Helsinki University of Technology Radio Laboratory Publications
Teknillisen korkeakoulun Radiolaboratorion julkaisuja
Espoo, September 2006 REPORT S 282

APPLICATIONS OF HOLOGRAM-BASED COMPACT RANGE: ANTENNA RADIATION PATTERN, RADAR CROSS SECTION, AND ABSORBER REFLECTIVITY MEASUREMENTS

Anne Lönnqvist

Dissertation for the degree of Doctor of Science in Technology to be presented with due permission for public examination and debate in Auditorium S4 at Helsinki University of Technology (Espoo, Finland) on the 20th of October 2006 at 12 o'clock noon.

Helsinki University of Technology
Department of Electrical and Communications Engineering
Radio Laboratory

Teknillinen korkeakoulu
Sähkö- ja tietoliikennetekniikan osasto
Radiolaboratorio

Distribution:
Helsinki University of Technology
Radio Laboratory
P.O.Box 3000
FI-02015 TKK
Tel. +358-9-451 2218
Fax. +358-9-451 2152

ISBN 951-22-8364-6
ISBN 951-22-8365-4 (PDF)
ISSN 1456-3835

http://lib.tkk.fi/Diss/2006/isbn9512283654/

Otamedia Oy
Espoo 2006

HELSINKI UNIVERSITY OF TECHNOLOGY P. O. BOX 1000, FI-02015 TKK http://www.tkk.fi	ABSTRACT OF DOCTORAL DISSERTATION
Author Anne Lönnqvist	
Name of the dissertation Applications of hologram-based compact range: antenna radiation pattern, radar cross section, and absorber reflectivity measurements	
Date of manuscript original 6.4.2006, revised 5.9.2006	Date of the dissertation 20.10.2006
☐ Monograph	☒ Article dissertation (summary + original articles)
Department Electrical and Communications Engineering Laboratory Radio Laboratory Field of research Radio Engineering Opponent(s) Dr. Jürgen Hartmann and Docent Taavi Hirvonen Supervisor Prof. Antti V. Räisänen (Instructor) Dr. Juha Mallat	

Abstract

This thesis focuses on applications of the hologram-based compact range at submillimeter wavelengths. The work is divided into two parts: compact range for antenna radiation pattern measurements, which can be used for testing satellite antennas and compact range for radar cross section (RCS) measurements, which can be used for radar system development, getting data needed for target recognition and target RCS reduction. The RCS range has also been used for measuring the reflectivity level of radar absorbing materials.

Compact antenna test range (CATR) has been developed and used for antenna measurements at 322 GHz and also successfully demonstrated at 650 GHz. A large-sized CATR was built for measuring a 1.5-meter reflector antenna ADMIRALS RTO at 322 GHz. Assembly of the CATR, testing of the antenna and the disassembly were all done within two months. The 3-meter hologram was constructed from three pieces of patterned copper-plated Mylar, which were joined together by soldering. The quiet zone had a 1.2 dB amplitude dip and a saddle-shaped equiphase surface (p-p deviation 250º). The co-polar radiation pattern of the RTO was measured at vertical polarization. The measured radiation pattern agrees reasonably well with the simulated one. The measured 3 dB beam width is 0.086º (E-plane) and 0.050º (H-plane) as the simulated widths are 0.053º and 0.045º. Differences between the simulated and measured patterns are partly caused by the antenna structure itself and partly by the measurement range.

A compact range based on a phase hologram was developed for RCS measurements. The hologram structure used in these measurements was fabricated on a 5 mm thick, 28 cm x 24 cm Teflon plate. In the horizontal and vertical directions the quiet-zone field amplitude and phase ripples are 3.3 dB and 23º, peak-to-peak, and 0.9 dB and 23º, peak-to-peak, respectively. The quiet-zone diameter is 12 cm. Radar cross sections of a cylinder and a “missile like” target were both simulated and measured. All the main features of the RCS could be seen from the results. The results are very promising. The range was also used for measuring reflectivity of absorbing materials. RCS method was used and the backscattered reflection was measured with horizontal and vertical polarizations in plane-wave conditions. The results agree well with those obtained in the previous studies and complement them with new materials, frequency, and angle information. The result can also be used in CATR development.

Keywords hologram, compact range, antenna measurements, radar cross section, submillimeter wave	
ISBN (printed) 951-22-8364-6	ISSN (printed) 1456-3835
ISBN (pdf) 951-22-8365-4	ISSN (pdf)
ISBN (others)	Number of pages 40 p. + app. 66 p.
Publisher Helsinki University of Technology, Radio Laboratory	
Print distribution Helsinki University of Technology, Radio Laboratory	
☒ The dissertation can be read at http://lib.tkk.fi/Diss/2006/isbn9512283654/	

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

VÄITÖSKIRJAN TIIVISTELMÄ

Tekijä Anne Lönnqvist

Väitöskirjan nimi

Hologrammiin perustuvan kompaktin mittauspaikan sovelluksia: antennin suuntakuvion, tutkapoikkipinnan ja radioaaltoja absorboivien materiaalien heijastavuuksien mittauksia

Käsikirjoituksen jättämispäivämäärä 5.9.2006	Väitöstilaisuuden ajankohta 20.10.2006
☐ Monografia	☒ Yhdistelmäväitöskirja (yhteenveto + erillisartikkelit)

Osasto	Sähkö- ja tietoliikennetekniikan osasto
Laboratorio	Radiolaboratorio
Tutkimusala	Radiotekniikka
Vastaväittäjä(t)	Dr. Jürgen Hartmann ja dosentti Taavi Hirvonen
Työn valvoja	Prof. Antti V. Räisänen
(Työn ohjaaja)	TkT Juha Mallat

Tiivistelmä

Tässä väitöskirjassa on tutkittu hologrammiin perustuvan kompaktin mittauspaikan sovelluksia alimillimetriaaltoalueella. Työssä kaksi osa-aluetta: amplitudihologrammiin perustuva kompakti antennimittauspaikka, jota voidaan käyttää satelliittiantennien testaukseen sekä vaihehologrammiin perustuva kompakti tutkapoikkipinnanmittauspaikka, jota voidaan käyttää tutkajärjestelmien kehittämiseen, kohteiden tunnistamisen tarvittavan tiedon keräämiseen sekä apuna kohteiden tutkapoikkipinnan minimoinnissa. Mittauspaikkaa on käytetty myös radioaaltoja absorboivien materiaalien heijastuvuuden tutkimiseen.

Kompaktia antennimittauspaikkaa on kehitetty ja käytetty antennimittauksiin taajuudella 322 GHz sekä se on osoitettu toimivaksi taajuudella 650 GHz. Mittauspaikassa on testattu 1,5 m heijastinantenni ADMIRALS RTO 322 GHz:n taajuudella. Koko mittauskampanja, paikan kokoaminen ja purkaminen mukaan luettuna, kesti noin kaksi kuukautta. Hologrammikuvio etsattiin kolmelle palalle metalloitua Mylar-kalvoa ja osat liitettiin juottamalla. Hologrammin tuottamassa hiljaisen alueen kentässä havaittiin 1,2 dB amplitudikuoppa ja satulanmallinen vakiovaihepinta (huipusta huippuun 250º). Antennin suuntakuvio mitattiin pystypolarisaatiolla. 3 dB:n keilanleveyksiksi mitattiin 0,086º E-tasossa ja 0,050º H-tasossa ja simuloidut keilanleveydet olivat 0,053º ja 0,045º. Erot mitatun ja simuloidun suuntakuvion välillä aiheutuvat antennin rakenteen epätarkkuudesta ja antennimittauspaikan hiljaisen alueen epäideaalisuudesta.

Vaihehologrammiin perustuvassa kompaktissa mittauspaikkassa voidaan mitata pienoismallien tutkapoikkipintoja. Mittauksissa käytetty, urakuviosta koostuva hologrammi valmistettiin 5 mm paksulle, 28 cm x 24 cm kokoiselle Teflon-levylle. Hiljaisen alueen amplitudi- ja vaihevaihtelut olivat vaakatason leikkauksessa 3,3 dB ja 23º huipusta huippuun ja pystytason leikkauksessa 0,9 dB ja 23º huipusta huippuun. Hiljaisen alueen halkaisija oli 12 cm. Sylinterin sekä yksinkertaistetun, ohjusta muistuttavan, kohteen tutkapoikkipinnat mitattiin ja simuloitiin. Kaikki kohteiden tutkapoikkipoikkipinnan pääpiirteet näkyivät mittaustuloksissa ja mittauspaikan kehitysmahdollisuudet näyttävät hyviltä. Mittauspaikkaa käytettiin myös radioaaltoja absorboivien materiaalien heijastavuuksien tutkimiseen tutkapoikkipinnan mittaukseen perustuvalla menetelmällä. Heijastavuus mitattiin sekä vaaka- että pystypolarisaatiolla. Tutkimustulokset täydentävät aiempia materiaalien heijastavuustutkimuksia sekä antavat lisätietoa eri materiaalien ominaisuuksista alimillimetrialueella. Tuloksia voidaan hyödyntää myös antennimittauspaikan kehitystyössä.

Asiasanat hologrammi, kompakti mittauspaikka, antennimittaukset, tutkapoikkipinta, alimillimetriaalto

ISBN (painettu) 951-22-8364-6	ISSN (painettu) 1456-3835
ISBN (pdf) 951-22-8365-4	ISSN (pdf)
ISBN (muut)	Sivumäärä 40 s. + liit. 66 s.

Julkaisija Teknillinen korkeakoulu, Radiolaboratorio

Painetun väitöskirjan jakelu Teknillinen korkeakoulu, Radiolaboratorio

☒ Luettavissa verkossa osoitteessa http://lib.tkk.fi/Diss/2006/isbn9512283654/

Preface

The work of this thesis has been carried out at the Radio Laboratory of Helsinki University of Technology during 2001-2006. The work was funded in SMARAD by the Academy of Finland and Tekes through their Centre-of-Excellence program, European Space Agency, Helsinki University of Technology and Graduate School in Electronics, Telecommunication and Automation, GETA. I have also received personal research grants from the Jenny and Antti Wihuri Foundation, the Foundation of the Finnish Society of Electronic Engineers, the Nokia Foundation, the Foundation of Technology (Finland), Finnish Cultural Foundation and the Emil Aaltonen Foundation. I am grateful for all the financial support I have received during the work.

I wish to thank Professor Antti Räisänen for the support during my research work and the opportunity to work at the Radio Laboratory. I would like to thank all my co-authors and other people who have participated in the work reported in this thesis. Special thanks go to Dr. Juha Mallat for instructing me during these years. Also the effort and feedback of the pre-examiners of the thesis, Dr. Richard Wylde and Dr. Randy J. Jost, is greatly appreciated.

I am thankful to my parents, Ulla and Jouko, and my little sister Erja for all the support they have given me during this thesis. At some points, I guess Erja was more confident on me some day defending my doctoral thesis than I was. Finally, I would like to thank my Mikko for the encouragement he has given me during this work.

Espoo, 5.9.2006

Anne Lönnqvist

List of publications

This thesis is based on the work presented in the following papers:

[P1] A. Lönnqvist, J. Ala-Laurinaho, J. Häkli, T. Koskinen, V. Viikari, J. Säily, J. Mallat, J. Tuovinen, and A.V. Räisänen, "Manufacturing of large-sized amplitude holograms for a submm-wave CATR", *Digest of 2002 IEEE Antennas and Propagation Society International Symposium*, vol. 4, 2002, pp. 394-397.

[P2] A. Lönnqvist, T. Koskinen, J. Häkli, J. Säily, J. Ala-Laurinaho, J. Mallat, V. Viikari, J. Tuovinen, and A.V. Räisänen, "Hologram-based compact range for submillimeter wave antenna testing", *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 10, pp. 3151–3159, Oct. 2005.

[P3] J. Häkli, T. Koskinen, A. Lönnqvist, J. Säily, J. Mallat, J. Ala-Laurinaho, V. Viikari, A.V. Räisänen, and J. Tuovinen, "Testing of a 1.5 m reflector antenna at 322 GHz in a CATR based on a hologram", *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 10, pp. 3142-3150, Oct. 2005.

[P4] T. Koskinen, J. Ala-Laurinaho, J. Säily, A. Lönnqvist, J. Häkli, J. Mallat, J. Tuovinen, and A.V. Räisänen, "Experimental study on a hologram-based compact antenna test range at 650 GHz", *IEEE Transactions on Microwave Theory and Techniques*, vol. 53, no. 9, pp. 2999-3006, Sept. 2005.

[P5] A. Lönnqvist, J. Mallat, and A.V. Räisänen, "A phase hologram based compact RCS range for scale models", *Proceedings of the 25th Annual Meeting & Symposium of the Antenna Measurement Techniques Association (AMTA*), Irvine, CA, USA, Oct. 19-24, 2003, pp. 118-123.

[P6] A. Lönnqvist, J. Mallat, and A.V. Räisänen, "Phase-hologram-based compact RCS test range at 310 GHz for scale models", *IEEE Transactions on Microwave Theory and Techniques,* vol. 54, no. 6, part 1, pp. 2391-2397, Jun. 2006.

[P7] A. Lönnqvist, A. Tamminen, J. Mallat, and A.V. Räisänen, "Monostatic reflectivity measurement of radar absorbing materials at 310 GHz", *IEEE Transactions on Microwave Theory and Techniques,* vol. 54, no. 9, pp. 3486-3491, Sept. 2006.

Contribution of the author

Paper [P1] was mainly contributed by the author. She wrote and presented the paper and carried out the measurements. Prof. Antti V. Räisänen was the supervisor of the work.

Paper [P2] is a result of collaborative work. The author was responsible for writing the manuscript. The author investigated the manufacturing and joining of the hologram pieces. She carried out the scale model tests (development of the soldering method) in co-operation with Tomi Koskinen. The author took part in building the measurement range and performing the actual measurements. The analysis of the manufacturing and alignment inaccuracies were done together with Tomi Koskinen.

Paper [P3] is a result of collaborative work. The author contributed to the design, preparation and execution of the antenna testing.

Paper [P4] is a result of collaborative work. The author contributed to preparation activities and measurements.

Paper [P5] describes work carried out by the author. The author was responsible for writing the manuscript. Dr. Juha Mallat and Prof. Antti V. Räisänen were the supervisors of the work.

Paper [P6] describes work carried out by the author. The author was responsible for writing the manuscript. Dr. Juha Mallat and Prof. Antti V. Räisänen were the supervisors of the work.

Paper [P7] was mainly contributed and written by the author. Aleksi Tamminen contributed to the measurements and the processing of the results under the instructions of the first author. Dr. Juha Mallat and Prof. Antti V. Räisänen were the supervisors of the work.

Contents

Abbreviations

ABmm	AB Millimètre (French company)
AUT	Antenna-under-test
BSMILES	Balloon-borne superconducting submillimeter-wave limb-emission sounder
BWO	Backward Wave Oscillator
CATR	Compact Antenna Test Range
CW	Continuous wave
dB	Decibel
dBsm	Decibels relative to a square meter
ESA	European Space Agency
ESA-1	External Source Association 1 (transmitter)
ESA-2	External Source Association 2 (receiver)
ESTEC	European Space Technology Centre
FDTD	Finite-Difference Time-Domain
FEKO	Commercial electromagnetic simulation software
LCLD	Laser-assisted Chemical Liquid phase Deposition
MilliLab	Millimetre Wave Laboratory of Finland
MIRO	Microwave instrument for the Rosetta orbiter
MoM	Method of Moments
MVNA	Millimeter Wave Vector Network Analyzer
NRL	Naval Research Laboratory
PCB	Printed Circuit Board
PO	Physical Optics
p-p	Peak-to-peak
RAM	Radar Absorbing Material
RCS	Radar Cross Section
RF	Radio Frequency
RX	Receiver
RTO	Representative Test Object
STL	Submillimeter Technology Laboratory
SWAS	Submillimeter Wave Astronomy Satellite
TELIS	Balloon-borne Terahertz and Submillimeter Limb Sounder
TKK	Helsinki University of Technology
TX	Transmitter

Symbols

D	the maximum dimension of the antenna, directivity of an antenna, the real target dimension
D_M	model dimension
d	distance between wedges
$\boldsymbol{E}^{scat}$	scattered electric field
$\boldsymbol{E}^{inc}$	incident electric field
G	gain
$d\Omega$	unit of the solid angle
G_R	receiver antenna gain
G_T	transmitter antenna gain
λ	wavelength
λ_M	model wavelength
n	integer
η_r	radiation efficiency
$P_n(\theta,\phi)$	normalized radiation pattern
P_R	received power
P_T	transmitted power
r	the distance where the maximum phase deviation in the AUT aperture is 22.5º when the AUT is pointed to a point source
r	distance from the target to the receiver
σ	radar cross section of the target
σ_M	radar cross section of the model
θ	angle of the maxima

1. Introduction

1.1. Background and motivation

In the near future, several scientific satellites carrying submillimeter-wave instruments and antennas will be launched. For example Planck, operating at frequency range from 25 GHz to 1000 GHz, is set out to analyze the first light that filled the universe, to give proof of the "big bang theory" [1]. Herschel Space Observatory, which is to be launched together with Planck, studies the way galaxies formed and evolved in the early universe and the way stars form and evolve and their interrelationship with the interstellar medium. It operates from 480 GHz to about 5 THz [2]. Microwave instrument for the Rosetta orbiter, MIRO, will investigate the nature of the cometary nucleus, out gassing from the nucleus and the development of the coma. Its center band operating frequencies are 188 GHz and 562 GHz [3]. There are also ongoing missions, such as the Submillimeter Wave Astronomy Satellite, SWAS which is used for studying star formation. It has focused on several spectral lines, such as water at 556.936 GHz, molecular oxygen at 487.249 GHz, neutral carbon at 492.161 GHz, isotopic carbon monoxide at 550.927 GHz and isotopic water at 548.676 GHz [4]. Swedish Odin-satellite is a dual operation satellite, which is used in studies of star formation and of the mechanisms behind the depletion of the ozone layer in frequencies 486 – 581 GHz and 118.75 GHz [5]. It was tested in a hologram-based compact range before launch [6]. In the tests, it was noticed that the feed of the antenna was misaligned. The feed was realigned before launch. The satellite has now been operating already seven years instead of the planned two years, providing valuable observations.

There are high-sensitivity limb sounders working at terahertz and submillimeter wavelengths which are used for remote sensing of the atmosphere. For example TELIS, balloon-borne Terahertz and Submillimeter Limb Sounder, is used to study atmospheric constituents which are associated with ozone depletion. Its operational frequencies are 500 GHz, 550 – 650 GHz and 1.8 THz [7]. BSMILES, the balloon-borne superconducting submillimeter-wave limb-emission sounder operating at 624–639 GHz, is used to observe thermal emission lines from stratospheric minor constituents, such as ozone and number of key species related to ozone destruction [8]. In all these missions, it is important that the instrument and the antenna are operating as planned.

Radiation characteristics of many antennas are rather easy to simulate. Some antenna designers do believe that there is no need for extensive measurements, and many antennas operating at a wide frequency range are tested for example only mechanically and at low frequencies. Practice has shown that measurements are needed to verify the design and manufacturing accuracy of the antenna. Possible corrections are a lot easier to make on the ground, before the launch. The antenna radiation pattern has to be exactly known to ensure proper functioning in the given application.

When measuring antenna radiation pattern or radar cross section of a target, the object-under-test has to be placed into a plane-wave region. This is possible by measuring the object-under-test in the far-field region or using a compact test range. Third option is to use near-field measurements with near-field to far-field transformation. At millimeter wavelengths, widely used methods to measure the radiation pattern of a satellite antenna are the reflector based compact antenna test range (CATR) and the near-field scanning. The hologram CATR is presented as an alternative to the reflector CATR [9], [10]. Holograms have several advantages when compared to reflectors. They are easier to manufacture, the cost is lower and a good quiet-zone field quality can be achieved while using only one collimating element.

We have been designing two different types of holograms, amplitude and phase holograms. Amplitude holograms have been used for antenna measurements [6], [11], [P1], [P2], [P3] due to the larger available size and also, so far, higher frequency [P4]. The hologram-based compact range has been used at 322 GHz for testing a 1,5 meter reflector antenna, the ADMIRALS RTO, which has been developed for demonstrating the current satellite antenna technology and for comparing the potential antenna testing methods at millimeter and submillimeter wavelengths [P2], [P3].

Measuring radar cross section (RCS) is related to antenna measurement since many of the methods used for antenna testing can also be used for RCS measurements. Target radar cross section data is needed for radar system development, target recognition and target RCS reduction. The data is especially interesting for military applications, for example developing stealth technology particularly in applications involving aircraft and ballistic missiles. Computer simulations are used for predicting the RCS but modeling of complicated structures is difficult and simulations are time-consuming. The results should be verified with measurements.

Phase holograms are better suited for RCS range applications due to their higher conversion efficiency [P5], [P6], [P7]. In both cases, part of the transmitted power is lost due to spill-over of the feed and part due to other diffraction modes produced by the hologram. The conversion efficiency of the hologram itself can be defined as the ratio between the field intensities in the quiet zone and before the hologram at the central axis. The conversion efficiency of the phase hologram has been evaluated by measuring the field magnitude first at the plane of the hologram surface and then at the quiet zone. According to measurements, the conversion efficiency of the phase hologram used here is –4 dB [12]. The conversion efficiency of a 60 cm amplitude hologram was measured the same way and it was estimated to be ca. –12 dB [13]. This is less than can be expected for reflector ranges but sufficient for antenna measurements.

While using a compact RCS test range, targets can be measured indoors due to the decreased measurement distance. Compact ranges can also be used for scale model measurements. The main advantage of a scale model RCS range is that the dimensions of radar targets are scaled down in proportion to the wavelength. Therefore, RCS data of originally large objects can be measured indoors in a controlled environment. The risk of unwanted observation, by satellites etc., is smaller and no consideration has to be paid to changing weather conditions. Contamination by dust is also a smaller and more controllable problem than in outdoor ranges. These all increase the available measurement time. After model measurements the obtained RCS data is scaled back in order to get the real sized target parameters.

In compact ranges, radar absorbing materials are needed to suppress unwanted reflections. Characteristics of absorbing materials need to be known when building a compact range. When the characteristics of absorbing materials are known, their placement in the range can be designed more precisely and also the amount of absorbers needed can be minimized with proper placement and still, low reflectivity level of the background can be assured. Possible standing waves can also be suppressed. Good absorbers are also needed in astronomical receivers. They can be used in radiometers as calibration loads so if reflections from these absorbers cause standing waves to the system, it can be seen as frequency dependent modulation in the detected power. For optimum performance, the reflections from the calibration loads need to be minimized [14]. The RCS range can be used for measuring the monostatic reflectivity of radar absorbing materials.

1.2. Scope and contents of this thesis

This thesis summarizes different applications of a hologram-based compact range. Both amplitude and phase-type holograms are used in compact ranges. In this thesis, amplitude-type holograms are used for a compact antenna test range and phase holograms for a compact radar cross section measurement range. The compact RCS range is also used for reflectivity measurements of radar absorbing materials. The research has been carried out in the Radio Laboratory of Helsinki University of Technology. The hologram CATR work has been related to projects carried out for ESA/ESTEC under ESA External Laboratory called MilliLab - Millimetre Wave Laboratory of Finland – which is a joint laboratory of TKK and VTT.

Chapter 2 concentrates on antenna measurements in a hologram-based compact test range. Basic antenna measurement methods are shortly described. Design, construction and measurements in a hologram-based compact range at 322 GHz are described. Development towards 650 GHz is also described. Chapter 3 discusses development of a radar cross section measurement range for scaled models at 310 GHz. Chapter 4 presents the reflectivity measurement of radar absorbing materials in a compact RCS range. Summary of publications is presented in Chapter 5, and conclusions and future work in Chapter 6.

1.3. New scientific results

The work presented in this thesis has produced new knowledge in the following areas:

1) A method for producing and joining large-sized amplitude holograms with good electromagnetic properties has been developed.

2) The applicability of compact antenna test range based on an amplitude hologram for large submm-wave antenna testing has been demonstrated. A 1.5 m reflector antenna has been measured at 310 GHz.

3) Feasibility of an amplitude hologram-based compact range at 650 GHz has been demonstrated.

4) The feasibility of a phase-hologram-based compact range for radar cross section measurements of scale models has been demonstrated at the submm-wave region (310 GHz).

5) Monostatic measurements of absorbing materials at 310 GHz in a phase-hologram-based compact range have been carried out and presented.

2. Antenna measurements and hologram-based compact antenna test range

2.1. Measurement methods

2.1.1. Far-field distance and parameters tested

Testing of electrically large reflector antennas at submillimeter wavelengths is a difficult task. Far-field measurements, which have been traditionally used for antenna testing, are not possible due to the large measurement distance and high atmospheric attenuation. The far-field distance is usually defined as

$$r = \frac{2D^2}{\lambda} \tag{2.1}$$

where D is the maximum dimension of the antenna, and λ is the wavelength. More exactly defined, r is the distance where the maximum phase deviation of the illuminating spherical wave is 22.5° in the AUT aperture plane. In many applications the phase error requirement is even stricter. While using the conventional antenna measurement methods with electrically large antennas at submillimeter wavelengths, this leads to very long measurement distances. Near-field testing and compact ranges have been developed to overcome this restriction.

How well the antenna fulfills the design criteria is usually of interest when testing antennas. The parameters tested include radiation pattern at least at E and H planes, directivity, phase pattern, polarization performance, impedance, bandwidth, radiation efficiency and gain. Many times all of these cannot be tested. For example, testing gain at submillimeter wavelengths can be difficult since there are no suitable reference antennas. One of the most important parameters to test is the antenna radiation pattern. To be able to compare the results achieved in different measurement places, first thing to do is to define the coordinate system. The standard coordinate system can be found in [15]. If the measurement instrumentation has phase measurement capability, the phase pattern can be measured at the same time. After the radiation pattern of the antenna is known, the directivity of the antenna can be calculated according to [16]

$$D = \frac{4\pi}{\int\int_{4\pi} P_n(\theta,\phi)d\Omega} \tag{2.2}$$

where D is the directivity, $P_n(\theta,\phi)$ the normalized radiation pattern, and $d\Omega$ unit of the solid angle. Gain G of the antenna is the directivity D multiplied by radiation efficiency η_r, so if two of these are known, the third can be calculated. Gain is usually measured using gain comparison with a known reference antenna [17]. Polarization performance can be verified by measuring the cross-polarization pattern of the antenna, i.e. using different polarization in feed as in the receiving antenna. Input impedance of the antenna can be determined by measuring the input reflection coefficient S_{11}. After all this is known, bandwidth can be determined as the frequency band where the design criteria are met.

2.1.2. Measurement methods at submillimeter wavelengths

Measurements in a compact antenna test range or near-field scanning have been found the most practical methods for testing antennas at submillimeter wavelengths [18], [19]. While using a compact range, antenna radiation pattern measurements can be carried out in the near-field of the antenna, but under plane-wave conditions needed for proper radiation pattern evaluation.

Different kinds of compact ranges have been introduced to overcome the far-field criteria. The focusing element in a compact range can be a lens [20], [21], a reflector or rather more often a set of two or three reflectors [22], [23], [24], [25], [26], [27], [28], an amplitude hologram [6] [9], [10], [11], [29], [30] or a phase-type hologram [31]. The focusing element is used to transform the spherical wave radiated by the feed into a plane wave needed for antenna or radar cross section measurements.

Since the dimensions of a compact range are relatively small, it can be situated indoors and most of the problems caused by the atmosphere can be avoided. The environment can controlled, i.e. humidity, temperature, dust, data security, etc. [17]. Typical criteria for the quiet-zone field are that the amplitude and phase ripples do not exceed 1 dB and 10°, peak-to-peak, respectively. In indoor measurements special attention has to be paid to reflections from the floor, walls and roof of the measurement chamber. Test procedures for the measurement of antenna properties can be found in [15]. Also different kinds of range designs and evaluation process of the range are covered.

In a compact range, the antenna radiation pattern measurements can be accomplished in a reasonably short period of time compared to near-field scanning. While using near-field scanning, large amounts of near-field data have to be acquired and the time needed for a measurement can be even several days and thus the measurement system has to be very stable [32]. Otherwise, near-field scanning has many of the same advantages as measurement in a compact range since a near-field measurement range can be situated indoors. In near-field scanning, the radiating near-field of an antenna is sampled and the far-field pattern is achieved by applying near-field far-field transformation. The measurement site can be really compact since only a few wavelengths need to be between the antenna and the field probe. Of the scanning geometries available, planar scanning has been found most suitable for submillimeter-wave antenna measurements. For cylindrical and spherical near-field scanning, the number of measurement points is considerably larger than for planar scanning.

Lenses have not been used much as a collimating element in a compact range. Compared to reflectors, its surface manufacturing accuracy requirements are less stringent. Also, there is no direct radiation to the quiet zone, the feed does not block the aperture and the cross polarization level is low [21]. There are also some drawbacks with this method; the lenses easily come impractically thick, there are trade-offs between the surface accuracy requirement, compactness of the measurement site, internal reflections and cross polarization level. The dielectric constant may be strongly dependent on frequency, i.e. the measurement site is narrowband [20].

In a conventional CATR, the focusing element is a reflector or a set of two or three reflectors. The main reflector has to be clearly larger than the AUT. A very high surface accuracy is required (~0.01λ), which makes the fabrication and maintenance of large reflectors very difficult and expensive in the submillimeter-wave range. Reflector-type CATRs are commercially available [28], nowadays advertised to operate even up to 500 GHz [33].

Special attention has to be paid to diffraction from the reflector edge. This can be done by tapering the amplitude of the illuminating field at the edges of the reflector, shaping or rolling the edges or using different kinds of serrations. These all either reduce the diffracted field or scatter it away from the quiet zone.

The ranges based on amplitude hologram use only a single focusing element. A hologram is relatively inexpensive to fabricate because it has a simple planar structure and its surface accuracy requirement is only ~0.1 λ due to the transmission type operation [34]. Also, due to a light weight and a compact structure of the amplitude hologram, the hologram can be transported to the test site and the CATR built up there. Transporting of heavy and sensitive satellites to the test site is not necessary.

2.2. Hologram-based compact range

The hologram-based compact range has been developed in the TKK Radio Laboratory from the beginning of 90's. It started with the invention and development of the compact antenna test range (CATR) based on a computer-generated amplitude type hologram [9], [10], [35], [36] and was later supplemented with the demonstration of the compact radar cross section measurement range [12], [37], [P5], [P6] using a phase type hologram. RCS range has also been used for absorber reflectivity measurements. The basic layout of hologram-based compact range is presented in Fig. 2.1.

The amplitude-type hologram used in a CATR is a binarized interference pattern of a spherical wave and a plane wave. It is a slot pattern, which is etched on a metal layer on top of a thin dielectric film. A typical cross-cut and pattern of amplitude type hologram are presented in Fig. 2.2. To avoid edge diffraction, tapering (narrowing of the slots) is needed near the hologram edges. The slots widths are about 0.04–0.4 λ and the slot spacing is in the order of the wavelength. In a 300 GHz hologram the slots are 40–400 μm wide. The estimated pattern accuracy requirement for a 300 GHz hologram is 10–20 μm (0.01–0.02 λ).

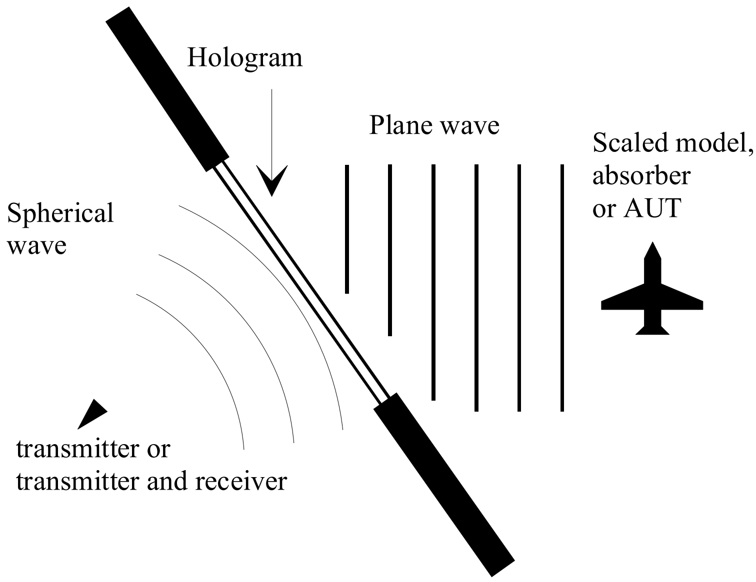
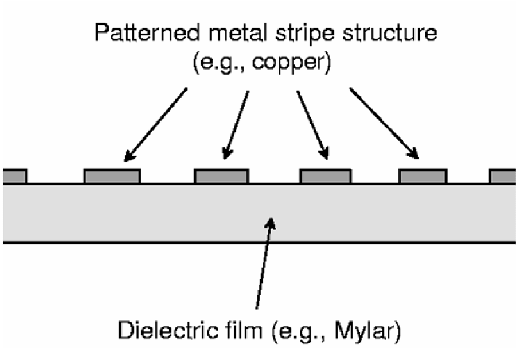


Fig. 2.1. Hologram-based compact range.



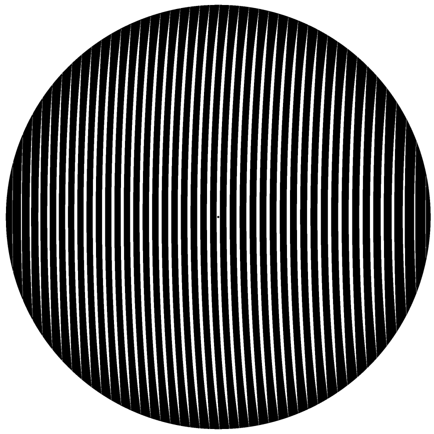


Fig. 2.2. Typical cross-cut and pattern of amplitude type hologram.

In a amplitude hologram, the amplitude of the transmitted field is modulated by a slot structure. Several possibilities for the manufacturing of a hologram were investigated, including conventional printed circuit board (PCB) process, wet etching with laser exposure, laser etching and laser-assisted chemical liquid phase deposition (LCLD). Wet etching with laser exposure was found to be accurate enough and a facility capable of manufacturing a 3 m hologram in three pieces was found. A large-sized (~3 m) amplitude hologram pattern is exposed with a laser on the photosensitive resist which is on top of the copper layer of the hologram material (17 µm copper on 50 µm Mylar). Chemical wet etching is used for processing the slots to the copper layer. Amplitude hologram can be manufactured in several pieces, which are joined together by soldering [P1]. The pieces are horizontal so the solder joint just forms a continuation of the copper strip and no effect can be seen in the quiet-zone field pattern. The continuation of the strips also facilitates a very accurate alignment process. Special alignment marks are also used to ease the process.

2.3. Measurements at 322 GHz

A CATR based on a 3 m amplitude hologram was constructed for testing a 1.5 m parabolic reflector antenna at 322 GHz. The results are reported in papers P2 and P3. The test verified the feasibility of a large-sized CATR at submillimeter waves and also demonstrated the portability of the test setup. The construction of the test range, the measurements and the disassembly of the test range were done in about two months. The reflector antenna tested, the ADMIRALS RTO, has been designed and constructed by ESA/ESTEC and EADS Astrium, Germany [38] for demonstrating the current satellite antenna technology and for comparing the potential antenna testing methods at millimeter and submillimeter wavelengths.

The hologram CATR was built in a large test hall dedicated for high voltage testing. The development work of the compact range setup included several practical aspects: manufacturing of the 3 m hologram, procurement of the quiet-zone scanner and the antenna positioner, absorber placement in the measurement room, and the development of the electrical measurement instrumentation ensuring adequate stability and dynamic range.

The dedicated transmit module for ADMIRALS RTO [39] was used as the transmitter both in the quiet zone probing and in the antenna measurements. AB Millimètre MVNA-8-350 millimeter-wave vector network analyzer with its receiver extension ESA-2 was used in the quiet-zone measurements. This configuration gave a sufficient dynamic range of about 50 dB and allowed also the phase measurement of the quiet-zone field. Phase errors due to the cable flexing during the probe movement were corrected with a phase correction system, which

Fig. 2.3. The measurement range (left) and the RTO (right).

measures cable flexing by using a pilot signal [40]. In the measurements of the high gain RTO the dynamic range was about 80 dB.

The quiet-zone field of the CATR was probed with a corrugated feed horn with light-weight receiver and a linear scanner. The planarity of the scanner was measured with a laser tracker, and the planarity data was used in the correction of the measured phase. The quiet-zone field of the 322 GHz CATR had a 1.0-1.2 dB amplitude dip and a saddle-shaped equiphase surface (peak-to-peak deviation 250º). A slight inaccuracy in the FDTD modeling of the hologram, the manufacturing, and alignment of the pieces were identified as the main reasons for the amplitude and phase deviations in the quiet-zone field.

The estimated dynamic range in the antenna measurements was about 85 dB. The measured radiation pattern corresponds reasonably well with the simulated pattern. The measured 3 dB beam width is 0.086º in the *E*-plane and 0.050º in the *H*-plane. The simulated beam widths are 0.053º and 0.045º. The measurements were carried out at vertical polarization. RTO and the measurement range are presented in Fig. 2.3.

2.4. Demonstration of the feasibility of a compact range at 650 GHz

Two 1-m holograms operating at 650 GHz were designed and fabricated to demonstrate the feasibility of hologram CATR at high sub-mm wave frequencies. The same design procedure used at 322 GHz could be used at 650 GHz and also, the same fabrication process was applicable. Instrumentation based on MVNA with improved ESA-2 extension and a phase locked BWO as the transmitter was developed. The hologram pattern was manufactured on two different materials, 5 µm copper on 25 µm Mylar and 17 µm copper on 50 µm Mylar. Both hologram patterns were slightly over etched. The quiet-zone field generated by the hologram manufactured on the 50 µm film had a higher quality. The measured ripples in the quiet-zone field were approximately 2 dB and 15º, peak-to-peak. Phase errors caused by the bending cable were corrected and the scanner planarity data was also used. The tests made and the results achieved are described in P4.

2.5. Error considerations on hologram-based compact range

The obtainable accuracy of antenna measurements in a hologram-based compact range is affected by measurement equipment, quiet-zone field quality, and effectiveness of possible antenna pattern correction methods, which are used to mitigate the effects of imperfect quiet-zone field quality. Ripple in the quiet-zone field caused by a scatterer can cause extra lobes in the measured radiation pattern when the main lobe is pointing toward scatterer. The measured antenna beam shape can also be changed. Eliminating this kind of scatterers is very important but if it is not possible the effects of the spurious signals on the measured radiation pattern can be compensated using antenna pattern comparison (APC) methods. [P3] Information on error compensation techniques developed at TKK Radio Laboratory can be found in [41], [42].

Quiet-zone field quality is affected by reflections from surroundings and quality of the hologram. The measurement environment and especially the quality of the absorbing materials affect the reflectivity level of the environment. Reflections from the environment may cause short-period amplitude and phase distortions [P3]. At high frequencies, it might be possible to use also unconventional absorbing materials such as carpets, but they need to be tested beforehand. Vicinity of the feed, the hologram, and the AUT are the most critical places so best absorbers available need to be used there.

The hologram itself has a big effect; the simulation accuracy, the material, the manufacturing accuracy, and joining of the hologram pieces affect the obtainable quiet-zone field quality. Simulation accuracy can be improved and a smaller FDTD cell size will be used in the design of future holograms. Most materials available have a layer of glue between the dielectric film and the copper. This causes uncertainty to the thickness and the relative permittivity of the effective substrate and complicates the hologram design. If the substrate material is too thick compared to wavelength, resonances inside the hologram structure can occur. The 25 µm Mylar substrate is expected to be usable up to 1 THz [P4]. It has been tested, but there are still some handling issues to overcome before big scale use.

The manufacturing accuracy is limited. The hologram pattern can be exposed with a laser with the accuracy of 5 µm. The measured average manufacturing error of the 3-meter hologram was 10 µm and no significant systematic error was seen [P2]. In the other direction of the hologram pattern, there was some kind of scaling error and few centimetres of the pattern were missing. This caused problems to the alignment of the hologram pieces and distortion to the quiet-zone field quality, but it is a problem which can be fixed for the next CATR generations. Over etching of the slots has also been a problem, but it can be fixed by tuning the manufacturing process.

The alignment of the hologram pieces needs to be done with care. With scale models the alignment accuracy of better than 30 µm was obtained and for the 3-meter hologram alignment accuracy of the pieces at the seams was better than 10 µm in the mid-section of the seams [P2]. The alignment accuracy needed for operation at 650 GHz seems to be achievable. Soldering is used as joining method. It does not cause disturbance to the quiet-zone field quality, but at some point with higher frequencies the metal stripes become too small for soldering and at that point, the holograms have to be manufactured in one piece.

The planarity of the scanner causes uncertainty to the measured quiet-zone field. This can be fixed with laser tracker measurements. The measurements can be done beforehand or for best accuracy, at the same time with the quiet-zone field measurement. The uncertainty of the planarity measurement was approximately ±5-10 µm [P4]. On-the-fly correction for the error caused by flexing cables is used. The uncertainty of the system was estimated to be approximately 5° at 644 GHz [P4]. The total uncertainty of the measured phase values is less than 10° (worst case rss) at 644 GHz with 32-dB dynamic range [P4]. This includes the phase uncertainty of the MVNA, cable correction system, planarity correction and jitter caused by phase locking loop of BWO. Solid state systems will be used in the future instead of BWO.

Overall, it seems that antenna measurements in a hologram-based compact range are relatively easily realizable at 650 GHz. When moving closer to 1 THz, the manufacturing methods of the hologram need to be improved.

2.6. Other hologram applications

In addition to plane wave generating holograms, also other types of holograms have been investigated [31], [43], [44]. The research has been done in collaboration with Material Physics Laboratory personnel. Many applications, which are better known in optics, have been brought down to millimeter and submillimeter-wave region. This includes Bessel beams of different orders and electromagnetic vortices. These holograms have been manufactured on a copper-plated Mylar film with the usual PCB process, i.e. wet etching with masks.

Electromagnetic vortex was designed and measured at 310 GHz. The amplitude of the vortex field is nearly constant in an area of diameter 20 cm but a deep null appears on the axis. This is because the phase of the vortex rotates a loop by 2π. The measured results agree with the simulated ones. Diffraction rings originating from the circular aperture of the hologram were observed around the vortex [44].

Diffraction-free Bessel beams of several orders were manufactured and measured. The measurement results of the zeroth-order and the first-order beam are presented in [44]. The focal line of a Bessel beam propagates without diffraction and it is surrounded by several Bessel fringes. The simulations and measurements verified that it is possible to transform an incident Gaussian beam to a Bessel beam.

No applications have been realized for these holograms yet, but these tests open up possibilities for new hologram applications in the future.

2.7. Conclusion

For the first time, real size antenna measurements were carried out in a hologram CATR at 322 GHz. It was shown that it is possible to manufacture a 3 meter hologram needed for this measurement, though not in one piece but by joining it from three pieces. Even though the manufacturing accuracy of the hologram proved to be non-ideal, a quiet-zone field adequate for antenna testing was achieved. In the future, the FDTD modeling of the hologram and the hologram manufacturing can be corrected. The alignment of the pieces should be studied more when considering building a hologram CATR for antenna testing at 650 GHz. Since the antenna measurements were carried out successfully and also the demonstration of the hologram CATR at 650 GHz was successful, it is certain that CATR operation can also be extended to real antenna measurements at 650 GHz. Possibilities for more abstract shaping of the fields using holograms have also been studied.

3. Measuring radar cross section in a compact range

3.1. Definition of radar cross section

Radar cross section (RCS) can be defined as scattering, absorption, extinction or forward cross section. The radar cross section which is of interest here is the scattering radar cross section, i.e. the measure of power scattered in a given direction when a target is illuminated by an incident wave [45]. The distance from the illumination source does not affect the RCS since it is normalized to the power density of the incident wave. The basic definition of RCS is [46]

$$\sigma = \lim_{r \to \infty} 4\pi r^2 \frac{\left| \mathrm{E}^{scat} \right|^2}{\left| \mathrm{E}^{inc} \right|^2}, \tag{3.1}$$

where σ is the radar cross section, r is the distance from the target to the receiver, $\boldsymbol{E}^{scat}$ is the scattered electric field, and $\boldsymbol{E}^{inc}$ is the field incident at the target.

The basic unit of radar cross section is square meter but due to the large dynamic range of RCS, logarithmic scale is used. The most usually used unit of radar cross section is dBsm defined as

$$RCS(\mathrm{dBsm}) = 10 \log_{10} \frac{\sigma}{1\mathrm{m}^2}. \tag{3.2}$$

3.2. RCS measurement methods

When measuring RCS, the target has to be illuminated with a plane wave. Thus, the target has to be at the far-field distance determined by the largest dimension of the transmitting antenna, the receiving antenna or the target. For very simple targets as cylinders and flat plates, first effects of measuring them at less than the standard far-field distance are filling in of nulls and reduction of amplitudes of sibelobes [45]. When measuring more complex targets, the near-field effects can be seen as a shift in the places of the lobes and the nulls of the measured RCS pattern. In indoor measurement ranges it is difficult to meet the far-field criteria for a real size target.

Traditionally, measurements have been done in outdoor far-field ranges. Outdoor ranges are subject to changing weather conditions, dust and unwanted observation. All these limit the time available for measurements. Many of these very large outdoor ranges have been placed to deserts to avoid problems caused by rain. Wind on the other hand is a major concern and though structures of the range are supported with lines, even a moderate wind can be a reason to halt the measurements. Dust causes problems to the measurement equipment and changes characteristics of the radar absorbing material used in the range. Reflections from the surrounding terrain have to be controlled, i.e., sources of individual reflections have to be known. It has been estimated that 35 % of the time is lost when doing measurements in an outdoor range [45].

In indoor ranges, many of the problems countered in outdoor ranges can be avoided. However, target sizes are limited and special attention has to be given to measurement chamber design to avoid unwanted reflections. Scaled models have been used to overcome the size limitation. Compact ranges have been used to overcome the far-field criteria [22], [46],

[47], [48]. Especially, when the use of scaled models is combined with the use of a compact range, very large targets can be measured in a small chamber. Ranges for scale model measurements have been reported at submillimeter-wave frequencies of 524 and 585 GHz [49], [50]. These ranges are based on reflectors. The difficulty with reflectors at submillimeter wavelengths is the high surface accuracy requirement. A phase-hologram-based compact range has been presented as an alternative to the reflector compact range [12], [31], [37], [P5], [P6].

Near-field measurements can also be used for measuring radar cross section. However, evaluating radar cross section from the near-field data is much more difficult than evaluating antenna radiation pattern. Full set of bistatic near-field measurements are needed to determine even a monostatic radar cross section. This requires a long measurement time and also the computational effort to transform the near-field data to far-field data is huge. Interest on this issue seems to have been more theoretical than practical and very few measurement results can be found in open literature [51], [52], [53], [54], [55].

3.3. Phase hologram

For a compact range used for radar cross section measurements, a collimating element having higher conversion efficiency than that of amplitude holograms was needed. As a solution, a phase type hologram was proposed. A computer-generated phase hologram was designed for plane-wave generation. Back-propagation approach with local rigorous optimization was used to design the hologram. It generates a uniform planar field with a diameter of 10 cm at 1 m distance from the hologram [31]. A phase-hologram-based compact range has the same structure as the amplitude hologram compact range as shown in Fig. 2.1. The hologram is designed in such a way that the angle between the hologram normal and the direction of the plane-wave propagation is 33°. This eliminates the disturbances from the other diffraction modes produced by the hologram. Also reflection type phase holograms have been designed [56] but their manufacturing technique still under development. With a reflection type phase hologram, the compact range could be made more compact and also the achievable dynamic range would be higher.

The phase holograms are realized as milled grooves on a dielectric plate (see Fig. 3.1). The field passing through the grooves acquires a phase difference with respect to that between the grooves, leading to a phase modulation of the transmitted field. Groove width and depth of the hologram profile is designed to locally produce the required amplitude and phase modulation [31]. Front view of the phase hologram during quiet zone testing can be seen in Fig. 3.2. Most of the surrounding absorbers are Eccosorb VFX-NRL-2.

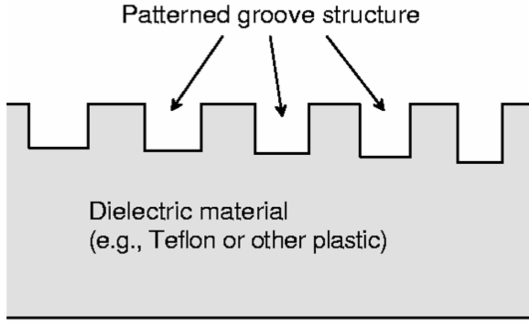


Fig. 3.1. Typical cross-cut of a phase type hologram.

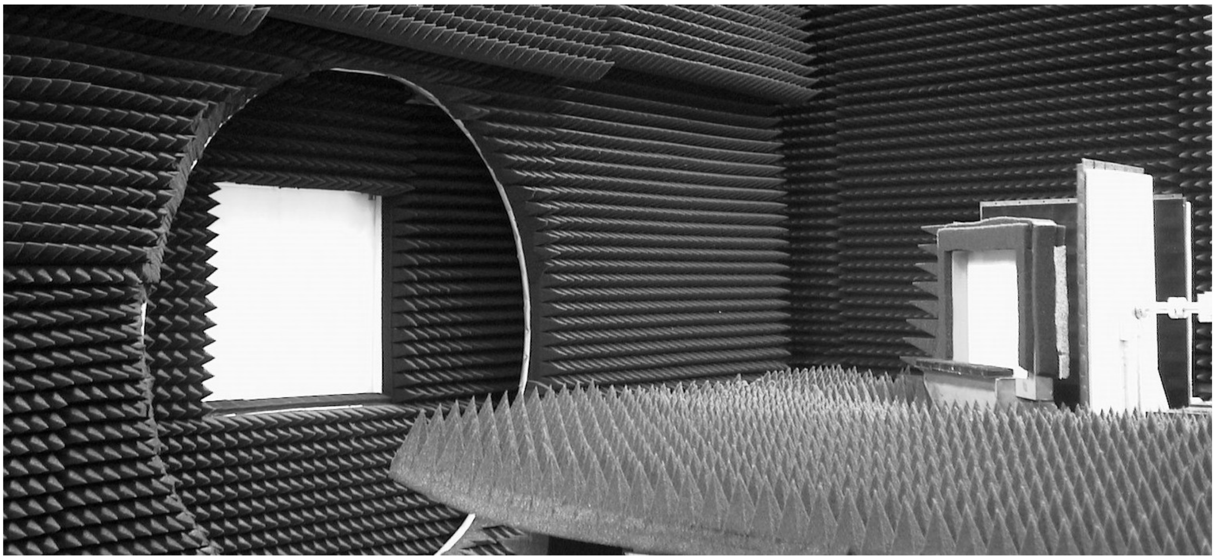


Fig. 3.2. Front view of the phase hologram during quiet zone testing.

The phase hologram structure can be manufactured on a dielectric plate by a computer-controlled milling machine. Teflon is a suitable material for holograms due to its machinability, its well-known characteristics at millimeter wavelengths and its low losses. So far, only small (~0.5 m) holograms have been made due to the restrictions of the manufacturing facility. Large and thin Teflon plates also have the tendency to bend. Using thicker plates is not an alternative due to the internal reflections of the plate. Joining techniques for phase holograms have not been studied.

3.4. Scaled models

Physical target size can be reduced by using dimensional scaling. In making target models, material parameters should stay constant, with the exception of conductivity (scaling ~ $1/\lambda$). If target dimensions in wavelengths, as well as real and imaginary values of permittivity and permeability, and impedance remain fixed, also the value σ / λ^2 remains fixed [46]. This means that target dimensions scale down proportionally to wavelength λ as stated in (3.3), where λ_M is the model wavelength, λ the actual radar wavelength, D_M model dimension, and D the true actual dimension

$$\frac{\lambda_M}{\lambda} = \frac{D_M}{D} . \tag{3.3}$$

For example, when making scale models of targets to be measured with actual 10 GHz, 35 GHz and 95 GHz radars, the actual target dimension of 1m scales to model dimension of 3.2 cm (10/310), 11.3 cm (35/310), 30.6 cm (95/310). After the model measurements, the results can be transformed to the actual radar frequency according to

$$\sigma = \frac{\lambda^2}{\lambda_M^2} \sigma_M , \tag{3.4}$$

where σ is the radar cross section of the target, σ_M is the radar cross section of the model, λ_M is the model wavelength, and λ the actual radar wavelength.

The manufacturing accuracy requirements for these scaled models are very strict since the dimensional tolerances should be reduced by the scale factor. If target is smooth, duplication of the target dimensions to a tolerance of a sixteenth of a wavelength at scaled wavelength is acceptable [46]. Also permittivity and permeability are usually frequency dependent so equivalent models also for materials needs to be found. With knowledge of a material's dielectric constant, a new material can be fabricated that possesses the original dielectric constant [57], [58] at the scale model measurement frequency. While measuring scaled models, also the environment surrounding the target in real measurement situation can be modelled as in [59] where scale models of ground planes have been used in scale model RCS measurements.

3.5. Range operation and results

3.5.1. Phase-hologram-based compact range

The phase hologram RCS range has been developed for measuring models scaled at 310 GHz. The RCS test measurement facility is shown in Fig. 3.3. In this test setup, the distance from the receiver/transmitter (RX/TX) to the hologram and also from the hologram to the target is 1 m. The hologram used in these measurements was 28 cm x 24 cm in size and it was fabricated on a 5 mm thick Teflon plate. The amplitude and phase variations in the quiet zone are approximately 2 dB and 10 degrees peak-to-peak, respectively. The diameter of the quiet zone is about 12 cm.

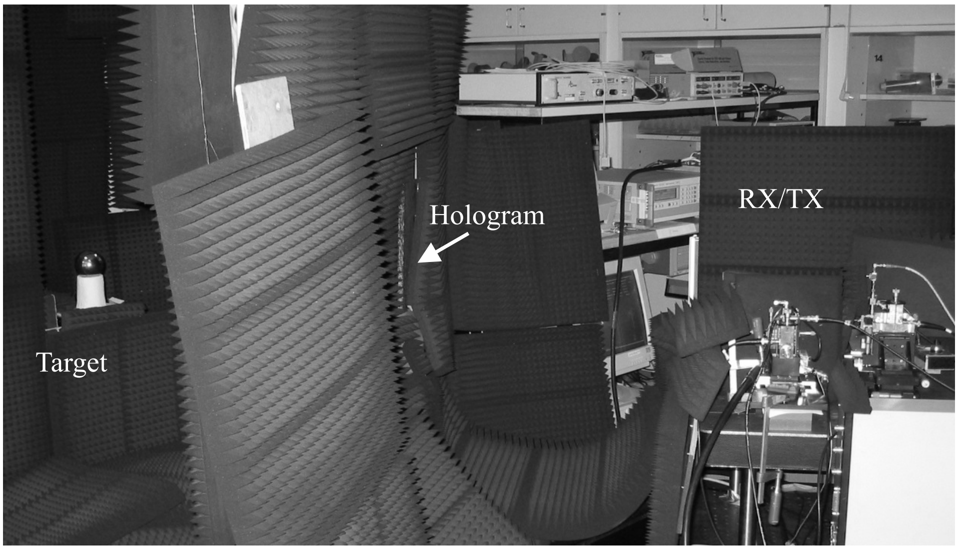


Fig. 3.3. Test RCS measurement facility [P5].

The instrumentation is based on the same millimeter-wave vector network analyzer and submm-wave extensions that were used for amplitude hologram tests. ESA-1 extension, the submm-wave source, uses a phase-locked Gunn oscillator followed by a harmonic multiplier. The receiver ESA-2 extension consists of a Schottky harmonic mixer pumped with a phase-locked Gunn oscillator. Corrugated horn antennas are used as the transmitting and receiving antennas. A planar scanner is employed to obtain the two-dimensional field profile of the quiet-zone field.

In RCS measurements the receiver is brought from behind to the front of the hologram so that the configuration is monostatic. The measurement system is made monostatic using a dielectric slab as a directional coupler. The target is placed behind the hologram in the quiet zone. The support column of the target is made of extruded polystyrene foam. The targets used in this experiment are light weight so it was possible to select this kind of low-density plastic foam column as the target support. Continuous wave (CW) operation instead of, e.g., pulsed operation has been considered most feasible since fast enough switching is a problem at submillimeter wavelengths.

The radar cross section of the target can be evaluated from the radar equation by taking into account the conversion efficiency of the hologram [12]:

$$\frac{P_R}{P_T} = G_T G_R \frac{\lambda^2 \eta_H^2 \sigma}{(4\pi)^3 R^4} \tag{3.5}$$

where P_R and P_T are the received and transmitted powers, G_R and G_T are the receiver and transmitter antenna gains, λ is the wavelength, σ is the RCS of the scale model target, and R is the distance from RX/TX to the hologram. The conversion efficiency of the hologram is squared as the received echo signal has passed through the hologram twice. The distance from the hologram to the scale model target does not appear in Equation (3.5) because, as the target stays in the quiet zone (i.e., in the waist of a Gaussian beam), this distance is irrelevant.[1]

The reflection from the target is separated from the background reflection by moving the target with a micro translation stage along the z-axis (direction of the plane propagation). From the variation of the power level, the field component caused by the moving target can be evaluated. Power reflected from the target can be calculated from the measured power. The measured power is proportional to the squared resultant of the coherent field vectors reflected from the background and the target:

$$P_{measured} \sim |\boldsymbol{E}_{background} + \boldsymbol{E}_{target}|^2. \tag{3.6}$$

$\boldsymbol{E}_{background}$ consists of the reflections from the absorbers and the surroundings. The collected data is Fourier transformed from time-domain to frequency domain. The peak coming from the target is selected and the data transformed back to time domain. The translation stage is combined with a rotation stage.

The measurements are done in the centre of the quiet zone. Using the basic radar equation a relation can be found between the radar cross sections and the measured power levels of the reference and the target:

$$\sigma_{\text{target}} = \sigma_{\text{reference}} \frac{P_{\text{target}}}{P_{\text{reference}}} . \tag{3.7}$$

[1] The conversion efficiency can be defined differently for some other applications, for example as the ratio of the power integrated over the quiet zone and power integrated over the area of the hologram. The conversion efficiency used in this thesis has been defined for the use in the radar equation as in (3.5). The correctness of the equation has also been verified with power level and RCS measurements in [37].

3.5.3. Simulation and measurement results

The radar cross section of two objects, a cylinder and a missile-like target was both simulated and measured. The simulations were done using commercial software called FEKO [60]. Since the targets used were large compared to the wavelength, a combination of method of moments (MoM) and physical optics (PO) was used. This hybridization reduces the computational resource requirement. The targets need to be metallic and relatively small; otherwise using FEKO is not possible.

The measured and simulated results agree reasonably well, i.e. the main characteristics of the target can be seen from the measurement result. They are thoroughly presented and analyzed in paper P6.

It was noticed that the repeatability of target placement, i.e., target support needs to be improved. Both the target and the cylinder were about 1º inclined from the intended position. Also the accuracy of manufacturing of the target itself needs to be improved. The residual background level was -42 dBsm for the vertical polarization and -36 dBsm for the horizontal polarization. Measuring cross polarization is not possible with the current setup and this is the next step to be taken to improve this measurement setup.

3.6. Conclusion

The feasibility of phase-hologram-based compact range for radar cross section measurements has been verified. The measurements were performed at 310 GHz using a monostatic configuration where the identical receiving and transmitting corrugated horn antennas were placed on opposite sides of a dielectric slab working as a directional coupler. Power division of 3 dB was used in the design of the coupler. Continuous wave operation was used.

Radar cross section of a cylinder and a "missile" target was measured at both vertical and horizontal polarization. A reasonably good sensitivity was achieved and the measurements were successful. There is still room for further development, for example in development of a measurement system, which is capable of measuring cross polarization of the target.

4. Radar absorbing materials and measurements

4.1. Absorbing materials

Radar absorbing materials (RAM) are needed to suppress unwanted reflections in measurement systems. The absorption is based on loss in the material, which can be electric or magnetic or it can be based on the structure of the absorber. Absorbing materials can be used for many different purposes, including decreasing the reflectivity level in anechoic chambers, being calibration loads in radiometers and reducing the RCS level of a target. The structure of the absorbing material is strongly application-specific, ranging from a layer of paint to a large foam structure.

Most of the absorbers used in anechoic chambers are geometrically shaped and made of carbon-loaded foam. The shaping forms a geometric transition from free space to the lossy medium and the carbon causes most of the losses in the medium. In anechoic chambers, pyramidal and wedge-shaped absorbers are most commonly used. This kind of absorber usually provides at least 50 dB reduction in reflectivity at microwave frequencies. Pyramidal and wedge-shaped absorbers scatter more energy to the directions satisfying the grating equation, i.e. Bragg's equation as shown in [61] with measurements below 18 GHz. When the wedges are against the polarization, the absorber forms a reflection grid according to Bragg's equation

$$2d \sin\theta = n\lambda \qquad (4.1)$$

where d is the distance between wedges (i.e. parallel slits), θ is angle of the maxima, n is a integer, and λ is the wavelength. For pyramidal absorbers, a 2-dimensional (2-D) pattern can be found.

Specially designed anechoic materials have been manufactured for submillimeter wavelengths. The Submillimeter Technology Laboratory (STL) has developed silicone-based anechoic materials using wedge-type surface geometries for use at terahertz frequencies [58], [62]. They have developed a method for tailoring the complex refractive index for artificial dielectric materials. Vinyl acetate, silicone, polyethylene and epoxy resin have been combined with powdered loading agents such as boron nitride, silicon, graphite, iron oxide and stainless steel flakes. Their commercial anechoic material called FIRAM is manufactured of iron oxide loaded silicone using cost efficient molding techniques, see Fig. 4.1. When the normal incidence and angles satisfying the grating equation are excluded, they promise an overall performance better than -60 dB (measured at 584 GHz) [58].

Space qualified Tessalating TeraHertz RAM for the 50 to 1000 GHz region is manufactured by Thomas Keating Ltd. [63]. TK THz RAM is made of carbon loaded polypropylene plastic. It is sold in small, 25 mm square tiles which clip together using integral pin and socket joints, see Fig. 4.1. It consists of small pyramids, i.e. it has a 2-D grating structure causing diffraction peaks to the angles satisfying the grating equation. It has very low monostatic scattering reflection, as low as -58 dB has been measured at STL [63]]. At 576 GHz the specular reflectivity has been measured to be -48.7 dB [14]. Thomas Keating Ltd. has also together with AEA Technology developed a calibrated hot load to be used as calibration load in radiometers. For this specially designed conical geometry reflectivity as low as -70 dB has

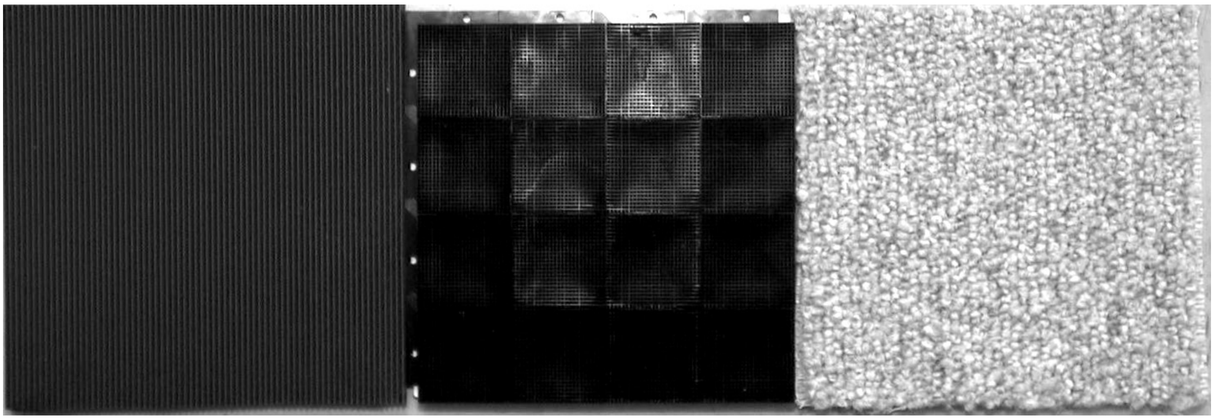


Fig. 4.1. FIRAM (left), TK THz RAM (middle) and polyamide floor carpet.

been measured at 406 GHz [64]. This kind of absorber can be used only as a load absorber so reflectivity as low as this one cannot be expected from absorbers used in anechoic chambers.

Anechoic materials for submillimeter wavelengths are very expensive. When building a compact range for testing large antennas, the amount of absorbing material needed can be very large. For example, the approximated need for anechoic material when testing a 1.5 m reflector antenna in a hologram-based compact range is 500 m^2. In [58], reflectivity level around -40 dB has been measured for a wool carpet. Wool carpets usually are also quite expensive. Many carpets are made of polyamide or polypropylene. These are raw materials which have also been used in specially designed anechoics, even though combined with loading agents. These carpets are a very cost effective solution to the uncritical parts of the compact range. In P7, reflectivity below -40 dB was measured for a carpet made of polyamide. When using carpets as anechoic materials, the material has to be tested before use. The structure of the carpet has a great effect on its performance as radar absorbing material. Adding some loading agents has not been studied yet, but it could a way to improve their performance. In P7, seven different materials were tested using a monostatic configuration. Bistatic and specular measurements of the absorbers investigated here also have been carried out in MilliLab [65], [66].

4.2. Measurements and results

Reflectivity level of absorbing material can be measured in several ways. The selection of the measurement method depends on the application were the data and the absorber is needed. When designing radar absorbing materials, the material basic characteristics and electromagnetic characteristics need to be known. Also the manufacturing process affects the properties so they must be verified with measurements. The relative permeability and permittivity can be measured using transmission lines, resonant cavities or admittance tunnels [45]. After knowing the material characteristics, the actual performance of the absorber still remains to be verified.

The reflectivity of absorbing material can be measured using free space methods, the NRL arch or a comparative RCS measurement. While using the NRL arch, the bistatic reflectivity can be measured in the near field of the antenna/absorber. In the RCS method, the monostatic reflectivity is measured in far field conditions. When using absorbers in a compact range, we are interested in both bistatic and monostatic measurement results. Combining both of these results, we can design the absorber placement very precisely.

Since bistatic measurements had been conducted for the absorbers of interest before, in this work the RCS method was selected for testing the absorbers in more realistic, i.e. far field conditions. The RCS measurement range described in Chapter 3 and in P6 was used to generate the needed plane-wave region. The absorber sample was placed on a support column made of extruded polystyrene foam and an aluminum plate was placed behind it to give the reference level to the measurement. The reflectivity level was measured from normal incidence to 45º.

FIRAM, TERASORB, TK THz RAM, Eccosorb VFX-NRL-2 and three carpets were tested. The results are not directly comparable with tests reported in literature since the frequency is different. Though, they are well in line with those presented in [14], [58], [64]. The order of superiority is the same as in [66] with the exception of Eccosorb which was now measured with the pyramids. TK THz RAM was found to have the best performance, around -60 dB. Eccosorb performed also surprisingly well for an absorber which is designed for lower millimeter wavelengths. The attenuation was better than -50 dB to all angles. Eccosorb used in these measurements was unpainted so carbon dust might cause problems in some applications. TERASORB and FIRAM are both designed for frequencies higher than the measurement frequency here, and they did not perform very well in these tests. Their performance is also polarization dependent. Carpets performed surprisingly well, the reflectivity level was around -40 dB. The results of the tests have been described with more detail in P7.

There is still room for development of the measurements system. The absorber support system could be improved to ease the replacement of the absorber. Also the alignment system could be developed further. The significance of these issues will grow when moving upward in frequency. The goal is to make this kind of measurements also at 650 GHz in the future.

4.3. Error considerations

Repeatability of the measurement results is significant to the reliability. Possible reasons for repeatability problems are the joining of the sample and the metal backing plate, network analyser errors and sample positioning errors. Since the samples and the backing plate were not permanently joined, this interface was not perfect but there was some air in between. It was estimated that this error and also the network analyser errors were insignificant compared to sample positioning errors. The sample positioning accuracy was estimated to be better than 0.12˚.

The non-uniformity of the samples can cause uncertainty in the measurement results. It is very difficult to estimate the uniformity of the samples. General non-uniformity and anisotropy in a sample can cause greater measurement error than the violations of the infinite planar sample/ infinite plane wave assumption [67].

Diffraction from edges of the sample can cause error in the measurement results. If radiated power at the sample edges is significant, the transverse dimensions of the sample and the calibration plate must be identical [68] to minimize the perimeter diffraction errors. However, the quality of illuminating wavefront can be a greater source of error than the diffraction.

The minimum measurable reflectivity level of the system is limited by the reflectivity of the background. Therefore, it is essential that high quality RAM is used in the area behind the sample. Also a submillimetre-wave transparent target support should be used. Extruded polystyrene foam is a usual choice. Its lack of rigidity can cause problems if the weight of the calibration target and the sample are very different and they have to be changed in between. Here, since the calibration target is attached to the sample, this kind of problem does not exist.

4.4. Conclusion

The measurement campaign of radar absorbing materials was successful and the results can be used in the development of our compact antenna test range. We were able to measure reflectivity levels down to -70 dB. The results gave valuable new information on the monostatic performance of the anechoic materials. Especially the possibility to use low cost carpets as absorbing materials is interesting. Comparing these results to previous results was possible only partly. However, the results obtained during this research are well in line with the previous results, supplementing them with new, useful information.

5. Summary of publications

Paper [P1] describes the development of hologram manufacturing. Several manufacturing methods were tested and also effect of joining hologram from several pieces was studied. Several different manufacturing techniques were studied; the conventional printed circuit board (PCB) process, wet etching with laser exposure, laser etching and laser-assisted chemical liquid phase deposition (LCLD). Wet etching with laser exposure was found to have highest potential for manufacturing holograms. Of the joining methods investigated, soldering was found to have smallest effect on the quiet-zone field quality; the alignment of the pieces was found to be the limiting factor.

Paper [P2] describes the development work of hologram-based compact antenna test range at 322 GHz. A large reflector antenna was tested in the CATR which was based on a 3-meter hologram. The CATR was a temporary setup. Only two months were needed for assembling the range, measuring an antenna, and disassembling the range. Scale model test results, manufacturing accuracy results, construction of the CATR instrumentation, the achieved quiet-zone field quality and the analysis of the quiet-zone test results are presented. This was the first time when a hologram-based compact antenna test range was used for measuring antennas at submillimeter wavelengths. The work verifies that it is possible to transport the hologram to the satellite test site and build the CATR there. Therefore, transporting expensive satellites can be avoided. The hologram has a low manufacturing cost, which makes a custom-built CATR possible.

Paper [P3] presents the measurement results of the antenna measured in [P2] and the analysis of the measurement results. The analysis of the effect of the quiet zone quality and the effect of the deviations in the structure of the antenna under test to the antenna radiation pattern measurement result is also presented. Both co-polar and cross-polar radiation patterns were measured. The measurement of the co-polar radiation pattern was carried out at the vertical polarization and the main beam region was measured in two dimensions. The cross-polar pattern cuts were measured by changing the AUT receiver polarization to horizontal. The measured results correspond reasonably well with the simulated pattern.

Paper [P4] discusses the hologram CATR operation at 650 GHz. The feasibility of hologram-based compact antenna test range was demonstrated at 644 GHz. The design and the simulation and measurement results of two demonstrative holograms are described. The effect of the manufacturing inaccuracy of the hologram pattern to the quiet-zone field quality is simulated. Hologram-based compact range is found feasible for use at high submillimeter-wave frequencies.

Paper [P5] presents first stages of the development of phase-hologram-based test range. The radar cross section of two small spheres was measured to verify the range operation. The effect of the quiet-zone field quality to the measured RCS was also studied. It was noticed that the quiet-zone field quality can have a significant effect on the measurement result.

Paper [P6] presents the development of phase-hologram-based compact radar cross section measurement range. The range is intended for measuring scaled models of real targets. The phase hologram converts the feed horn radiation to a plane wave needed for RCS determination. The radar cross section of two objects, a cylinder and a missile-like target was both simulated and measured. The measurements were performed at 310 GHz using a monostatic configuration, where the identical receiving and transmitting corrugated horn antennas were placed on opposite sides of a dielectric slab working as a directional coupler. Power division of 3 dB was used in the design of the coupler. Continuous wave operation was used. The reflection from the target was separated from the background reflection by moving the target in the direction of the plane-wave propagation and Fourier transforming the data.

Paper [P7] discusses monostatic reflectivity measurements of radar absorbing materials in the compact range described in [P6]. Radar cross section method was used for determining the reflectivity of absorbing materials. The backscattered reflection was measured with horizontal and vertical polarizations in plane-wave conditions and transmission was also studied. The reflectivity was measured over an incidence angle of 0º-45º. Seven different materials were studied, four commercial absorber materials and three carpet materials. The results agree well with those obtained in the previous studies of reflectivity and complement them with new materials, frequency and angle information. Also some of the carpet materials were found to be suitable for use as absorbers in the less critical places of the CATR.

6. Conclusions and future work

Compact ranges based on amplitude and phase holograms have been developed and shown to be applicable at submillimeter wavelengths. This thesis comprises of the development of two different compact ranges, one for antenna measurements and another for RCS measurements.

An amplitude hologram-based compact range has been used for testing of a 1.5 m reflector antenna at 322 GHz. The measurement campaign was successful as a first demonstration of the hologram CATR for testing of large reflector antennas at submillimeter wavelengths. For this purpose, a 3 meter hologram was needed and a method for producing and joining large-sized amplitude holograms has been developed. The results are described in this thesis and in P1, P2, and P3. The operation of hologram CATR was also verified at 650 GHz with a small test setup having a 1 m hologram [P4]. Future activities will look into applying the hologram CATR principle at even higher frequencies.

A phase-hologram-based compact range has been demonstrated for measuring RCS of target models and reflectivity level of radar absorbing materials at the submm-wave region (310 GHz). The measurements were performed using a monostatic configuration with a vector network analyzer as instrumentation. A dielectric slab was used as the directional coupler needed in the monostatic configuration. The results are very promising. The same range has been used for monostatic measurements of absorbing materials at 310 GHz. These results can also be used for the development of compact antenna test range. The work and the development have been described in this thesis and in papers P5, P6 and P7.

The development of a compact antenna test range at 650 GHz is continuing. The objective is to test a 1.5 m class reflector antenna with a same kind of CATR as has been done in this work. The instrumentation has been developed, quiet-zone scanner made more accurate and design method of holograms has been improved to overcome the problems noticed during the work described in this thesis. Results of scale model tests are very promising. Dual polarization operation has also been studied [69].

Development of phase-hologram-based compact range is going on and there are also initial plans to start working at 650 GHz. Improvement of the phase hologram itself would be beneficial. Better quiet-zone field quality would enable more accurate measurements. Also cross-polarization performance of the whole system could be improved. So far, no cross-polarization data have been measured. According to the simulations, the cross-polarization level of targets used here is below -48 dBsm so the cross-polarization cannot be measured with the current setup. In the future, this could be achieved by using wire grids to clear up the polarization and using a proper cross-polarization calibration with a disk and dihedral. Also manufacturing accuracy of the target can be improved. When doing scale model measurements, the accuracy of the model target is critical to the accuracy of the results.

In the future, making also bistatic measurements in far field conditions would be of interest. With a phase hologram setup containing two holograms on moving axis this would be possible. This system could be used for both radar cross section measurements and radar absorbing material reflectivity level measurements to acquire better understanding of the scattering behaviour of the absorber/target. Also the cross polarization performance of absorbers/targets should be tested. Low reflectivity/RCS may be due to energy transforming from one polarization to another. Furthermore, getting larger samples of the materials to the tests or a smaller quiet-zone diameter would eliminate the effect of diffraction from the edges of the absorber sample / back plate showing in the measurement results.

The results of this thesis have been presented in several scientific papers both in journals and conferences. The work ranges from the development of manufacturing methods to the development of measurement methods and scattering studies, all done at submillimeter wavelengths. The results give new scientific information and possible new applications on these areas. The amplitude hologram can be expected to work properly at least up to 1 THz with the currently available materials. It would be possible to test for example Planck telescope in such a compact range. The phase hologram provides interesting possibilities for radar cross section measurements, both in military and commercial applications.

References

[1] http://sci.esa.int/science-e/www/area/index.cfm?fareaid=17

[2] http://sci.esa.int/science-e/www/area/index.cfm?fareaid=16

[3] http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=35061

[4] http://cfa-www.harvard.edu/swas

[5] H. L. Nordh, et al., "The Odin orbital observatory", *Astronomy & Astrophysics*, vol. 402, no. 3, pp. L21-L25, May 2003.

[6] J. Ala-Laurinaho, T. Hirvonen, P. Piironen, A. Lehto, J. Tuovinen, A.V. Räisänen, and U. Frisk, "Measurement of the Odin telescope at 119 GHz with a hologram type CATR", *IEEE Transactions on Antennas and Propagation*, vol. 49, no. 11, pp. 1264–1270, 2001.

[7] P. L. Yagoubov et al., "TELIS—Development of a new balloon borne THz/submm heterodyne limb sounder," Proceedings of 14th International Symposium on Space Terahertz Technology, Tucson, Arizona, Apr. 2003. [Online]. Available: http://soral.as.arizona.edu/STT03/.

[8] Y. Irimajiri, T. Manabe, S. Ochiai, H. Masuko, T. Yamagami, Y. Saito, N. Izutsu, T. Kawasaki, M. Namiki, and I. Murata, "BSMILES - a balloon-borne superconducting submillimeter-wave limb-emission sounder for stratospheric measurements", *IEEE Geoscience and Remote Sensing Letters*, vol. 3, no. 1, pp. 88- 92, Jan. 2006.

[9] J. Tuovinen, A. Vasara, and A. Räisänen, "A new type of compact antenna test range", *Proceedings of the 22nd European Microwave Conference,* Espoo, vol. 1, 1992, pp. 503−508.

[10] T. Hirvonen, J. Ala-Laurinaho, J. Tuovinen, and A.V. Räisänen, "A compact antenna test range based on a hologram", *IEEE Transactions on Antennas and Propagation*, vol. 45, no. 8, pp. 1270−1276, 1997.

[11] T. Sehm, J. Ala-Laurinaho, T. Hirvonen, and A.V. Räisänen, "Antenna measurements using a hologram CATR", *Electronics Letters*, vol. 35, no. 10, pp. 757–758, 1999.

[12] J. Mallat, J. Ala-Laurinaho, E. Noponen, V. Viikari, A. Lönnqvist, T. Koskinen, J. Säily, J. Häkli, J. Meltaus, and A.V. Räisänen, "A phase hologram RCS range for scale model measurements", *Digest of Technical Papers, URSI/IEEE XXVII Convention on Radio Science*, Espoo, Finland, 2002, (Report S 257, Helsinki University of Technology Radio Laboratory Publications), pp. 143−145.

[13] T. Koskinen, V. Viikari, J. Häkli, A. Lönnqvist, J. Ala-Laurinaho, J. Mallat, and A.V. Räisänen, "A reflection-type amplitude hologram as a collimating element in compact antenna test range", *Proceedings of the 27th Annual Antenna Measurement Techniques Association (AMTA) Meeting & Symposium*, Newport, RI, USA, Oct. 30 – Nov. 4, 2005, pp. 417–421.

[14] A. Murk, N. Kämpfer, and N.J. Keen, “Baseline measurements with a 650 GHz radiometer”, *Proceedings of 2nd Workshop on Millimeter Wave Technology and Applications: Antennas, Circuits and Systems,* MilliLab, Espoo, Finland, 27-29 May 1998, pp. 121–126.

[15] IEEE Standard Test Procedure for Antennas, IEEE Std 149-1979, IEEE Inc., 1979.

[16] A. Lehto and A.V. Räisänen, *Mikroaaltomittaustekniikka*, 4. edition, Otatieto Oy, Helsinki, 1999.

[17] G.E. Evans, *Antenna Measurement Techniques*, Artech House, Boston, 1990.

[18] P. R. Foster, D. Martin, C. Parini, A.V. Räisänen, J. Ala-Laurinaho, T. Hirvonen, A. Lehto, T. Sehm, J. Tuovinen, F. Jensen, and K. Pontoppidan, *Mmwave antenna testing techniques Phase 2*, MAAS Report 304, Issue No. 2, ESTEC Contract No. 11641/95/NL/PB(SC), December 1996.

[19] J. Tuovinen, “Methods for testing reflector antennas at THz frequencies”, *IEEE Antennas and Propagation Magazine*, vol. 35, no. 6, pp. 7−13, 1993.

[20] A.D. Olver and A.A. Saleeb, “Lens-type compact antenna range”, *Electronics Letters*, vol. 15, no. 14, pp. 409–410, 1979.

[21] T. Hirvonen, J. Tuovinen, and A. Räisänen, ”Lens-type compact antenna test range at mm-waves”, *Proceedings of the 21st European Microwave Conference*, Stuttgart, 1991, pp. 1079−1083.

[22] R.C. Johnson, H.A. Ecker, and R. A. Moore, “Compact range techniques and measurements”, *IEEE Transactions on Antennas and Propagation*, vol. AP-17, pp. 568−586, September 1969.

[23] E. Dudok, D. Fasold, and H.-J. Steiner, “Development of an optimized compact test range”, *Proceedings of 11th ESTEC Workshop on Antenna Measurement*, Gothenburg, Sweden,1988, ESA WPP-001, pp. 81−86.

[24] J. Habersack, W. Lindemer, and H.-J. Steiner, “High performance mm-wave measurements up to 200 GHz in the compensated compact range”, *Proceedings of the 2nd ESA Workshop on Millimeter Wave Technology and Applications: Antennas, Circuits and Systems,* WPP-149, Espoo, Finland, May 27-29, 1998, pp. 529−535.

[25] J.A. Hammer and J.T. Riera, “Mini compact antenna range at ESTEC”, *Proceedings of 11th ESTEC Workshop on Antenna Measurement*, Gothenburg, Sweden, 1988, ESA WPP-001, pp. 253−258.

[26] C. Parini, M. Rayner, and C. Rieckmann, “Design and construction of a 200 GHz demonstrator of a trireflector compact antenna test range with spherical main reflector”, *Proceedings of 22nd ESTEC Antenna Workshop on Antenna Measurements,* WPP-164, Netherlands, 1999, pp. 147−152.

[27] A.D. Olver, “Compact antenna test ranges”, *Proceedings of International Conference on Antennas and Propagation ICAP*, York, UK, 1991, pp. 99−109.

[28] Scientific Atlanta Inc., “The Compact Range”, *Microwave Journal*, vol. 17, no. 10, October 1974, pp. 30–32.

[29] W.-H. Lee, “Computer-generated holograms: Techniques and applications”, *Progress in Optics XVI*, E. Wolf (ed.), Elsevier, Amsterdam, 1978, pp. 121–231.

[30] J. Säily, J. Ala-Laurinaho, J. Häkli, J. Tuovinen, A. Lehto, and A.V. Räisänen, “Test results of 310 GHz hologram compact antenna test range”, *Electronics Letters*, vol. 36, no. 2, pp. 111–112, 2000.

[31] J. Meltaus, J. Salo , E. Noponen, M. M. Salomaa, V. Viikari, A. Lönnqvist, T. Koskinen, J. Säily, J. Häkli, J. Ala-Laurinaho, J. Mallat, and A.V. Räisänen, “Millimeter-wave beam shaping using holograms”, *IEEE Transactions on Microwave Theory and Techniques*, vol. 51, no. 4, pp. 1274–1280*,* Apr. 2003.

[32] A. D. Yaghjian, “An overview of near-field antenna measurements”, *IEEE Transactions on Antennas and Propagation*, vol. AP-34, no. 1, pp. 30–45, Jan. 1986.

[33] http://www.astrium.eads.net/corp/prod/00000983.htm

[34] J. Ala-Laurinaho, T. Hirvonen, and A.V. Räisänen, “On the planarity errors of the hologram of the CATR”, *Digest of 1999 IEEE Antennas and Propagation Society International Symposium*, vol. 3, 11–16 July, 1999, pp. 2166–2169.

[35] J. Ala-Laurinaho, T. Hirvonen, J. Tuovinen, and A.V. Räisänen, “Numerical modeling of a nonuniform grating with FDTD”, *Microwave and Optical Technology Letters,* vol. 15, no. 3, pp. 134–139, 1997.

[36] T. Koskinen, J. Ala-Laurinaho, J. Säily, J. Häkli, A. Lönnqvist, J. Mallat, J. Tuovinen, and A.V. Räisänen, “On the design of sub-mm wave amplitude holograms for CATR”, *Proceedings of the Thirteenth International Symposium on Space Terahertz Technology*, Cambridge, MA, USA, 2002, pp. 537–543.

[37] A. Lönnqvist, J. Mallat, E. Noponen, J. Ala-Laurinaho, J. Säily, T. Koskinen, J. Häkli, and A.V. Räisänen, “A phase hologram compact RCS range for scale model measurements”, *Proceedings of 3rd ESA Workshop on Millimeter Wave Technology and Applications*, Espoo, Finland, 21-23 May 2003, pp. 511−516.

[38] J. Hartmann, J. Habersack, H.-J. Steiner, J. Lemanczyk, and P. de Maagt, “Calibration and verification measurements in compensated compact ranges up to 500 GHz”, *Proceedings of the 23rd AMTA Symposium*, Denver, CO, USA, October 21–26, 2001, pp. 377–382.

[39] J. Hartmann, J. Habersack, H.-J. Steiner, Th. Rose, and P. Zimmermann, “Transmit and receive modules for measurement of future space applications in the terahertz region”, *Proceedings of the 23rd AMTA Symposium*, Denver, CO, USA, 2001, pp. 171–176.

[40] J. Säily, P. Eskelinen, and A.V. Räisänen, “Pilot signal based real-time measurement and correction of phase errors caused by microwave cable flexing in planar near-field tests”, *IEEE Transactions on Antennas and Propagation*, vol. 51, no. 2, pp. 195–200, Feb. 2003.

[41] V. Viikari, J. Häkli, J. Ala-Laurinaho, J. Mallat, A. V. Räisänen, "A feed scanning based APC technique for compact antenna test ranges", *IEEE Transactions on Antennas and Propagation*, vol. 53, no. 10, pp. 3160 – 3165, Oct. 2005.

[42] V. Viikari, J. Mallat, J. Ala-Laurinaho, J. Häkli, A. V. Räisänen, "A frequency shift technique for pattern correction in hologram-based CATRs", accepted for publication in *IEEE Transactions on Microwave Theory and Techniques* [appears in October 2006].

[43] J. Salo, J. Meltaus, E. Noponen, J. Westerholm, M.M. Salomaa, A. Lönnqvist, J. Säily, J. Häkli, J. Ala-Laurinaho, and A.V. Räisänen, "Millimeter-wave Bessel beams using computer holograms", *Electronics Letters*, vol. 37, no. 13, pp. 834–835, 2001.

[44] J. Salo, J. Meltaus, E. Noponen, M.M. Salomaa, A. Lönnqvist, T. Koskinen, V. Viikari, J. Säily, J. Häkli, J. Ala-Laurinaho, J. Mallat, and A.V. Räisänen, "Holograms for shaping radio-wave fields", *Journal of Optics A: Pure and Applied Optics,* pp. S161–S167, 2002.

[45] E.F. Knott, J.F. Shaeffer, and M.T. Tuley, *Radar Cross Section*, 2nd edition, Artech House, Norwood, 1993.

[46] R.B. Dybdal, "Radar cross section measurements", *Proceedings of the IEEE,* vol. 75, no. 4, pp. 498–516, April 1987

[47] E.K. Walton and J.D. Young, "The Ohio state university compact radar cross-section measurement range", *IEEE Transactions on Antennas and Propagation*, vol. 32, no. 11, pp :1218–1223, Nov. 1984.

[48] R. Dybdal and C. Yowell, "Millimeter wavelength radar cross section measurements", *Antennas and Propagation Society International Symposium*, vol. 11, Aug 1973, pp. 49–52.

[49] M.J. Coulombe, T. Ferdinand, T. Horgan, R. H. Giles, and J. Waldman, "A 585 GHz compact range for scale model RCS measurements", *Proceedings for the Antenna Measurements and Techniques Association AMTA 93*, Dallas, TX, October 1993, pp. 129−134.

[50] M. J. Coulombe, T. Horgan, J. Waldman, G. Szatkowski, and W. Nixon, "A 524 GHz polarimetric compact range for scale model RCS measurements", *Proceedings of 21st Annual Meeting and Symposium AMTA 99*, Monterey Bay, California, October 4–8, 1999, pp. 458–463.

[51] D.G. Falconer, "Extrapolation of near-field RCS measurements to the far zone", *IEEE Transactions on Antennas and Propagation*, vol. 36, no. 6, pp. 822–829, June 1988.

[52] B.J. Cown and C.E. Ryan Jr., "Near-field scattering measurements for determining complex target RCS", *IEEE Transactions on Antennas and Propagation*, vol. 37, no. 5, pp. 576–585, May 1989.

[53] J.W. Odendaal and J. Joubert, "Radar cross section measurements using near-field radar imaging", *IEEE Transactions on Instrumentation and Measurement*, vol. 45, no. 6, pp. 948–954, Dec. 1996.

[54] I.J. LaHaie, “Overview of an image-based technique for predicting far-field radar cross section from near-field measurements”, *IEEE Antennas and Propagation Magazine*, vol. 45, no. 6, pp. 159–169, Dec. 2003.

[55] O.M. Bucci and M.D. Migliore, “Effective estimation of 2-D monostatic radar cross sections from near-field measurements”, *IEEE Transactions on Antennas and Propagation*, vol. 54, no. 2, Part 2, pp. 750–752, Feb. 2006.

[56] E. Noponen, J. Häkli, T. Koskinen, A. Lönnqvist, V. Viikari, J. Ala-Laurinaho, J. Mallat, and A.V. Räisänen, ”Synthesis of refection-type phase hologram for compact antenna test range at 310 GHz”, *Proceedings of 4th ESA Workshop on Millimeter-Wave Technology and Applications*, Espoo, Finland, 15-17 February 2006, pp. 391–396.

[57] K. Bober, R. H. Giles, and J. Waldman, “Tailoring the microwave permittivity and permeability of composite materials”, *International Journal of Infrared and Millimeter Waves,* vol. 18, no. 1, pp. 101–123, 1997.

[58] R.H. Giles, A.J. Gatesman, J. Fitz-Gerald, S. Fisk, and J. Waldman, “Tailoring artificial dielectric materials at terahertz frequencies”, *The Fourth International Symposium on Space Terahertz Technology*, Los Angeles, CA, April 1993, pp. 124–133.

[59] A.J. Gatesman, T.M. Goyette, J.C. Dickinson, R.H. Giles, J. Waldman, J. Sizemore, R.M. Chase, and W.E. Nixon,"Polarimetric backscattering behavior of ground clutter at X, Ka, and W-band", *Proceedings of SPIE*, *Algorithms for Synthetic Aperture Radar Imagery XII*; Edmund G. Zelnio, Frederick D. Garber; Eds., Vol. 5808, May 2005, pp. 428–439

[60] http://www.feko.info/

[61] B.T. DeWitt and W.D. Burnside, “Electromagnetic scattering by pyramidal and wedge absorber”, *IEEE Transactions on Antennas and Propagation*, vol. 36, no. 7, pp. 971–984, July 1988.

[62] http://stl.uml.edu/research/materials.html#millimeter

[63] http://www.terahertz.co.uk

[64] A. Murk, N. Kämpfer, and N.J. Keen, “Baseline issues in an airborne 650 GHz radiometer”, *COST-712 Workshop on Microwave Techniques in Meteorology*, 9./10. Bern, Dec. 1999, pp. 42 – 51.

[65] J. Säily, J. Mallat, and A.V. Räisänen, “Reflectivity measurements of various commercial absorbers at millimetre and submillimetre wavelengths”, *Electronics Letters*, vol. 37, no. 3, pp. 143–145, 2001.

[66] J. Säily and A.V. Räisänen, “Characterization of submillimeter wave absorbers from 200-600 GHz”, *International Journal of Infrared and Millimeter Waves*, vol. 25, no. 1, pp. 71–88, 2004.

[67] F.C. Smith, “A review of UK facilities for characterizing the performance of radar absorbing material (RAM)”, *Proceeding of Ninth International Conference on*

Antennas and Propagation, ICAP '95 (Conf. Publ. No. 407), Eindhoven, 4-7 Apr. 1995, vol.1, pp. 445–449.

[68] F.C. Smith, B. Chambers, and J.C. Bennett, "Methodology for accurate free-space characterisation of radar absorbing materials" *IEE Proceedings on Science, Measurement and Technology*, vol. 141, no. 6, pp. 538–546, Nov. 1994.

[69] T. Koskinen, J. Häkli, J. Ala-Laurinaho, A. Lönnqvist, V. Viikari, J. Mallat, and A.V. Räisänen, "Study on the dual polarized operation of the hologram-based compact antenna test range," *Proceeding of the 28th ESA Antenna Workshop on Space Antenna Systems and Technologies*, ESTEC, Noordwijk, The Netherlands, May 31 – June 3, 2005, pp. 401–406.