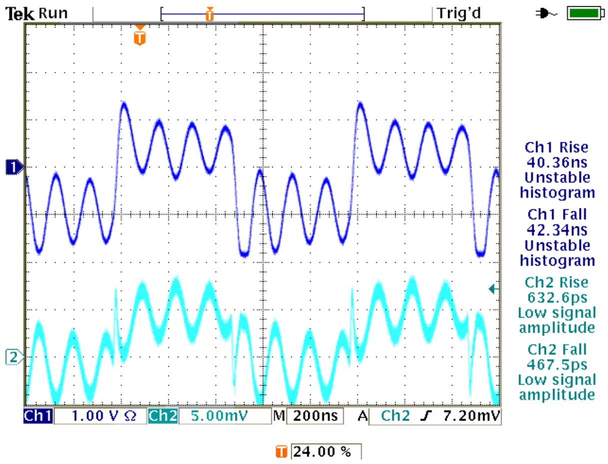

Figure 3.5: Step response of the first video amplifier. Ringing is caused typically by a design problem, which in this case was incompatible amplifier circuits. The ripple in the output signal is ca. 1 V peak to peak (trace 1). The ringing interferes also the input signal (trace 2).

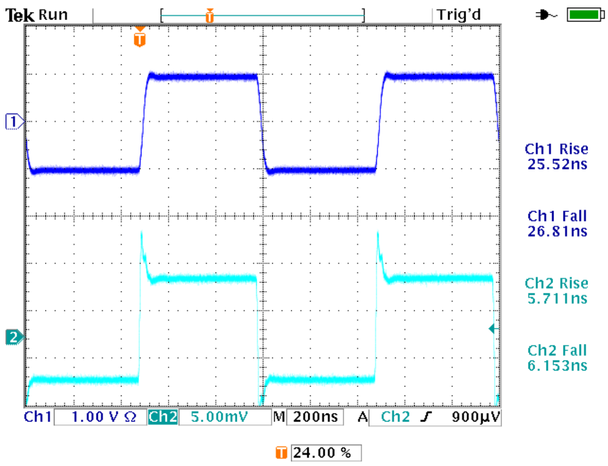

Figure 3.6: Step response of the improved video amplifier with new second stage amplifier circuit. Rise time is 25.5 ns and fall time is 26.8 ns. The pulse shape is reproduced well. The lower trace is the input signal and the upper trace is the output.

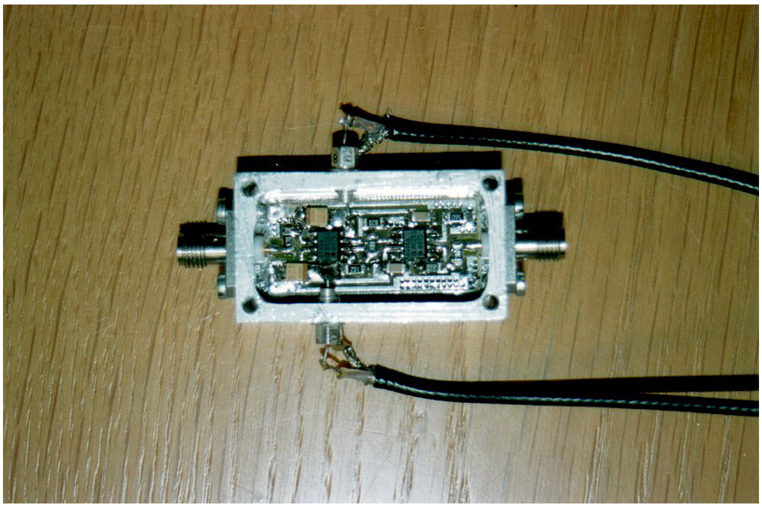

Figure 3.7: When surface mounted components were used, the circuit board could be attached directly to the bottom of the enclosure. This provided better grounding, which solved some instability and noise issues.

The receiver is built in a diecast aluminum box, and therefore, it is almost immune to electromagnetic interference (EMI). It can be calibrated with low uncertainty using a power meter and a frequency synthesizer. The uncertainty of the receiver is in fact so low, that it does not contribute to the overall uncertainty of the waveform or power measurements. Therefore the uncertainty of the receiver itself cannot be measured with the available instruments.

The receiver must be calibrated separately for all frequencies used. With this calibration method, however, we cannot verify the uncertainties of the pulsed signals. The performance of the receiver can be ensured in different way, which is described later in Section 4.2.

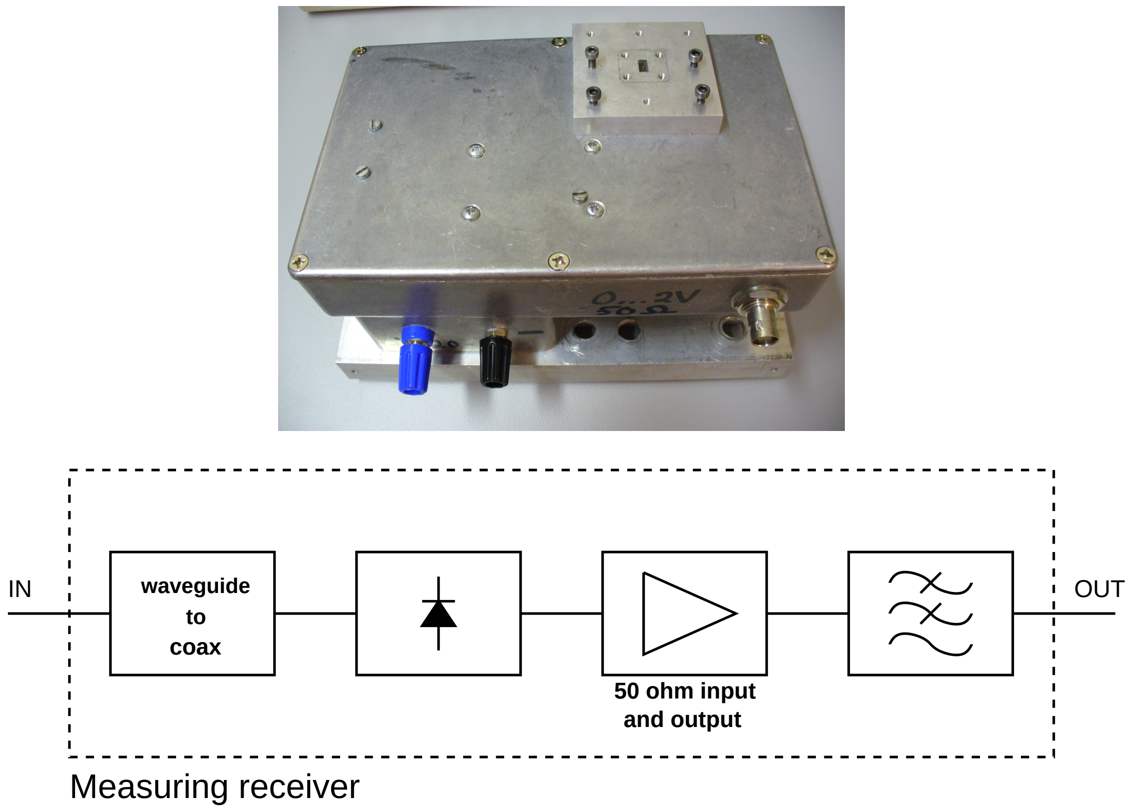

Figure 3.8: A separate microwave measuring receiver was built for power and waveform measurements. The receiver has a WR28 UG-599U waveguide interface, and the incoming signal is detected by a fast and sensitive detector diode. The signal is then amplified by a video amplifier, whose gain is 390. Finally, the video signal is filtered by a low-pass filter. The sensitivity of the receiver is calibrated separately for all used frequencies.

3.3 Microcontrollers

In some devices and systems very precisely controlled operation is necessary. For that purpose, PIC microcontrollers, manufactured by Microchip, were used [55].

In the radar calibration setup, the microcontroller monitors the operating voltage and the injection current of the laser diode with the internal 10-bit analog-to-digital converter (ADC). The startup sequence of the current driver is controlled, operating voltages are switched on in a certain order, and finally, the laser diode is connected to the supply. Normally the operating voltage pins of the diode are grounded.

In the radar presented in publication VI, PIC is used as an RCS display controller. A 12-bit digital-to-analog converter (DAC), driven by the microcontroller, generates the reference voltage, which decreases after each pulse. The reference voltage is compared with the amplified and filtered detector signal. When the correct signal level is found, the respective RCS-value is searched from the table in the memory of the microcontroller and is shown on the display. The display system is triggered with a push-button.

4 Pulsed radar measurements

In this section, pulsed radar measurements, related equipment and their limitations are discussed. Typically, no ”off-the-shelf” measurement device can be used in pulsed radar measurements. The main challenge is the length of the pulse, which is typically 20 ns – 10 μs [56]. Often precise measurement instruments rely on a long integration time, or in some cases, signal processing.

For obvious reasons, long integration times cannot be used, but also signal processing may cause surprising results (e.g. non-existent frequency fluctuations may be indicated). An example of this behaviour can be seen in Section 4.1, where a modulation domain analyzer performance is discussed. With spectrum analyzers, short pulse measurements call for a wide resolution bandwidth, otherwise the power level of the pulse cannot be measured reliably. With other instruments, the rise time is a critical issue. The stray capacitance of diodes, for example, may cause problems if the input impedance of the next device (e.g. amplifier or oscilloscope) is high. A wide range of radar measurements is described in [29].

4.1 Frequency measurements

This section concentrates on the measurement methods of small frequency changes during the pulse. These kinds of frequency changes are typically under study, when moving targets have to be detected, but are located, for example, in a forest. Trees, especially leaves, cause significant amount of clutter, and sometimes even such a large target as a tank might not be observed if it remains stationary.

The tank moves rather slowly in difficult terrain, so the frequency change caused by the Doppler effect is also quite small. If a tank is moving 5 km/h, and the radar operates at

Table 4.1: Frequency changes caused by Doppler effect for typical targets in different carrier frequencies. Harpoon is an anti-ship missile manufactured by Boeing. Velocities used in calculation are typical for each vehicle type. Tank is thought to be moving in a rough terrain.

		Frequency band (frequency)		
Vehicle	Velocity (km/h)	C (5 GHz)	K_u (15 GHz)	K_a (30 GHz)
Tank	5	23 Hz	69 Hz	139 Hz
Car	80	371 Hz	1 112 Hz	2 224 Hz
Harpoon missile	864	4 003 Hz	12 008 Hz	24 016 Hz
Supersonic fighter	1 500	6 949 Hz	20 847 Hz	41 694 Hz

K_a-band (e.g. 30 GHz), a frequency change is ca. 139 Hz according to Equation 2.2. To be able to reliably detect and measure such targets, the spectral behavior of the transmitted pulse must be known. Typical Doppler frequencies of some targets are listed in Table 4.1.

Frequency can be measured directly, in a reciprocal way, or by using an added interpolator circuit for enhanced resolution [57, ch. 19]. Often a spectrum analyzer or a frequency counter is the instrument of choice when planning frequency measurements. With the frequency counter, very low uncertainties may be achieved, and if more information is needed, the spectrum analyzer provides an overview of the situation in the frequency domain.

Frequency counters are very accurate with long integration times, but the measurement rate is not fast enough for pulse measurements. With careful tuning, counters typically achieve a speed of hundreds of readings per second [58]. Special pulsed microwave counters can trigger their measurement on the incoming signal. However, this method causes long trains of pulses to be averaged for one frequency reading and thus short-term variations get masked.

Most spectrum analyzers used in radar work are of the sweeping super heterodyne principle [57, ch. 21], and by definition, they are not intended for accurate frequency measurements. With a spectrum analyzer, the power level of pulses can be measured quite accurately - see publication IV - if the resolution bandwidth (RBW) is wide enough (tens of megahertz). With a narrower bandwidth the frequency measurement is, of course, more accurate and the pulse may be detected but the power level is not correct. [59]

The sweep time T_{sweep} of the heterodyne spectrum analyzer depends on the resolution bandwidth. If high frequency resolution is needed, the resolution bandwidth B_{res} must be narrow. This has been shown to be of the form of

$$T_{sweep} = k_f \cdot \frac{\Delta f_{span}}{{B_{res}}^2} , \tag{4.1}$$

where k_f is a constant depending on the filter slope (the value of k is in the 2 to 3 range for the near-Gaussian filters used in many analyzers) and Δf_{span} is the frequency span [60]. This is due to the fact that any signal to be measured has to remain stable within the selected resolution bandwidth longer than the filter's rise time[2]. This increases the sweep time, and thus short pulses are usually not detected at all. Even if the desired frequency resolution is somehow achieved, spectrum analyzers cannot be used to measure rapid dynamic frequency changes. Instead, they indicate the frequency components that are or have been present during the pulse.

A modulation domain analyzer is a really promising measurement device for this kind of purpose. However, the results obtained proved to be quite peculiar (see Publication II). The measurement method is not precisely published, so the results cannot be considered thrustworthy, when operating at the limits of the measurement range. During this research, a Hewlett-Packard (HP) 53310A modulation domain analyzer was available, and it's performance was evaluated. It's production ended lately, and a direct substitute has

[2]There are also other components in the spectrum analyzer, which need a certain time to stabilize, but long sweep time sets the most fundamental limit in measuring fast frequency changes with a spectrum analyzer.

not been introduced.

Recently, there have been developed some new measurement systems for the purpose, for instance, Agilent Z2090B-170 pulse analyzer system for radar [61] and Agilent U1050A time-to-digital converter [62]. They were not available, however, to be tested during this work.

In Figure 4.1, the obtainable resolution of a HP 53310A modulation domain analyzer is presented. The limitation of the input frequency range can be overcome by downmixing the measured signal, but a more important factor is the rather poor frequency resolution with short sampling intervals.

In our experiments, a modulation domain analyzer was used in combination with a spectrum analyzer. A C-band radar signal was measured using the HP 8566B spectrum analyzer with RBW of 3 MHz. The span was set to zero, so our analyzer was used as a tunable receiver. The intermediate frequency (IF) output of the spectrum analyzer was connected to the input of the modulation domain analyzer. A block diagram of this setup can be seen in Figure 4.2.

With this arrangement, the high quality analog mixers and the stable local oscillator (LO) of the spectrum analyzer were used to move the measured pulse to a more convenient frequency band, which in this case was centered around 21.4 MHz. With frequency this low, a modulation domain analyzer provides quite accurate frequency information even with short pulses (see Figure 4.1).

Only synthesized high-end spectrum analyzers can be utilized here, because all local oscillator instabilities and phase noise components would spoil the obtainable result, no matter how good the original signal to be measured was. In our case the HP 8566B specification for short-term frequency drift is $< 1 \cdot 10^{-9}$/day, and the center frequency drift is < 10 Hz/minute of sweeptime [64].

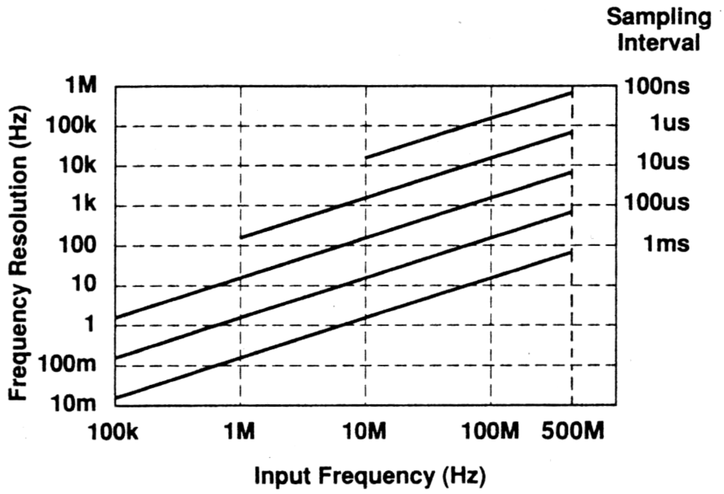

Figure 4.1: Obtainable single-shot frequency resolution of the modulation domain analyzer as a function of selected sampling interval and nominal input frequency. [63]

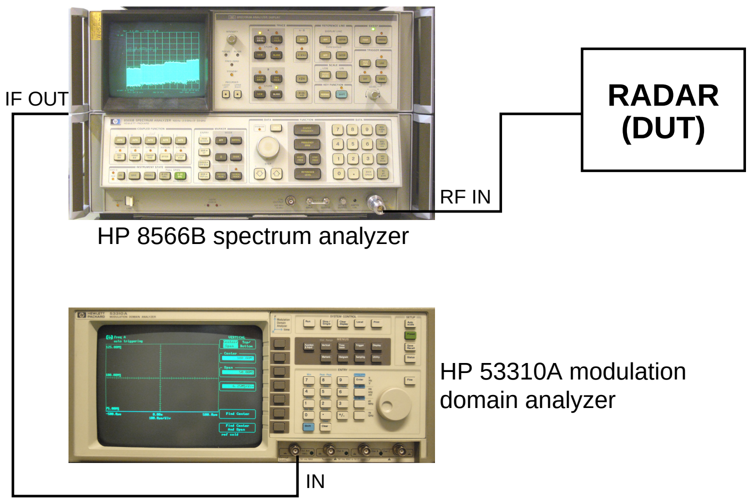

Figure 4.2: Frequency measurement as a function of time by using a spectrum analyzer and a modulation domain analyzer. The span of the spectrum analyzer is set to zero, so the spectrum analyzer is used as a tunable receiver. Intermediate frequency (IF) output from the spectrum analyzer is measured using a modulation domain analyzer. The RF signal from the radar is down-converted to 21,4 MHz and amplified using high-quality analog components in the spectrum analyzer, so the frequency information of the radar signal remains practically unchanged.

This method is useful especially in measuring possible Doppler shifts, because the frequency resolution is relatively high. An example of this kind of measurement is presented in Figure 4.3. A rather long pulse is measured, the pulse length being ca. 1 second. The frequency range shown in this figure is 200 Hz, and the frequency resolution is better than 2 Hz. The resolution drops significantly, however, when the measuring time is shorter.

Two alternative methods for frequency measurements have been developed. Both are based on a phase detector. The first one, presented in Publication II, is designed for the measurement of small frequency changes with a moderate sampling frequency. The demonstrated uncertainty of the frequency measurement is 1.6 Hz with the sampling rate of 10 000 s^{-1}. This setup can only be used to measure relative frequency changes, not the absolute frequency, since it uses the input signal as a reference. One comment that is missing in Publication II is that a reactive splitter must be used in dividing the signal in order to get proper isolation between the ports (see further e.g. [65]).

Another setup is presented in Publication III. It uses a reference oscillator and a phase detector to detect frequency changes during a short pulse. With this setup, absolute frequency values cannot be measured but the setup is intended to detect frequency differences. With the center frequency of 2.06 GHz, a frequency difference of 200 kHz was detected, when the pulse length was 200 ns. This result proves, that this method may be used to detect frequency changes even *during* a pulse. This requires, however, some further research on signal analysis.

In the measurement setup presented in Publication III, a pulse modulated frequency synthesizer was used as a device under test (DUT). The output signal is similar as in a pulsed radar. Both synthesizers use the same time base, so the exact frequency difference is always known. When a short pulse is mixed with a CW signal of almost the same frequency, the mixing product is a short section of a sine wave. The frequency of this sine wave is the same as the frequency difference between the input signals. High frequency components are filtered out.

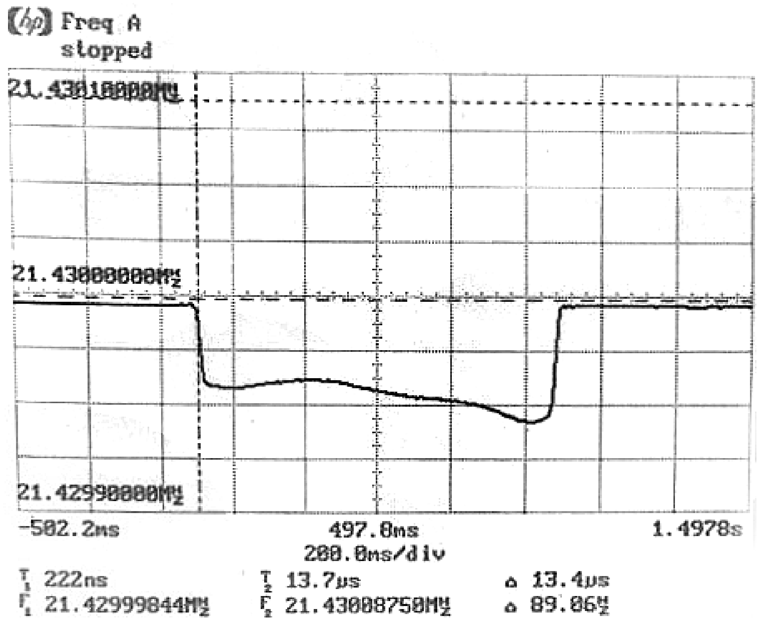

Figure 4.3: An example of a frequency measurement using the setup described above. In this measurement the frequency resolution is better than 2 Hz, but it drops when shorter measurement times are used. In this photo, vertical scale is 25 Hz/div and horizontal scale 200 ms/div.

One drawback with this method is that the shape of the input pulse is reproduced when it passes through the mixer. Unless the pulse shape is an almost ideal square, this method is useless, since it cannot be determined, if the inclination of the pulse peak is caused by a frequency difference or a badly-shaped pulse.

4.2 Power measurements

Besides the pulse length, also the low power level sets some challenges in pulsed power measurements. The power of the transmitted pulse may be really high. For example, the Zaslon radar of the MiG-31 (Mikoyan-Gurevich), which is considered as the most powerful fighter radar in the world, has an average transmission power of 2.5 kW.

On the other hand, the received signals are usually very faint. This sets limitations particularly to the detector that is used. Typically radars have a certain power range, in which the performance of the radar is at its best. Therefore the transmission power cannot be increased as much as one would perhaps desire.

As can be seen in Equation 2.1, the RCS calculation is based on the received RF power, so in order to have reliable and comparable RCS results, both the transmitted and received power must be known accurately. Pulsed power measurements have been discussed in Publication IV; in this section, the operating principles of some measurement instruments are explained.

Modern sensor modules are typically based on rectifier diodes or they can be of the thermocouple type [66]. When a diode is used, we are actually dealing with voltage measurements. Most precision instruments rely on the thermal principle, but due to the thermal dependency of the metering probe, one must pay special attention to the measurement process. Problems caused by temperature changes are solved by calibrating the probe often enough by using a calibration output found on the front panel of the power meter.

[67, 68]

First power sensors were based on a resistor, which was heated by the measured RF-power. The temperature change was measured with a bridged thermistor. Sometimes one thermistor was used to compensate for the changes in the ambient temperature. [69]

Thermocouple sensors, that were introduced in 1974, are also heat-based and thus true averaging detectors, so fast pulses cannot be measured. An example of the step response of such a power meter is presented in Figure 4.4. The power response of a thermocouple sensor has also a significant frequency dependence. Typically power meters feature some kind of an automatic numerical correction scheme to fix this [66].

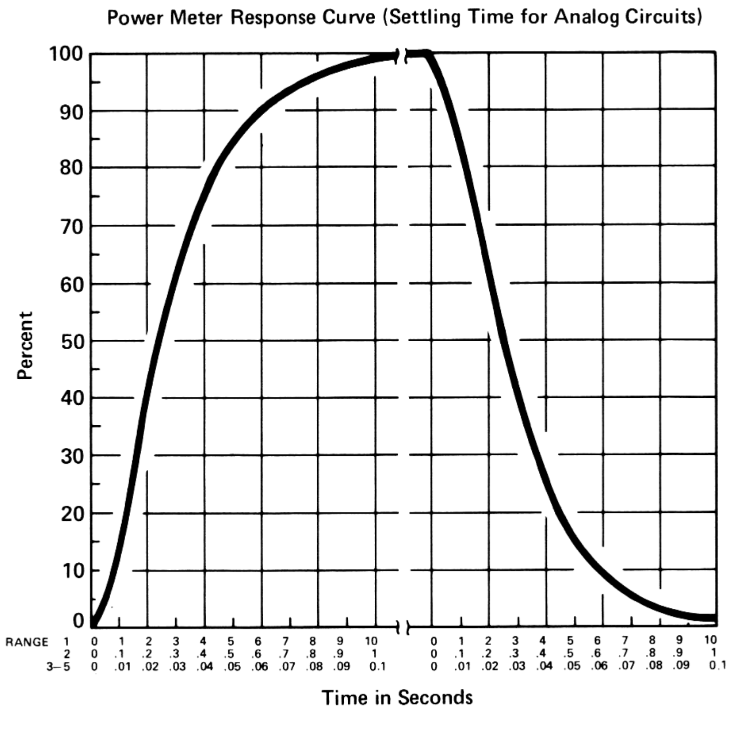

Figure 4.4: An actual recorded step response of a power meter sensor. Range, in this figure, means sensitivity, 5 being the most sensitive. It may take even 10 seconds for the sensor to reach the full power level. [70]

Recently some manufacturers, most notably Agilent and Rohde & Schwarz, have introduced sensors for power meters, that are based on diodes instead of thermoelectric couples. They offer a significantly higher dynamic range (from -70 to 20 dBm) than thermocouple sensors, whose usable power range starts from -30 dBm. Nowadays the most used diode is a planar-doped-barrier (PDB) diode, which offers some 3000 times more efficient RF-to-DC conversion than thermocouple sensors [69]. Discrete diode detectors are discussed more thoroughly in the following chapter.

Diode sensors also enable us to measure the peak power with a normal power meter. In some limited cases they can also be used to measure radar pulses. For example in a Rohde & Schwarz NRV-Z series, there are peak power sensors that are able to measure the peak envelope power (PEP) of signals during peaks from 2 μs to 100 ms [71]. In radars, the pulse length typically varies from 20 ns to 50 μs. The frequency range of the NRV-Z sensors is 30 MHz to 6 GHz, which is rather limited with regard to modern radars. Also HP has a peak power analyzer (HP 8990A and 8991A) and suitable sensors. These have reasonably fast rise times, less than 10 ns at their best, but the required power level is high, even in excess of 0 dBm [72, 73]. Anritsu just recently introduced their own pulse power meter, ML2490A series, which, with MA2411B sensor has 8 ns rise time and 11 ns fall time [74].

Even with numerically linearized diode sensors, linearity errors may occur outside the square-law region. They are caused by the voltage dependent junction capacitance (varactor effect) and become evident when the diode starts affecting the RF behavior of the sensor – as a rule of thumb: From 1/4 of the upper frequency limit. Since the junction capacitance decreases with increasing input power, there is normally an increase in the frequency response, i.e. the linearity error is positive (see Figure 4.5). [66]

During the research, it was found out that spectrum analyzers may feature a significant systematic power level error. In consequent measurements, when the settings of the instruments and the measured signal remain unchanged, the repeatability is good. In this case, the most important contributor to the measurement uncertainty is noise [75]. One

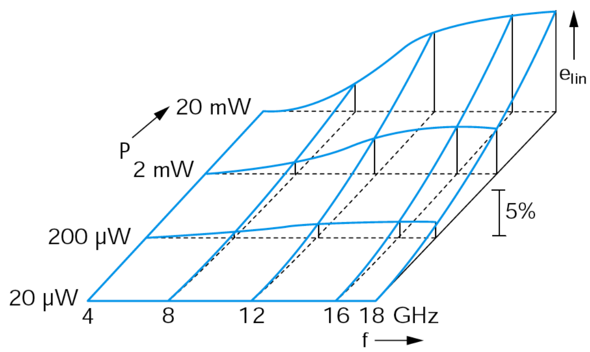

Figure 4.5: Measured linearity error e_{lin} due to the varactor effect of an 18 GHz detector. [66]

also has to ensure, that the RBW of the spectrum analyzer is wide enough for pulsed power measurements. The long rise time of the filter (narrow RBW) lowers the indicated power level. Also the sampling interval of the analog-to-digital converter (ADC) may limit the results and skew the pulse shape. [76, 77, 78, 14]

One significant contributor to the uncertainty of the power measurements is the standing wave ratio (SWR). If the input detector is not well matched to the source, simple and multiple mismatch errors will result, reducing the accuracy of the measurement. The graph on the right in Figure 4.6 shows the error introduced by multiple reflections caused by the mismatch between the detector and the source.

In the power measurements, calibration is maybe more important than with the other quantities discussed in this thesis. This is due to the relatively low accuracy in power measurements in general, but also because in many cases the power level is measured with a device that is not initially intended for that purpose.

In this research, a recently calibrated HP 437B RF power meter was used as the reference, against which other power detectors were calibrated. The uncertainty of the power meter is much lower than the reading accuracy of other devices used in these experiments.

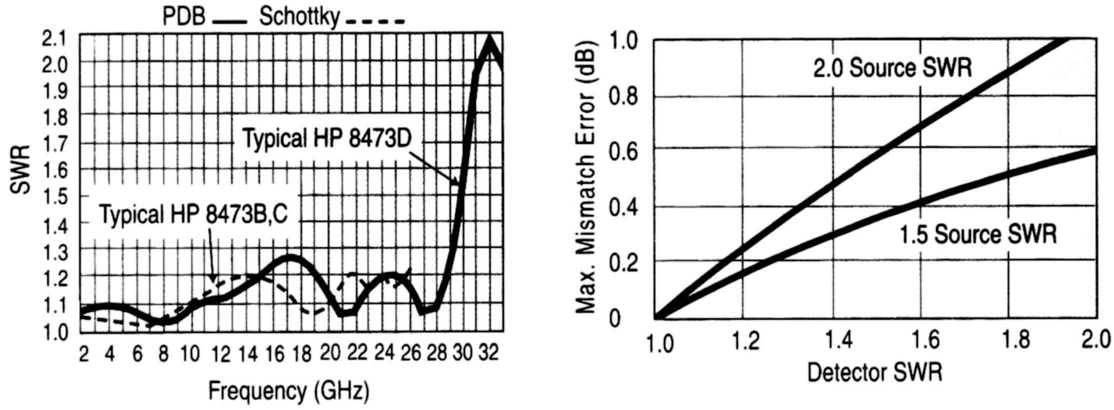

Figure 4.6: Typical SWR of the detectors on the left. On the right, error from the detector and source mismatch. For a detector SWR of 2,0 and source SWR of 2,0, the uncertainty is ± 1,0 dB. [50]

The power measurement performance of two spectrum analyzers (Rohde & Schwarz FSU 46 and HP 8566B) was evaluated. Also the sensitivity of a discrete detector diode (HP 8471D) and the self-made measurement receiver (see Chapter 3.2) were tested. A frequency synthesizer (HP 8341B) in combination with a frequency multiplier was used as a radar simulator in many measurements, and therefore the power reading of the synthesizer was calibrated when this source was used.

In actual measurements, an adjustable attenuator was used, and this component was also calibrated to clarify the attenuation of the device with certain micrometer screw settings.

Since a power meter can only be used for CW measurements, some other device needs to be calibrated and used as a pulsed power reference. We used an HP8341B synthesizer, which has pulse modulation capabilities. An HP 8112A pulse generator was used as a modulator.

The block diagram of the evaluation setup and procedure is presented in Figure 4.7. First, the power level indicator of the synthesizer was calibrated. A frequency doubler was connected to the output of the synthesizer and the output signal of the doubler was measured

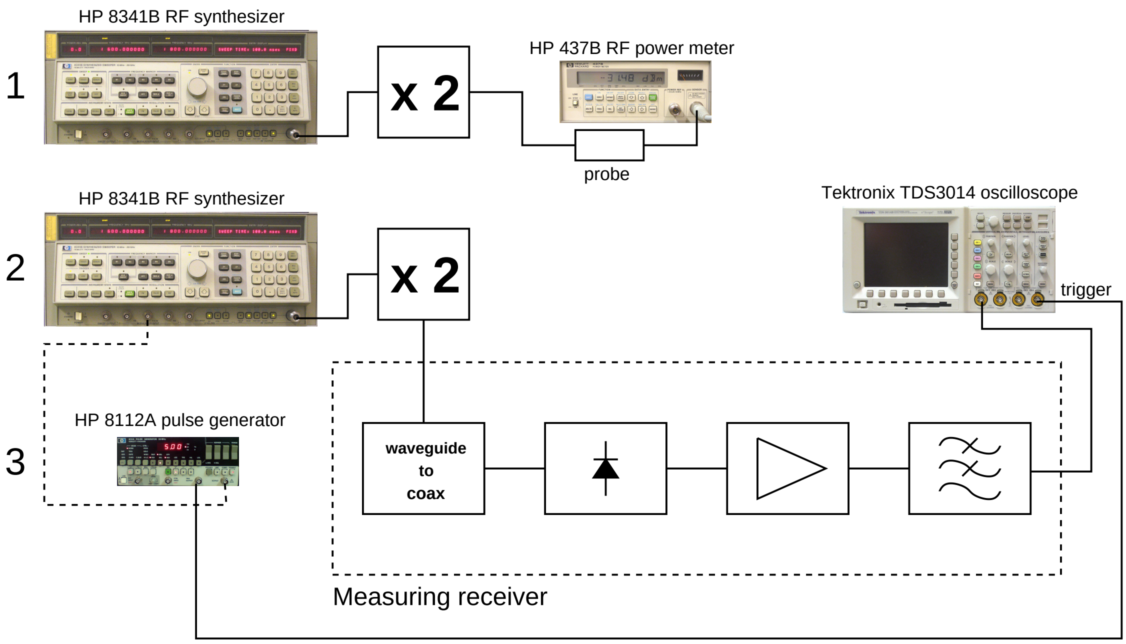

Figure 4.7: Calibration of the HP 8341B RF synthesizer for pulsed signals. First the power indicator of the synthesizer is calibrated against an HP 437B power meter, which is used as the laboratory reference. A frequency doubler is needed, because most of the measurements are made in the K_a-band region, and the upper frequency limit of the 8341B is 20 GHz. Then (step 2), a measuring receiver and an oscilloscope are used to measure the same signal and the measuring receiver is calibrated for different power levels and frequencies. Finally (step 3), a pulse generator is added and the pulse modulated signal is measured to verify, that the setup can also be used for pulsed signal measurements. The system was extensively tested with varying pulse widths at different frequencies, and no discrepancies were observed when switching from the CW to the pulse modulated signal. The pulse modulation was also tested with an RF switch, with the synthesizer transmitting CW signal. No change in the output signal level was detected.

with the power meter. At this point, a CW signal was used and the power reading of the synthesizer was checked against the reading of the power meter, as can be seen in Section 1 of the block diagram.

Then, the output signal of the doubler was measured using a separate measuring receiver and an oscilloscope. In this way the receiver could be calibrated for different power levels and frequencies. This is demonstrated in Section 2 of the block diagram. As the final step, a pulse modulator was added (Section 3). This proves, that with this setup, the power level does not depend on the pulse length and also that the measuring receiver is capable of measuring pulsed signals. This system can also be used to verify the performance of other components with pulsed and CW signals, if those components to be measured are added between the frequency doubler and the receiver.

4.3 Pulse shape measurements

The motivation for waveform evaluation is clear. If the shape of the transmitted pulse is not known, no assumptions about the target can be made by looking at the waveform of the received pulse. Sometimes, especially with short pulses, it may be difficult to produce an ideal square-shaped waveform, but as long as the shape transmitted is known, it can be taken into account when the received signal is processed. The influence of the waveform in target recognition is discussed more in, for example, [79, pp. 63–64] and [80].

Waveform evaluation does not significantly differ from power measurements. Usually the measurement setup consists of a receiver or a detector and an oscilloscope. A spectrum analyzer can also be used if the measurement is made in the time domain with the span set to zero. One still has to remember the effect the resolution bandwidth has on the pulse shape and indicated power. In some cases, some additional devices, for example, amplifiers, frequency multipliers and custom made receivers may be required. [81]

In Publication VI, an instrumentation radar for foliage attenuation and selected clutter measurements was demonstrated. The new hardware replaced the RF part of the radar presented in Publication V. The new design featured ultra-short pulses – the half-power width was 17 ns – which reduced the clutter coming from the forest or from other objects behind the target.

The transmitted pulse is measured using a zero-biased diode detector and a high-speed oscilloscope. Since the measurement is made directly from the output of the transmitter, the power level is high and a separate amplifier is not needed. Modern oscilloscopes are well capable of measuring such short pulses, sampling rates being even several gigasamples per second, but only when we have this kind of a repetitive waveform. More attention must be paid to the diode. The bandwidth should be wide and the rise time fast enough, and also the oscilloscope must have 50 Ω input impedance in order to achieve the best combination of sensitivity and rise time.

Especially in these kind of measurements, an additional video amplifier comes in handy. The output voltage of a bare detector diode may be really low, in the order of millivolts or even less, so the sensitivity of an oscilloscope is not enough. For example, the output voltage of an HP 8471D diode is 1 mV with -10 dBm input signal [50].

While the screen of an oscilloscope usually does not provide enough information, the results may be saved in numerical form for further processing. In Figure 4.8 an example of a pulsed power measurement made using a diode and an oscilloscope is presented. The upper illustration shows the waveforms as they appear on the oscilloscope screen. A magnified view of the saved and processed data can be seen on the bottom. Both the time and the voltage resolution are far better than when a waveform is viewed with an oscilloscope. The data is, however, clearly quantized, due to the low signal amplitude.

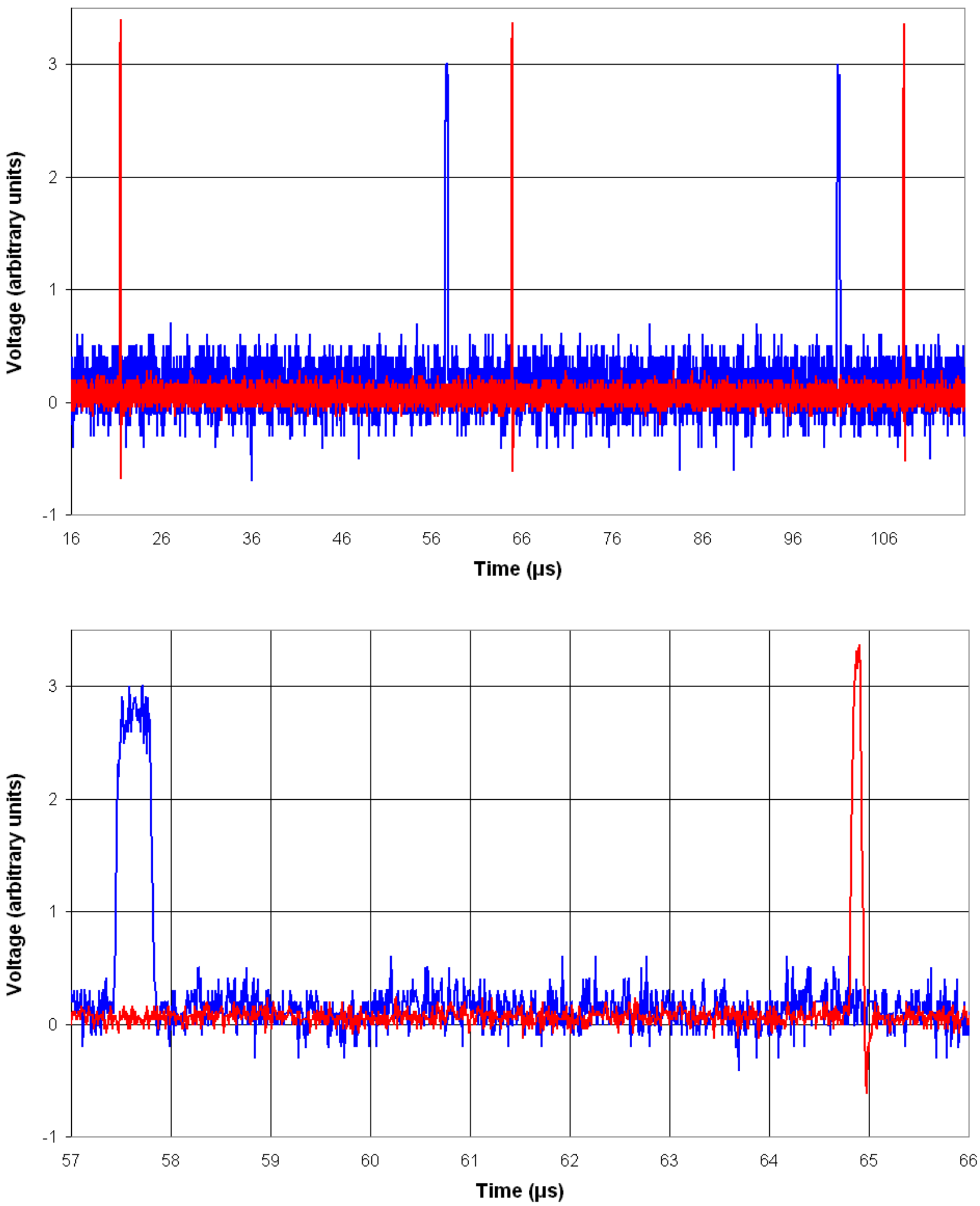

Figure 4.8: Power measurement data saved with an oscilloscope and processed with software. In the upper figure the waveforms are shown as they appear on the oscilloscope screen. One cannot really tell anything about the pulse shape. It is interesting to note, however, that the blue signal is clearly quantized. The lower figure is a magnified view of the same saved data. Two pulses in the middle are shown. The power and waveform can be easily evaluated. Both traces are pulsed radar signals that are measured with a detector diode. The length of the shorter pulse (red) is ca. 200 ns.

5 Conclusions and discussion

In this thesis, measurement methods and related hardware for pulsed radar experiments were presented and evaluated. Additionally, several uncertainty issues were discussed.

The most difficult challenges a radar engineer will face when dealing with modern pulsed radars come from the pulse length, and in some cases also from the really high or really low power levels. Even the most modern measuring instruments cannot handle radar signals properly; radar technologies develop rapidly and instrument manufacturers have always been one step behind the *latest* developments.

Several measurement methods for verifying the operation of the radar have been demonstrated. The equipment and methods have been designed keeping the usability in the field in mind, which sets some additional challenges, when, for example, robustness, portability, effects of the weather and electromagnetic compatibility have to be taken into account.

With some clever arrangements, normal laboratory equipment can be used and still very good results will be achieved. The performance of different kind of equipment has been extensively tested in practice and thoroughly documented in this thesis. The achieved results will provide some alternative tools for a researcher, when other measuring methods or instruments are not either commercially available, or cannot be used in challenging environment.

A radar calibration system was presented in Publication I. It provides a convenient way to use the radar's own signal in calibration, and it still is a rather simple setup. Similar ideas have been published earlier, but this was the first time when the performance of the optical delay line was comprehensively demonstrated.

In addition, frequency, power and waveform measurements were also discussed. Frequency changes during the pulse were proven to be difficult to measure. Two methods based on a phase detector were introduced in Publications II and III. The first one provides lower uncertainty and higher resolution, while the second has far greater sampling frequency. Frequency counters, spectrum analyzers and modulation domain analyzers have certain shortcomings preventing their use in measuring short pulses, or at least some special arrangements have to be made.

Issues concerning power measurements were an extensively covered topic in this thesis. In Publication IV, power measurements made using different detectors and instruments were presented. In the summary part of this work, the factors contributing to power measurement uncertainty were discussed. Also a calibration method for pulsed power reference was presented.

An important part of this whole research concerns the two instrumentation radars that were built for the purpose of testing. Their performance is demonstrated in Publications V and VI. They can be used in long-term measurements, and they provide data on the seasonal effects on clutter, that has never been made publicly available before. In our most recent radar, an ultra-short, 17 ns pulse is employed, which greatly improves the overall performance of the radar in foliage attenuation measurements by reducing clutter. During the development of this radar, also equipment that is needed to detect the waveform of such short pulses was developed and tested. The results are documented in Chapter 4.

Real-life measurements are often the only way to reliably define the clutter and attenuation characteristics of a certain landscape. In Finland, also seasonal changes have a significant effect on the aforementioned things, and thus long lasting measuring campaigns in the field are needed to create a comprehensive and trustworthy model. The equipment used in this purpose has to be, first of all, reliable and durable. An important part of our research work was to test the developed equipment in their natural environment, and we are convinced, that the radars and measuring methods presented in this thesis fulfill the named key requirements very well.

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ISBN 978-951-22-9803-7
ISBN 978-951-22-9804-4 (PDF)
ISSN 1795-2239
ISSN 1795-4584 (PDF)