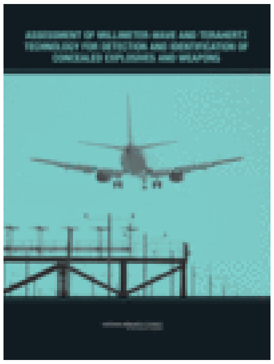

Assessment of Millimeter-Wave and Terahertz Technology for Detection and Identification of Concealed Explosives and Weapons

Committee on Assessment of Security Technologies for Transportation, National Research Council

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THE NATIONAL ACADEMIES
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ASSESSMENT OF MILLIMETER-WAVE AND TERAHERTZ TECHNOLOGY FOR DETECTION AND IDENTIFICATION OF CONCEALED EXPLOSIVES AND WEAPONS

Committee on Assessment of Security Technologies for Transportation
National Materials Advisory Board
Division on Engineering and Physical Sciences

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This study was supported by Contract No. DTFA03-99-C-00006 between the National Academy of Sciences and the Transportation Security Administration. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

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EMILY ANN MEYER, Study Director (from November 2006)
TERI G. THOROWGOOD, Administrative Coordinator

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[1] Dr. Daly passed away in April 2006.

[2] Dr. Janata resigned from the committee in April 2006.

[3] Mr. Rowe recused himself from all dealings with this report due to a potential conflict of interest.

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Preface

The Committee on Assessment of Security Technologies for Transportation was appointed by the National Research Council (NRC) in response to a request from the Transportation Security Administration (TSA) for a study of technologies to protect the nation's air transportation system from attacks by terrorists and others of like mind. The committee judged that the best way to provide a timely response would be to produce a series of short reports on promising technologies, focusing on specific topics of greatest interest to the sponsor. This is the third of four such topical reports, all of which focus on air transportation security.[1] The committee believes that the air transportation

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[1] The first report was *Opportunities to Improve Airport Passenger Screening with Mass Spectrometry* (The National Academies Press, Washington, D.C., 2004). The second report was *Defending the U.S. Air Transportation System Against Chemical and Biological Threats* (The National Academies

environment provides a test case for the deployment of security technologies that could subsequently be used to protect other transportation modes as well.

This report focuses on the currently maturing millimeter-wavelength and terahertz imaging and spectroscopy technologies that offer promise in meeting aviation security requirements through airport screening. The millimeter-wave through the terahertz region is now the subject of aggressive university research driven by the availability of short-pulse generators, which produce a wide spectrum of frequencies through this region. The committee believes that millimeter-wave/terahertz technology has potential for contributing to overall aviation security but that its limitations must be recognized. In light of some common misconceptions, the committee decided that this report should briefly and systematically address expectations, both real and fictional, and help bring into focus cases in which this technology has promise and instances in which it offers no potential benefit as an antiterrorism technology. Additionally, although there are many potential long-range uses for this technology, the committee's assessment focuses primarily on the near-term uses to interdict imminent threats.

Historically the millimeter band extended from 30 GHz to 300 GHz and the submillimeter band extended from 300GHz to 3 THz. In the current literature the terahertz region has subsumed the submillimeter band and extended it to 10 THz. In this report the term "submillimeter" is used only to be consistent with historical citations.

The committee acknowledges the speakers from government and industry who took the time to share their ideas and experiences in briefings at the committee's meetings. The committee would like to offer a special thanks to two of its members, Richard McGee and H. Bruce Wallace, who were the major contributors to the writing of this report. Former committee member Thomas S. Hartwick, chair through May 31, 2005, also greatly assisted the work of the current committee through his participation in many of its activities. Finally, the committee acknowledges the contributions to the completion of this report from National Materials Advisory Board director Gary Fischman and NRC staff members James Killian and Teri Thorowgood.

James F. O'Bryon, *Chair*
Sandra L. Hyland, *Vice Chair*
Committee on Assessment of Security
Technologies for Transportation

Press, Washington, D.C., 2006). The fourth and final topic to be addressed will be fusion of data to improve airport security.

Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Eliot D. Cohen, EBCO Technology Advising, Inc.,
Angela Gittens, HNTB,
Erich N. Grossman, National Institute of Standards and Technology, Boulder,

Eddie Jacobs, U.S. Army, Research Development and Engineering Command,
Samuel H. Moseley, Jr., NASA Goddard Space Flight Center,
Andrew Poggio, Lawrence Livermore National Laboratory, and
James C. Wiltse, Georgia Tech Research Institute.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Steve Berry, University of Chicago. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests solely with the authoring committee and the institution.

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In Memoriam

The members of the Committee on Assessment of Security Technologies for Transportation are deeply saddened by the recent loss of one of the committee's members. John B. Daly had a distinguished career serving the nation in a broad range of positions involving transportation security and technology, and he was the recipient of numerous awards and commendations for his outstanding contributions to the field. He was appointed to this committee in 2005 and continued to serve with distinction until his illness no longer permitted his participation. He was a hardworking professional of the highest integrity. We dedicate this report to his memory as a token of our appreciation for his contributions.

Executive Summary

The security of the U.S. commercial aviation system has been a growing concern since the 1970s when the hijacking of aircraft became a serious problem. Since the early days of screening airline passengers, the aviation security system has grown increasingly complex and comprehensive. Current protocols include the screening of passengers and their carry-on baggage for threat items that could be used to damage the aircraft or threaten the crew and passengers and the screening of passengers' checked baggage for items that could damage the aircraft. While many threats exist in the nation's transportation infrastructure, the Committee on Assessment of Security Technologies for Transportation focused this effort on the aviation security portion of the U.S. national infrastructure because, with the air transportation environment's more controlled passenger access and its experience with passenger screening, the committee believes that the air transportation environment can serve as a ready testbed for assessing screening technologies that might be extended or modified for use in securing other transportation modes.

Prior to the terrorist bomb that brought down Pan Am Flight 103 over Lockerbie, Scotland, in December 1988, the focus of airline passenger security checkpoints was the detection and interdiction of metallic weapons, either carried on the person or concealed within carry-on items. Since the introduction in 1994 of certified explosive detection systems for checked luggage, a technology based on computed x-ray tomography, explosive threat detection has significantly improved.

While potential attacks on all modes of transportation are of concern, the committee believes that the U.S. air transportation system continues to have a high priority for counterterrorism resources, both because of its economic importance and because of the intensified public perception of risk following the September 11, 2001, attacks.

The Transportation Security Administration (TSA) provided the National Research Council (NRC) with the following statement of task for this study:

> This study will explore opportunities for technology to address national needs for transportation security. While the primary role of the committee is to respond to the government's request for assessments in particular applications, the committee may offer advice on specific matters as required. The committee will: (1) identify potential applications for technology in transportation security with a focus on likely threats; (2) evaluate technology approaches to threat detection, effect mitigation, and consequence management; and (3) assess the need for research, development, and deployment to enable implementation of new security technologies. These tasks will be done in the context of current, near-term, and long-term requirements.
>
> The committee will perform the following specific tasks:
>
> 1. Identify potential applications for technology in transportation security with a focus on likely threats derived from threat analyses that drive security system requirements. Review security system developments structured to meet the changing threat environment. Assess government and commercial industry plans designed to address these threats.
> 2. Evaluate technology approaches to threat detection, effect mitigation, and consequence management. Delineate the benefits of the insertion of new technologies into existing security systems. Evaluate the trade-offs between effectiveness and cost, including the cost of changing the security system architectures.
> 3. Assess the need for research, development, and deployment to enable implementation of new security technologies. Review and assess the potential benefit of existing and advanced detection technologies, including scanning technologies, sensing technologies, and the use of computer modeling and databases. Review and assess emerging approaches to effect mitigation and consequence management.

An overarching goal of this committee has been to provide timely reports that meet the technology-evaluation priorities of the Transportation Security Administration for defeating terrorist threats. The committee judged that this could best be done by issuing a series of short reports, of which this report is the third.

This report focuses on maturing millimeter-wave and terahertz imaging and spectroscopy technologies that may offer promise in meeting aviation security requirements. The committee considered the spectrum often mistakenly referred to as the terahertz region to encompass the radio frequencies from 10 GHz to 10,000 GHz, the latter being the top of the true terahertz region (10,000 GHz or 30 micron wavelength). When referring to this entire spectrum, the committee has chosen the nomenclature “millimeter wavelength/terahertz.”

To assess the potential for millimeter-wavelength/terahertz technologies to detect weapons and explosives in an airport screening environment, the committee examined four aspects of the problem:

1. The currently available phenomenology associated with the atmosphere, concealing materials, and materials to be detected;
2. The maturity of electronic and electro-optic components;
3. The suite of millimeter-wavelength/terahertz scanning systems currently undergoing development; and
4. A potential implementation strategy for the Transportation Security Administration (TSA).

BACKGROUND

The sense of urgency about addressing emerging terrorist threats and the availability of funds to develop potential technologies to address these threats have combined to elicit a plethora of proposals for funding. However, the committee believes that there has been significant overselling of the potential of these technologies to address screening requirements. Proposals that are not well founded on the principles of physics or that are driven by those who lack a sound understanding of the technology and its strengths and limitations appear to exaggerate the potential benefits of millimeter-wavelength/terahertz technology as being more widely applicable to security screening than it is.

The electromagnetic spectrum from submillimeter wave through terahertz can be used both to create an image of an object by measuring the intensity of reflected or emitted energy and to gather information on the chemical makeup of an object by measuring the absorption of electromagnetic energy. There are two general classes of millimeter-wavelength/terahertz imaging techniques examined in this report: passive and active.

Passive imaging detection techniques rely on collecting naturally occurring radiation and using the contrast between apparently “warmer” and “colder” objects, which usually results from contrasts between the emissivities of different materials. For example, millimeter-wavelength/terahertz technologies are being examined for their ability to detect metal guns concealed underneath clothing by detecting the contrast between the warmer human body and the apparently cooler metal weapon.

Active imaging systems illuminate the detection space with a beam of millimeter-wavelength/terahertz power, either by illumination of the entire space or as a focused beam scanned over the object, with detectors specifically sensitive to the illuminating frequencies. Although millimeter-wavelength/terahertz energy passes through typical clothing materials, this non-ionizing energy penetrates the human body to only about skin depth. Therefore, the potential health effects of this radiation are significantly lower than those from the competitive imaging technology using ionizing x-rays, although the general population may not fully understand this.

There are debates about the relative quality of imagery from a passive versus an active imaging system. The active system has an advantage, however, in that it can illuminate people and objects with the amount of power sufficient to penetrate materials, whereas a passive system must rely on the natural radiation, which is much lower intensity. Some portal-type[1] active systems have already demonstrated the capability of providing sufficient information to locate and identify concealed items on people.

The terahertz region is now the subject of aggressive university research driven by the availability of short-pulse generators that can produce a wide spectrum of frequencies through this region. These short-pulse generators are being used as sources for collecting broadband spectral features of solid materials as well as in performing slow imaging experiments. As frequencies increase, spectral features of solid materials of interest become more apparent, but the ability to penetrate materials, a desirable feature for the identification of concealed objects, is reduced.

The hope for transportation security is that millimeter-wavelength/terahertz energy may provide detection and identification capability for explosive materials concealed underneath a person's clothing or in nonmetallic baggage. The challenge to detecting and classifying the spectra of explosive materials is that they are not as clearly defined as the spectra from gaseous materials and may be difficult to discern through the atmosphere or through other benign materials that may have their own spectral features. So while there appear to be some unique spectral features of explosive materials in the millimeter-wavelength/terahertz spectrum, conducting screening without corroboration with other sensor modalities could prove to be difficult in other than very controlled situations.

In addition to having the capability of imaging concealed objects, a millimeter-wavelength/terahertz imager also has the capability of revealing some anatomical features of the individuals being screened. In the United States, displaying detailed anatomical features of a person is considered a violation of that individual's privacy. The issue of whether the acquisition of an image with anatomical detail, even though the image is never publicly displayed, needs to be addressed rigorously by experts in the legal, human factors, and psychology areas.

CONCLUSIONS

As a result of this study, the committee concluded the following:

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[1] A system through which a passenger passes.

1. The technology base for millimeter-wavelength/terahertz security screening is expanding rapidly internationally, yet there is insufficient technology available to develop a system capable of identifying concealed explosives.
2. Millimeter-wavelength/terahertz technology has potential for contributing to overall aviation security, but its limitations need to be recognized. It will be most effective when used in conjunction with sensor technologies that provide detection capabilities in additional frequency regions.
3. Millimeter-wavelength/terahertz technology in portal applications has been demonstrated for detecting and identifying objects concealed on people.
4. Millimeter-wavelength/terahertz image quality raises personal privacy issues that need to be addressed.
5. Millimeter-wavelength/terahertz technology and x-rays provide images of similar quality. However, millimeter-wavelength/terahertz energy has the safety benefit of being non-ionizing radiation, while x-rays are ionizing radiation. Millimeter-wavelength/terahertz energy cannot penetrate metal objects.
6. Universities, national laboratories, and the commercial sector (both national and international businesses) continue to increase investment in millimeter-wavelength/terahertz technologies for security, medical, nondestructive inspection, and manufacturing quality-control applications.
7. A decision by the TSA to invest in an imaging portal depends on the potential threat posed by passengers carrying either weapons or explosives or other material. The cost of a system, the probability of detection, the false-alarm rate, and the throughput versus that of a competing x-ray system would impact the management decision.

RECOMMENDATIONS

Building on the conclusions presented above, the committee makes the following recommendations to the Transportation Security Administration regarding the application of millimeter-wavelength/terahertz technology to security screening.

1. To perform an accurate assessment of the applicability of millimeter-wavelength/terahertz-based technology to explosive detection, the TSA will need to do the following: (1) decide on the range of materials to be detected, (2) assess the state of knowledge of what chemical structures and/or features of the scope of materials lend themselves to detection by millimeter-wavelength/terahertz-based spectroscopy, (3) assess the presence of these features in other common materials (such as clothing) within the range of uncertainty for such features, and (4) assess the contribution of additives to explosives to the millimeter-wavelength/terahertz signature.
2. The TSA should examine how millimeter-wavelength/terahertz technology can be employed with other technologies to enhance the detection of weapons and explosives.

3. The TSA should commence developmental and operational testing of millimeter-wave-based portals to assess their effectiveness and suitability.
4. As with x-ray-based passenger imaging, the TSA needs to address issues associated with personal privacy raised by millimeter-wavelength/terahertz imaging.
5. The TSA should actively pursue joint projects through agreements such as cooperative research and development agreements with industry, academia, the Department of Defense, and the national laboratories to benefit from their investments in millimeter-wavelength/terahertz technology and applications.
6. The TSA should follow a two-pronged investment strategy:
    - Focus on millimeter-wave imaging as a candidate system for evaluation and deployment in the near term, and
    - Invest in research and development and track national technology developments in the terahertz region.

1

Introduction

BACKGROUND

The security of the U.S. commercial aviation system has been a concern since the 1970s when hijacking became a serious problem. A number of aviation security programs have been implemented at public airports throughout the United States. However, weaknesses continue to exist. These weaknesses were observed and exploited by terrorists on September 11, 2001, enabling them to hijack four commercial aircraft, with tragic results. Terrorists and others with similar intent can be expected to continue to examine transportation security operations, both overtly and covertly, to find weaknesses that can be exploited.[1]

With hundreds of commercial airports, thousands of commercial aircraft, tens of thousands of daily flights, and millions of passengers using the system daily, providing security to the nation's commercial aviation system is clearly a daunting challenge. Figure 1-1 illustrates some of the threat vectors that may exist in the nation's largest airports. At the security checkpoint,[2] different kinds of screening are used for passengers and for carry-on luggage.

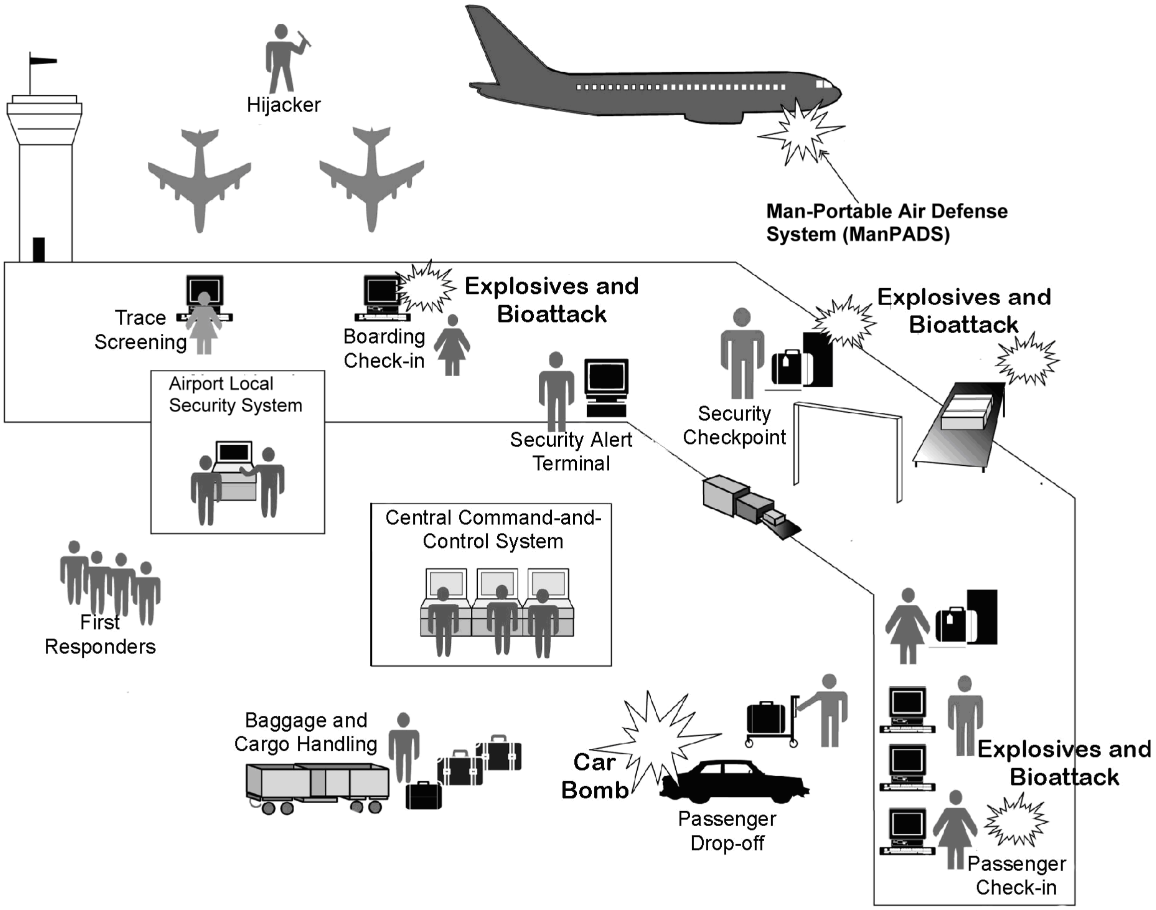

FIGURE 1-1 Generic airport diagram showing various airport spaces and some likely sites for attacks. Certain locations are particularly vulnerable to a terrorist attack by explosion or release of chemical and biological agents; these are shown by the explosion symbol and the type of threat in boldface type near that symbol.

Prior to the terrorist bomb that brought down Pan Am Flight 103 over Lockerbie, Scotland, in December 1988, the focus of airline passenger security checkpoints was the detection and interdiction of metallic weapons, either carried on the person or concealed

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[1] Al Qaeda Training Manual. Available at http://www.fas.org/irp/world/para/manualpart1.html. Accessed June 25, 2006.

[2] "Security checkpoint" is the term that the Transportation Security Administration uses to describe the point at which passengers and their carry-on baggage are checked.

within carry-on items. Security equipment included transmission x-ray systems for carry-on bags and walk-through metal detectors for passengers. However, with this tragic event, the focus immediately turned to technologies capable of also interdicting explosives devices in carry-on and checked bags. Since the introduction in December 1994 of the first certified explosive detection systems (EDSs) for checked luggage, a technology based on computed x-ray tomography, explosive threat detection has significantly improved. Furthermore, the development and insertion of threat image projection capability into security systems such as those used for scanning passenger carry-on bags have also served to improve screener performance and awareness.

On November 19, 2001, President George W. Bush signed into law the Aviation and Transportation Security Act (ATSA) (Public Law No. 107-071), which mandated the federalization of passenger and baggage screening at more than 440 commercial airports in the United States by November 19, 2002, and the EDS screening of all checked baggage. On March 1, 2003, the Transportation Security Administration (TSA) was transferred from the Department of Transportation to the newly created Department of Homeland Security, as required by the Homeland Security Act of 2002 (Public Law No. 107-296). Virtually all aviation security responsibilities are assigned to the TSA. These responsibilities include conducting passenger and baggage screening and overseeing security measures for airports, commercial aircraft, air cargo, and general aviation. The TSA programs dealing with these matters are intended to form a layered system that maximizes the security of passengers, aircraft, and other elements of the aviation infrastructure.

The TSA has undertaken several programs to measure and improve the performance of passenger screeners in the detection of threat objects. In March 2004, the General Accounting Office (now the Government Accountability Office) completed a study of the performance of the passenger-screening system that identified numerous performance deficiencies, such as inadequate staffing and poor supervision of screeners. These deficiencies in performance were the result of a lack of skills and knowledge, low motivation, an ineffective work environment, and wrong or missing incentives. The TSA is taking steps to remedy these deficiencies, and although it is making progress in its checked-baggage screening operations, it continues to face technical, operational, and funding challenges in accomplishing the EDS screening of all checked and carry-on baggage as mandated by ATSA.[3]

The 9/11 Commission Report,[4] issued in 2004, recommended that the Transportation Security Administration and the Congress improve the way screeners look for explosives at airports. “As a start, each individual selected for special screening should be screened for explosives.” Former Navy Secretary John Lehman, a member of that commission, told the House Aviation Subcommittee that the prospect of suicide bombers boarding U.S. aircraft is “a very real threat.” He said that it is more likely now

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[3] U.S. Government Accountability Office. 2004. Aviation Security: Improvement Still Needed in Federal Aviation Security Efforts. GAO-04-592T. Washington, D.C. Available at http://www.gao.gov/cgi-bin/getrpt?GAO-04-592T. Accessed June 25, 2006.

[4] Available at http://www.9-11commission.gov/report/index.htm. Accessed June 25, 2006.

that terrorists will try to smuggle explosives aboard U.S. airplanes because commercial airplanes have been made more secure against other threats.[5]

Current requirements for the security screening of passengers were developed in response to an increase in hijackings prior to 1972. Inspection systems at airport security checkpoints include metal detectors for passengers and x-ray systems for hand-carried items. While effective, these systems have shortcomings, including the inability to address evolving threats. The current x-ray inspection and trace-explosive screening, or swabbing, of carry-on baggage provide some limited capability against explosives in luggage and carry-on items, although in effect this capability may be more a matter of deterrence than of detection. Conventional metal detectors are usually limited in capability to detecting metal targets, such as ordinary handguns and knives. The effectiveness of these detectors can vary depending on the size, shape, orientation, and type of material of the object in question. Furthermore, because no discrimination is possible between simple, innocuous metallic items (e.g., eyeglasses, belt buckles, keys, coins, and prostheses) and actual threats, a high number of nuisance alarms occurs. Possible threats have evolved to include plastic or ceramic handguns and knives as well as explosives, none of which are detectable with metal detectors.

STATEMENT OF TASK

The Transportation Security Administration provided the National Research Council (NRC) with the following statement of task for this study:

> This study will explore opportunities for technology to address national needs for transportation security. While the primary role of the committee is to respond to the government's request for assessments in particular applications, the committee may offer advice on specific matters as required. The committee will: (1) identify potential applications for technology in transportation security with a focus on likely threats; (2) evaluate technology approaches to threat detection, effect mitigation, and consequence management; and (3) assess the need for research, development, and deployment to enable implementation of new security technologies. These tasks will be done in the context of current, near-term, and long-term requirements.
>
> The committee will perform the following specific tasks:
>
> 1. Identify potential applications for technology in transportation security with a focus on likely threats derived from threat analyses that drive security system requirements. Review security system developments structured to meet the changing threat environment. Assess government and commercial industry plans designed to address these threats.
> 2. Evaluate technology approaches to threat detection, effect mitigation, and consequence management. Delineate the benefits of the insertion of new technologies into existing security systems. Evaluate the trade-offs between

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[5] Leslie Miller. August 28, 2004. Most air passengers not screened for bombs. AP News. Available at http://209.157.64.200/focus/f-news/1201875/posts. Accessed November 17, 2006.

effectiveness and cost, including the cost of changing the security system architectures.

3. Assess the need for research, development, and deployment to enable implementation of new security technologies. Review and assess the potential benefit of existing and advanced detection technologies, including scanning technologies, sensing technologies, and the use of computer modeling and databases. Review and assess emerging approaches to effect mitigation and consequence management.

APPROACH OF THE COMMITTEE

An overarching goal of this committee has been to provide timely reports that meet the technology-evaluation priorities of the Transportation Security Administration for defeating terrorist threats. The committee judged that this could best be done by issuing a series of short reports. In consultation with the TSA, the committee selected the following four topics for review, of which this report is the third:

1. Opportunities to improve airport passenger screening with mass spectrometry,
2. Defending the U.S. air transportation system against chemical and biological threats,
3. Millimeter-wavelength and terahertz technology for the detection and identification of concealed explosives and weapons, and
4. Fusion of sensor data to improve airport security.

Taken together, these reports will satisfy the first part of the statement of task, which calls for an identification of applications for technology in transportation security. Individually, each report assesses its particular technology focus and identifies additional research needs.

By mutual agreement between the committee and the sponsor, the broad focus on "transportation security" in the statement of task was narrowed to the threat of attacks on the air transportation system. While potential attacks on all modes of transportation are of concern, the Committee on Assessment of Security Technologies for Transportation believes that the U.S. air transportation system continues to have a high priority for counterterrorism resources, both because of its economic importance and because of the intensified public perception of risk following the September 11, 2001, attacks. The air transportation system can also serve as a testbed for the development of defensive technologies and strategies that can subsequently be applied to other transportation modes.

SCOPE OF THE REPORT

The increasing level and variety of threats to transportation systems have resulted in an urgent search for effective security screening. The electromagnetic spectrum from radio frequencies up to gamma rays has been studied with varying degrees of success.

The region with wavelengths from approximately 3 mm to 12 μm has been investigated with somewhat limited success because of the lack of electromagnetic sources and detectors. The shortage of high-quality instrumentation has also resulted in limited reliable information about the properties of materials from which system performance can be estimated. As requested by the TSA, this report serves as an evaluation of the potential of millimeter-wavelength and terahertz technology for threat detection and as an assessment of the research needed to bring this promising technology into wide-scale use.

There has been widespread misuse of the term "terahertz" owing to the significant interest in what terahertz technology might potentially achieve. The committee reviewed papers that used the term for frequencies as low as 10 GHz (X band) and as high as 150 THz, which is in the infrared region. Historically the millimeter band extended from 30 GHz to 300 GHz and the submillimeter band extended from 300 GHz to 3 THz. In the current literature the terahertz region has subsumed the submillimeter band and extended it to 10 THz. In this report the term "submillimeter" is used only to be consistent with historical citations, and the committee has chosen the following nomenclature for use elsewhere (see Figure 1-2):

- *Millimeter:* the region from 30 GHz to 300 GHz;
- *Submillimeter:* the region from 300 GHz to 1,000 GHz; and
- *Terahertz:* the region from 1,000 GHz to 10,000 GHz.

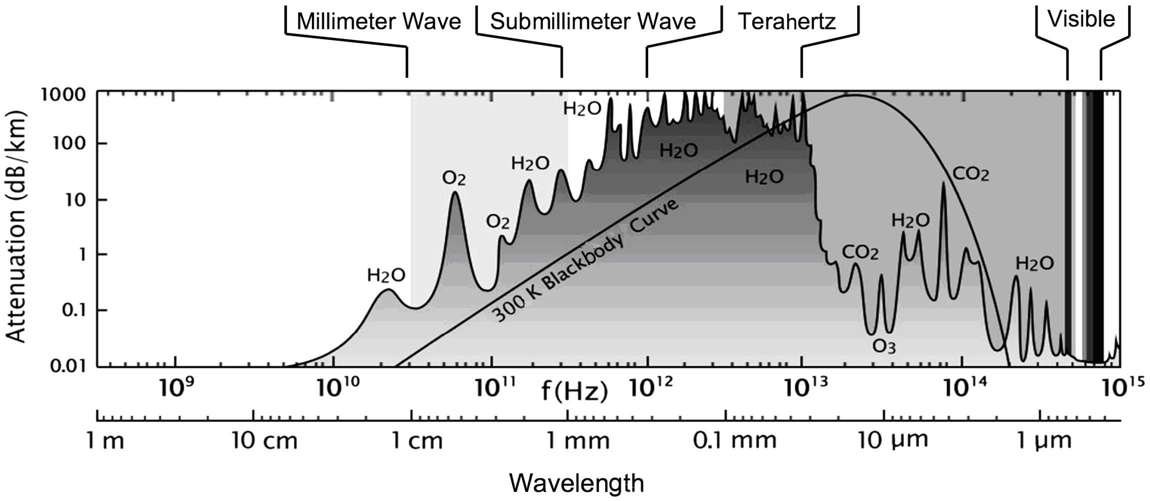

FIGURE 1-2 The three regions—millimeter wave, submillimeter wave, and terahertz—of the electromagnetic spectrum considered in this report. SOURCE: Courtesy of ESA (European Space Agency).

Additionally, the committee uses the following definitions with regard to threat interdiction:

- *Detection:* the process for discriminating objects of possible interest from their surroundings,
- *Identification:* determination of the threat, and
- *Classification:* determination of the threat's characteristics.

The millimeter-wave through the terahertz region is now the subject of aggressive university and national laboratory research driven in part by the availability of short-pulse generators, which produce a wide spectrum of frequencies through this region. The experience of the Transportation Security Laboratory (TSL) with these techniques is very limited apart from experience with the Manhattan II projects,[6] which were initiated by the TSL. Hence the need for this NRC report.

Based on the state of the art of this technology and on input from the sponsor on how the committee can best address its needs, this report addresses the following four areas:

1. The physical phenomena limiting or enhancing imaging and spectroscopy performance of millimeter-wavelength and terahertz instrumentation and an assessment of what unique capabilities may result to complement other sensors. These phenomena include the interaction of electromagnetic radiation with the atmosphere, clothing, and explosives.
2. The state of the art of electronic components in the millimeter-wavelength and terahertz region of the electromagnetic spectrum and what advances will result in the enhanced performance of these components, or may even be the minimum required to provide a useful capability.
3. Descriptions of the operation of developmental systems, including short-pulse systems and active millimeter-wave passenger scanners.
4. An implementation strategy for the development of millimeter-wavelength/terahertz technologies for application to aviation security.

While numerous references are cited throughout the report they are not all-inclusive, as the literature on millimeter-wavelength and terahertz technology is voluminous. A recent Internet search on the word “terahertz” alone generated over a million hits, and a formal bibliographic reference search will result in several hundred citations. When reviewing the literature describing the ability of these technologies to find and identify explosives and concealed weapons, the reader must carefully examine the data that are presented and the conclusions that are extracted from the data. In many cases, the information, although correct, may be incomplete and/or misleading.

The combination of a sense of urgency about addressing the emerging terrorist threats and the perceived availability of new funds to bring potential technologies to address these threats has yielded a plethora of technological proposals. Unfortunately, some of these proposals are neither well founded on the principles of physics nor have they been successfully demonstrated by sound experimentation and testing. Some of these proposals also appear to have been driven by exaggerated claims made by others who may lack a sound understanding of the technology and of its strengths and limitations. This situation has resulted in some unsubstantiated and unfulfilled performance expectations regarding the application of some of this antiterrorism

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[6] The ongoing long-term research and development program focusing on developing highly efficient and fast next-generation EDSs.

technology. One example is the claim of being able to image through building walls.[7] Another is the claim of being able to identify shipwrecks and their contents on the ocean floor.[8] While millimeter-waves can "see through" some wall material such as drywall or dry plywood, they cannot see through structural materials (see Chapter 2, Figure 2-5).

In light of such misconceptions, the committee decided that this report should briefly and systematically address expectations, both real and fictional, and help bring into focus cases in which this technology has promise and instances in which it offers no potential benefit as an antiterrorism technology.

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[7] Robert Roy Britt. 2003. First Image from Revolutionary T-Ray Camera: Sees Through Fog, Clothing and into Deep Space. Available at http://www.space.com/businesstechnology/technology/t-ray_camera_020613.html. Accessed June 25, 2006.

[8] Gaiacomm International Corporation. 2004. 20 Business Applications That Will Benefit from Gaiacomm's TeraHertz-Based Technology: A Technical Discussion of TeraHertz Technology. Available at http://www.gaiacomminternational.com/GIC_20Apps.pdf. Accessed September 13, 2006.

2

Basic Operation of Systems and Phenomenology

While the parts of the millimeter-wave region of the electromagnetic spectrum have been extensively investigated since Bose in the 1800s,[1] the region above 100 GHz is one of the least-explored ranges of the electromagnetic spectrum. Until relatively recently, it was difficult to generate and detect terahertz radiation efficiently. Recent advances in both electro-optic and radio-frequency (RF) techniques have enabled the undertaking of new investigations. These investigations have been directed toward two applications of importance to aviation security. The first is to produce imagery of

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[1] D.T. Emerson. 1997. The work of Jagadis Chandra Bose: 100 years of mm-wave research. IEEE Transactions on Microwave Theory and Techniques 45(12): 2267-2273.

passengers and baggage that takes advantage of the ability to penetrate clothing and other nonmetallic coverings. This application is intended to find objects such as knives, guns, and explosives by detecting their shapes through the concealment. A second, more advanced application is intended to be able to classify materials, which also may be concealed, by observing their differential absorption or reflectance of radiation—in effect, spectroscopy. Recent data have shown that solid explosives do exhibit some repeatable spectroscopic features in the spectrum above 800 GHz that may be used to differentiate them from other solids.

This chapter describes passive and active imaging technologies, fundamental characteristics and technical limitations of these technologies, and spectroscopic technologies.

IMAGING TECHNOLOGIES

Imaging detection techniques rely on the contrast between warmer and colder objects or on the contrast between objects that have high and low emissivity of radiation or, equivalently, low and high reflectivity of radiation. For example, these technologies are being used to detect guns concealed underneath clothing by the detection of the contrast between the warmer human body and the apparently cooler metal weapon.[2] Imaging technologies can be either passive or active. Passive systems are not designed to generate or emit radiation but use natural background radiation for the illumination of the detection space. Active-illumination systems generate and emit radiation that is used to illuminate the detection space.

Passive Imaging

Every object generates electromagnetic emissions at all wavelengths with intensity proportional to the product of its physical temperature and its emissivity in accordance with Planck's radiation law. Objects also reflect the radiation emanating from the environment to a degree of reflectivity which is the complement of their emissivity; the sum of the emissivity and the reflectivity is 1. Thus, an object that reflects 90 percent of the radiation striking it will have an emissivity of 10 percent. These values are generally a function of wavelength, so what might be reflecting at long wavelengths in the radio-frequency region may appear to be emissive in the infrared region. An example of this would be a metal mirror with a coating of dull black paint. An infrared sensor would sense an emissivity close to 1 and would respond to the temperature of the coating, while an RF sensor would sense the reflecting surface as the mirror, since the coating is readily penetrated by the long wavelengths.

The human body has an emissivity of about 65 percent at 100 GHz, increasing to about 95 percent at 600 GHz (Table 2-1). This would make a human body appear warm relative to a metal object, which would have a low emissivity and would thus reflect the

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[2] David J. Cook, Brian K. Decker, and Mark G. Allen. 2005. Quantitative THz Spectroscopy of Explosive Materials. Presentation at Optical Terahertz Science and Technology, Orlando, Florida, March 14-16, 2005.

generally cooler temperatures in the environment around the body. Plastics and ceramics have emissivities higher than those of metal but lower than those of human flesh, so they would also contrast against the body, though to a lesser extent.

Figure 1-2 in Chapter 1 has a curve labeled "300 K Blackbody Curve" that shows the amount of radiation versus wavelength for a perfectly emissive body at 300 kelvin (K), approximately room temperature. Both the amplitude and the wavelength of the radiation peak are dependent on the temperature of the object. The higher the temperature of the body, the shorter the wavelength of radiation where the peak of the curve occurs.

TABLE 2-1 Examples of Object Emissivity

Object	Emissivity (%)
Human skin	65 to 95
Plastics	30 to 70, depending on type
Paper	30 to 70, depending on moisture content
Ceramics	30 to 70
Water	50
Metal	~0

Passive imaging systems require that there be an apparent temperature difference, either positive or negative, between the body and its surroundings. While the surrounding environment is generally cooler than the human body, some passive imaging systems use noncoherent sources that surround the body to enhance contrast by making reflective objects appear warmer than the body. These detection systems require the ability to differentiate between the temperatures of adjacent areas within the target area. The operation of a passive millimeter-wave imager can be compared with the operation of a camera. The equivalent of light for a millimeter-wave imager is the millimeter-wave energy, and the equivalent of film in a camera is the detector array in a millimeter-wave imager.

There are various millimeter-wave imagers being developed for concealed-weapon-detection applications. The difference in these devices is in the implementation of the detection hardware. These devices are at present in the development stage, and none has been deployed or tested in actual use. Several of these devices are described in Chapter 4, "Systems Concepts."

Active Imaging

Active millimeter-wave imaging technologies operate as short-range radar systems that project a beam of millimeter-wavelength energy against a target and detect the reflected rays. The beam may illuminate the entire body or may scan over the body to produce an image of the subject. The U.S. Department of Energy's Pacific Northwest National Laboratory has developed a system for screening people based on active millimeter-wave technology that sequentially scans both the transmitter and receiver over the body and uses a technique called computed tomography to form an image. This imaging technique, similar to that used in medical computerized axial tomography scans, involves illuminating the subject with millimeter-wave radiation. Since the power levels are low and the radiation only penetrates to skin depth, no adverse health effects occur.

However, the popular perception of the dangers of microwave radiation may cause public concern over this imaging technique.

Until recently, most terahertz sources were either low-brightness emitters, such as thermal sources, or cumbersome, single-frequency molecular vapor lasers. Detection usually relied on bolometric methods, which required cryogenic operation, or Golay cells, which have little dynamic range. Recently, however, a revolution has occurred in terahertz technology as a number of newly discovered or rediscovered generation and detection schemes have revitalized the field. These techniques rely either on frequency conversion using nonlinear optics or on quantum cascade lasers, which depend on devices formed from superlattices of semiconductors. They are often simpler, more reliable, and potentially much less expensive than the more traditional approaches. Chapter 3 presents a general description of these devices.

The promise is that terahertz imaging will provide an orthogonal detection capability that will allow the identification of explosive materials concealed on a person's body or in nonmetallic carry-on luggage. In simple terms, the terahertz waves can penetrate materials such as clothing and leather with enough residual energy to excite molecular vibrations, rotations, and phonon-band resonances in solid materials. This excitation can be detected using spectroscopy techniques and the substance identified by an analysis of the unique signatures from different molecules. While spectroscopy will provide additional capability, it is expected that the transmissivity of explosives to x-rays is different from their transmissivity to millimeter-wavelength/terahertz technology.

The technology challenge for active imaging rests on the development of components that operate in the millimeter-wavelength/terahertz region. Poor performance and high cost have historically limited research and development efforts at millimeter-wave/terahertz wavelengths. New techniques for wave generation and detection that are unique to the terahertz spectrum are being developed in research laboratories worldwide. A literature search will yield hundreds of recent citations covering all aspects of terahertz research.

In order to form a terahertz image using time domain spectroscopy, the terahertz beam is brought to an intermediate focus using a pair of lenses or parabolic reflectors, which are inserted into the region where the terahertz beam is collimated. An object is placed at the focus of the terahertz beam, and then the amplitude and delay of the wave that has traversed through the object is measured. By translating the object and measuring the transmitted terahertz waveform for each position of the object, one can build an image pixel by pixel.

An imaging system in which the terahertz beam is reflected from the sample rather than being transmitted through it can be used for tomographic imaging. If the sample consists of several separate dielectric layers, the interface between each pair of layers reflects a portion of the terahertz beam. The reflected waveform therefore consists of a series of isolated pulses. Each pulse in this pulse train contains information about each of the layers through which it propagated, as well as about the interface from which it originated. With this information, a tomographic image may be constructed.

Resolution Versus Antenna Size

Another issue facing the application of RF techniques is that of resolution versus antenna size. When imaging in the far field of a circular aperture, the resolution *R*, in angle can be approximated by:

$$R = 1.22c/FD$$

where *R* is the angular resolution in radians, *c* is the speed of light, *F* is the frequency of operation in hertz, and *D* is the diameter of the aperture of the imaging system.

Since resolution is inversely proportional to the frequency of the radiation, an imaging system would be desirable at as high a frequency as possible, given limitations in components and atmospheric propagation. Figure 2-1 shows the change in resolution across frequency for an imaging system with a 2 meter (m) diameter antenna or optical system. This linear curve shows the resolution for a passive imaging system. Passive system images are lower resolution because they are incoherent and have poor signal to noise at moderate scanning rates. Resolution can be increased by a factor of two by using an illuminator transmitting through the same aperture and thus focusing the transmitted resolution on the spot being imaged, a so-called confocal system.

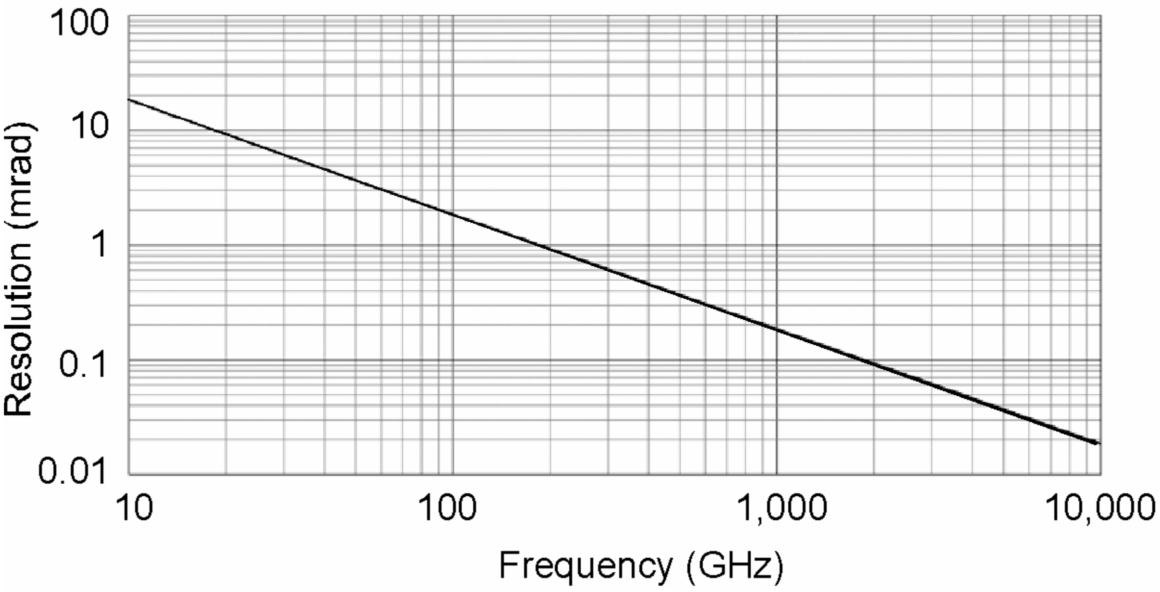

FIGURE 2-1 Antenna resolution for an imaging system with a 2 meter aperture.

While a 2 m diameter antenna seems inordinately large, to achieve "eyeball" resolution—about 1 foot at 1 kilometer—an antenna at 100 GHz would have to be approximately 14 m in diameter. While it should be understood that eyeball resolution is not necessary for the detection of concealed objects or the identification of explosives, it is a convenient metric for examining relative aperture sizes of millimeter-wavelength/

terahertz sensors versus optical sensors. Figure 2-2 shows the diameter of an antenna required to achieve the resolution of the human eye versus frequency.

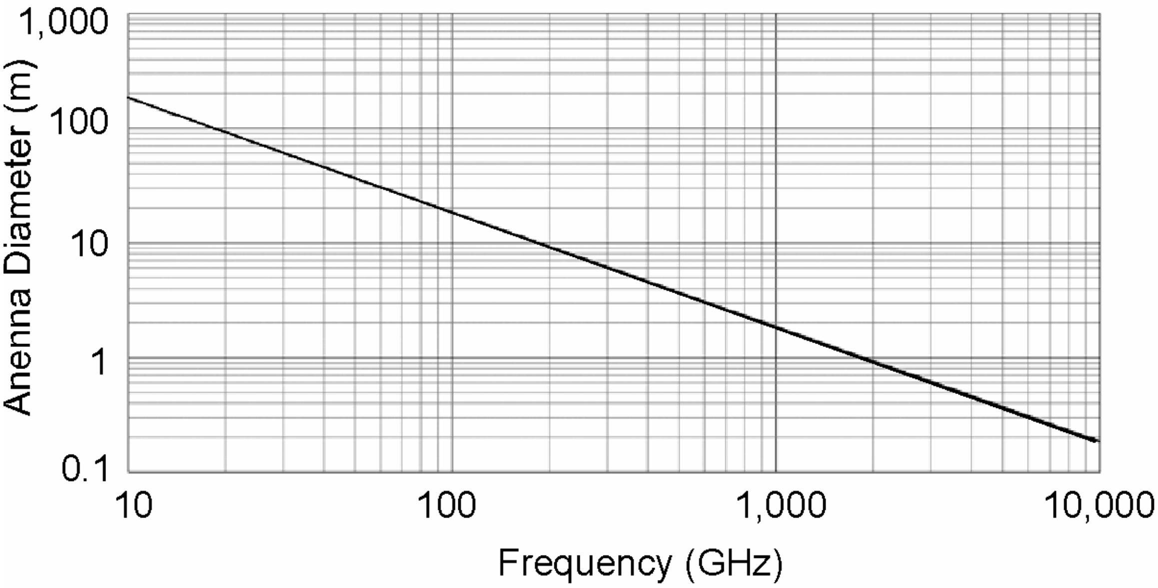

FIGURE 2-2 Antenna diameter required for an imaging system to achieve the resolution of the human eye.

Atmospheric Propagation

The atmosphere attenuates millimeter-wave radiation at frequencies determined by molecular absorption by water vapor, oxygen, and other atmospheric molecules. The atmospheric attenuation characteristics must be accounted for in any system design.

Figure 2-3 shows the atmospheric attenuation under various environmental conditions from 10 GHz to 10,000 GHz. The conditions are typical for what may be experienced outdoors in various locations. The “clear” condition, which represents the U.S. standard atmosphere, is typical for a climate like that of the mid-Atlantic states in the springtime, while the curve labeled “humid” represents what would be expected in the same region in August (hazy, hot, and humid) when the atmosphere may contain up to five times the water vapor contained by the standard atmosphere. This is an example of a worst-case condition. The data labeled “dust” are predicted on the basis of a dust model[3] that has been validated at 10 GHz and represent the attenuation from a storm that has a visibility of 10 m.

The minima in Figure 2-3 clearly show the atmospheric windows that are used to define the normal frequencies of operation for these systems. While systems tend to operate around specific frequencies, both for historical reasons and because of requirements of the Federal Communications Commission, the minima where the attenuations are lower are somewhat broad. In the millimeter-wave region they are typically 26 to 40 GHz, 70 to 110 GHz, 140 GHz, and 220 GHz. In the submillimeter-

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[3] J. Goldhirsh. 2001. Attenuation and backscatter from a derived two-dimensional duststorm model. IEEE Transactions on Antennas and Propagation 49(12): 1703-1711.

wavelength region they are 340, 410, 650, and 850 GHz. Above 1 THz, the primary window of interest is centered at 1.5 THz.

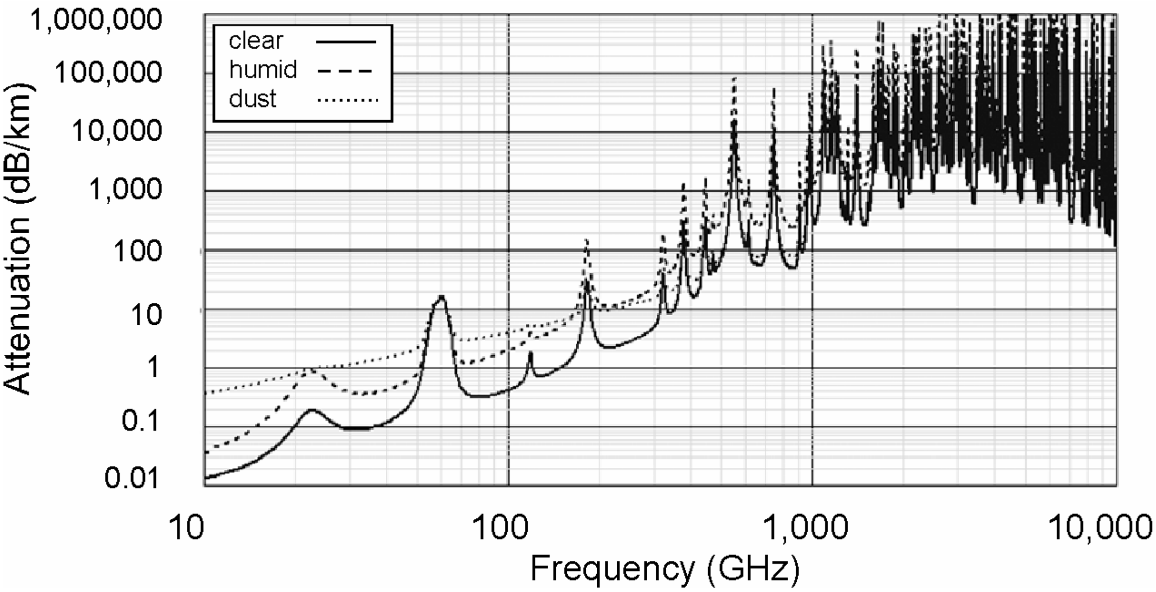

FIGURE 2-3 Atmospheric attenuation under various environmental conditions from 10 GHz to 10,000 GHz.

If an imaging or spectroscopic system were to be employed in an air-conditioned facility such as an air terminal, the curve for the clear air would be appropriate. Figure 2-3 clearly shows that lower frequencies transmit through the atmosphere with less attenuation than higher frequencies for all three conditions shown.

While atmospheric attenuation by itself is not a measure of possible performance, it does give insight into the difficulty of performing imaging and spectroscopy at various distances. As the attenuation increases, contrast will be reduced for a given distance. In a passive system that relies on natural illumination or emissions from objects, attenuation exceeding 20 decibels (dB) (100:1) will reduce contrast of typical natural scenes to the point of being indecipherable. The decibel is a means of describing relative power. It is defined as:

$$dB = 10 \log(P1/P2)$$

where $P1$ and $P2$ are two power levels that are being compared. So 10 dB is equivalent to a 10:1 ratio, 20 dB is equivalent to a 100:1 ratio, and so forth. With active systems, if transmitter power could be increased an unlimited amount, contrast could still be maintained, assuming the atmosphere does not contain particulate matter that also might reflect energy. To a first order, it can be stated that as the atmospheric attenuation increases, the range at which good image quality can be maintained will decrease.

CHARACTERISTICS OF MATERIALS

The utility of these millimeter-wavelength/terahertz systems lies primarily in their ability to penetrate materials that might shield concealed weapons or explosives from detection. Typically these materials may be normal clothing, but they could also include luggage. For the Terahertz Imaging Focal Plane Array Technology (TIFT) program of the Defense Advanced Research Projects Agency (DARPA), Ohio State University (OSU) and the University of California at Santa Barbara (UCSB) have characterized numerous articles of clothing (Figure 2-4). The OSU data were collected on clothing provided by the U.S. Army from southwest Asia, while the data measured by UCSB were from clothing provided by university students and staff. Without making an attempt to characterize the particular articles of clothing in a parametric sense, these sets of measurements indicate that transmission through clothing is generally better than 80 percent (−1.0 dB) at frequencies below 300 GHz but decreases as the frequency of operation increases. It is also apparent that transmissivity varies greatly with different types of clothing.

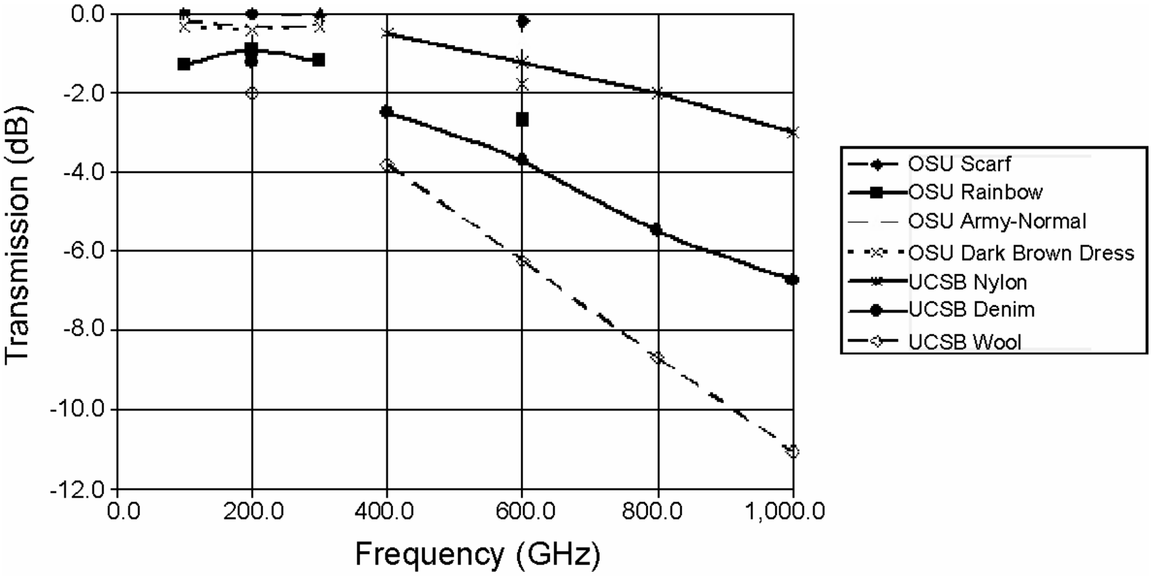

FIGURE 2-4 Transmission measurements through various clothing materials. SOURCE: Data courtesy of Ohio State University (OSU) and University of California, Santa Barbara (UCSB).

The data collected by UCSB generally appear to have reduced transmissivity when compared with OSU data. The difference may be in the clothing from southwest Asia being of a lighter material than that examined at UCSB, where the climate is generally cooler. Any system that would be required to image through clothing would be expected to operate through at least two layers of clothing, perhaps a cotton shirt and a wool sweater. The one-way transmissivity through the combination could thus be less than 50 percent at 300 GHz and 25 percent at 600 GHz. Whether the system is active or passive, the worst-case transmission, for the purpose of discerning concealed items, would be the square of this, or 6.25 percent at 600 GHz, because the attenuation would affect the illuminating radiation from either the environment or the active illuminator.

It has also become commonplace to ascribe to millimeter-wavelength/terahertz systems the ability to image objects through walls and buildings. Figure 2-5 shows measurements made by OSU of the transmission through common building materials of signals from 100 GHz to 600 GHz. Some measurements made with millimeter-wave imagers at 95 GHz have been published, but these are through drywall or dry plywood which, as can be seen in Figure 2-5, have little effect. For materials of a structural nature such as oak or pine, the attenuation is severe.

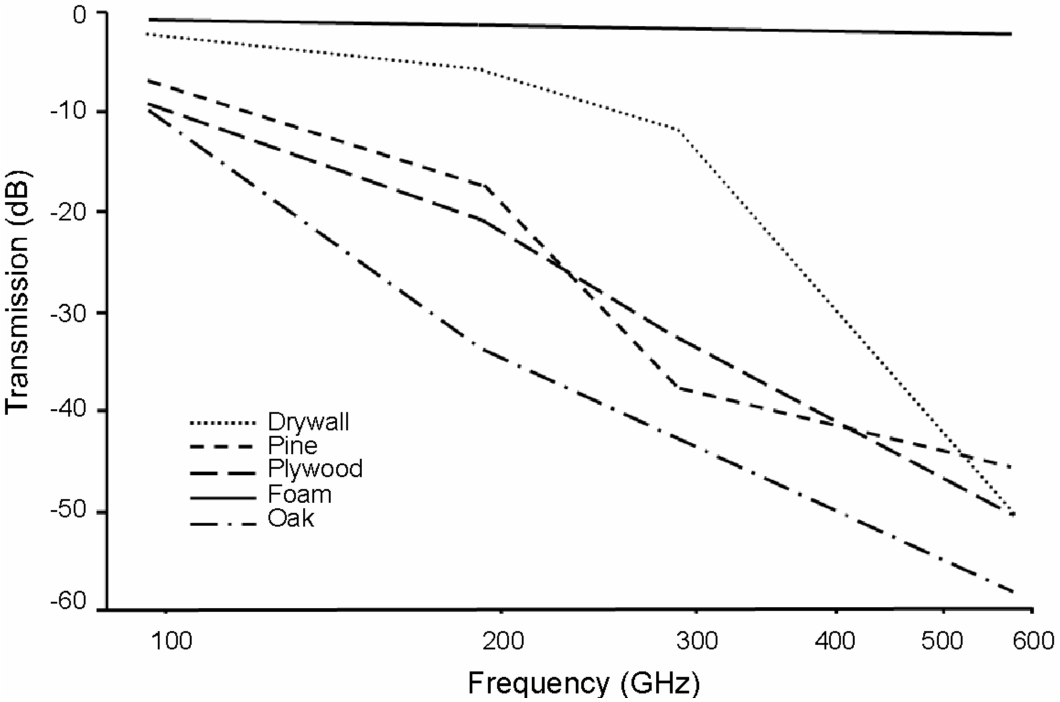

FIGURE 2-5 Measurements made with millimeter-wavelength/terahertz imaging systems of transmission through various building materials. SOURCE: Data courtesy of Ohio State University.

SPECTROSCOPY OF MATERIALS

Terahertz time domain spectroscopy (TTDS) is a new technique that has offered the promise of detection and identification of concealed explosives. The system uses a short-pulse laser and a pair of specially designed transducers as transmitters and receivers. By gating these transducers with ultrafast optical pulses, one can generate subpicosecond bursts of electromagnetic radiation, and subsequently detect them with high signal to noise using gated detectors. These transients consist of only one or two cycles of the electromagnetic field, and they consequently span a very broad bandwidth. Bandwidths extending from 100 GHz to 2 or 3 THz are routine, although the power generated is concentrated more in the lower frequencies of the emission band. Although the average intensity of the radiation is quite low, the high spatial coherence produces a brightness that exceeds that of conventional thermal sources. The gated detection is orders of magnitude more sensitive than typical bolometric detection, and it requires no cooling or shielding of any kind. Because TTDS does not require any cryogenics or shielding for the detector, it has the potential to be the first millimeter-wavelength/ terahertz chemical sensor that is portable, compact, and reliable enough for practical application in real-world environments. Note that TTDS by itself is not an imaging technique. Research conducted at Physical Sciences, Inc., has suggested that TTDS is able to distinguish, by resonances attributed to phonon bands, among the following explosives: cyclotetramethylene-tetranitramine[4] (HMX), cyclotrimethylene-trinitramine[5] (RDX), pentaerythritol tetranitrate (PETN), and trinitrotoluene (TNT).

Figure 2-6, compiled by Ohio State University, shows some of the spectral features of energetic materials as a function of frequency. The data from various sources differ in quality, but it is apparent that there are consistent features in the range above 1 THz, while below that only the plastic explosive (PE4) and RDX exhibit any feature. The detection of explosive features will therefore depend on the development of equipment that works well at frequencies greater than 600 GHz.

The compiled spectroscopic data should be contrasted with the spectra from gaseous materials and, specifically, the atmospheric gases. Spectra from gaseous materials are well defined under different pressures and temperatures and can be used to readily identify disparate materials. The published data for the explosive materials are less well defined.

An additional point is that there are few data available on materials such as cheese or thick liquids that might be confused, using other techniques such as x-ray, with explosives. Significant effort needs to be placed on characterizing confusing materials to ensure that there is sufficient information available in the spectra for distinguishing explosives. While there is some information to show that some materials may exhibit "colors," there is little evidence to support an analysis of broadband versus narrowband techniques. Any investigation of materials properties needs to examine emissivities across the broad bandwidth, not just at single frequencies. As many terrorist organizations may use nonconventional or improvised explosive formulas that contain no nitrogen, research into the ability of the technology to detect these materials is needed. These confusing materials must also include human body and any other background materials that may be present in the same field of regard as the material to be detected.

One final concern that must be addressed is to distinguish the spectra of the materials when examined at a distance from which the spectra of the atmosphere itself will act to change the spectral intensity. As shown previously (see Figure 1-2 in Chapter 1), the atmosphere in the 1 THz to 10 THz region, where the bulk of the explosives features reside, is very complex, with transmission and absorption lines that further compound the problem of detecting spectral features. This problem may lead to the conclusion that the use of millimeter-wavelength/terahertz techniques for identifying explosives will be limited to very short range (<1 m), perhaps for baggage scanning or as an adjunct to a portal system.

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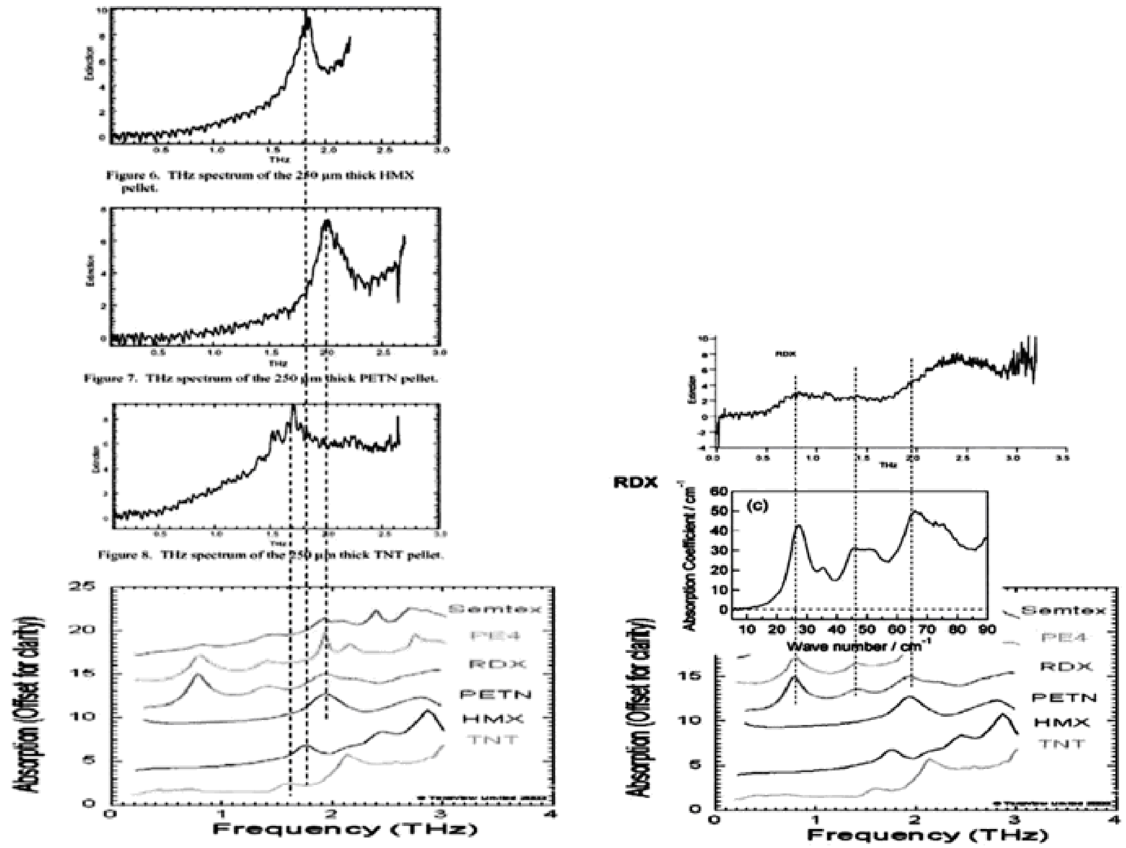
[4] Other names include octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine, tetrahexamine tetranitramine.

[5] Other names include hexahydro-1,3,5-trinitro-1,3,5-triazine.



Comparison of PSI (top three: HMX, PETN, TNT) and Teraview (bottom) spectra.

Comparison of PSI (top), Osaka(middle), Teraview (bottom)

FIGURE 2-6 Intercomparison of published explosives phonon bands spectra conducted by Ohio State University. NOTE: PSI, Physical Sciences, Inc. SOURCE: Courtesy of Ohio State University. Unpublished.

3

Component Technology

This chapter reviews areas in which the committee believes there is potential for technology breakthrough devices or techniques that will result in enhanced performance of millimeter-wavelength/terahertz technologies or that may even serve as the minimum required to provide a useful capability. This information could serve as a flag for the attention of Transportation Security Laboratory (TSL) personnel in the future.

One of the best reviews of component maturity in the millimeter-wavelength/ terahertz region is by Siegel,[1] describing in detail the state of the art of numerous

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[1] P.H. Siegel. 2002. THz technology. IEEE Microwave Theory and Techniques 50(3): 910.

techniques for the generation and detection of radiation above 100 GHz. Although there are a few exceptions, little has changed in the state of the art since that review was written. The present report provides a more basic review of the technology, and the referenced paper can be consulted where additional details are required.

The three regions of the electromagnetic (EM) spectrum being examined in this chapter have different levels of component maturity but are not divided along the lines previously defined (millimeter wave, submillimeter wave, and terahertz). The component development has been led by military applications and then followed by commercial applications. Starting from the radio-frequency (RF) side of the electromagnetic spectrum, numerous commercial foundries exist to provide components below 50 GHz, and limited capability is available up to about 100 GHz. Above 100 GHz, choices are more limited. Some amplifiers have been developed to date that operate up to 200 GHz, primarily as low-noise amplifiers (LNAs) for receivers. Above 200 GHz, high-sensitivity receivers and associated low-power sources have been primarily developed for the radio astronomy and remote sensing community.

SOURCES

Sources are probably the first component requirement for active spectroscopy or imaging systems operating in the millimeter-wavelength/terahertz spectra. They serve as a means to calibrate systems, as illuminators for sensors measuring reflections from or transmissions though materials, or as the local oscillator (LO) for heterodyne receivers. Heterodyne receivers convert a received signal into a lower frequency through multiplication with a reference source. The heterodyne receiver is generally more sensitive than a direct detecting receiver, as this down-conversion process allows the use of lower frequency and thus more sensitive detection schemes. The use of stable narrow-band sources with a heterodyne receiver also provides an ability to measure spectral features rapidly with high resolution.

Figure 3-1 briefly summarizes the challenge with achieving a system concept between 0.1 THz and 10 THz. Generally, the approach to achieving source power has been either to use multipliers to generate radiation from RF sources or to translate down in frequency from optical regions using laser and various forms of nonlinear mechanism. There are exceptions to this trend in that backward wave oscillators (BWOs), a vacuum electronic device, and carbon dioxide (CO_2) pumped gas lasers have been available for many years and have provided power adequate for the applications of interest, namely, spectroscopy. The various techniques currently being investigated for generating power for security are discussed below with respect to the frequency range over which they function most efficiently.

Figure 3-2 shows the state of the art in RF sources. A first point is that obviously there appears to be a “cliff” that technology falls off above 100 GHz. Most source advances in the past 30 to 40 years have been due either to high-energy physics research or to military applications, with most of the investment in affordable and readily manufacturable sources below 100 GHz for the military. While commercial interest has further improved the affordability of sources, primarily below 30 GHz, it has done little to improve power levels. Little has happened since Figure 3-2 was developed to change these performance levels. The Defense Advanced Research Projects Agency (DARPA) has recently funded a program developing new sources in the region of 0.5 THz to 2.0 THz and a second, which began in 2006, to produce useable monolithic microwave integrated circuits (MMICs) up to 340 GHz.

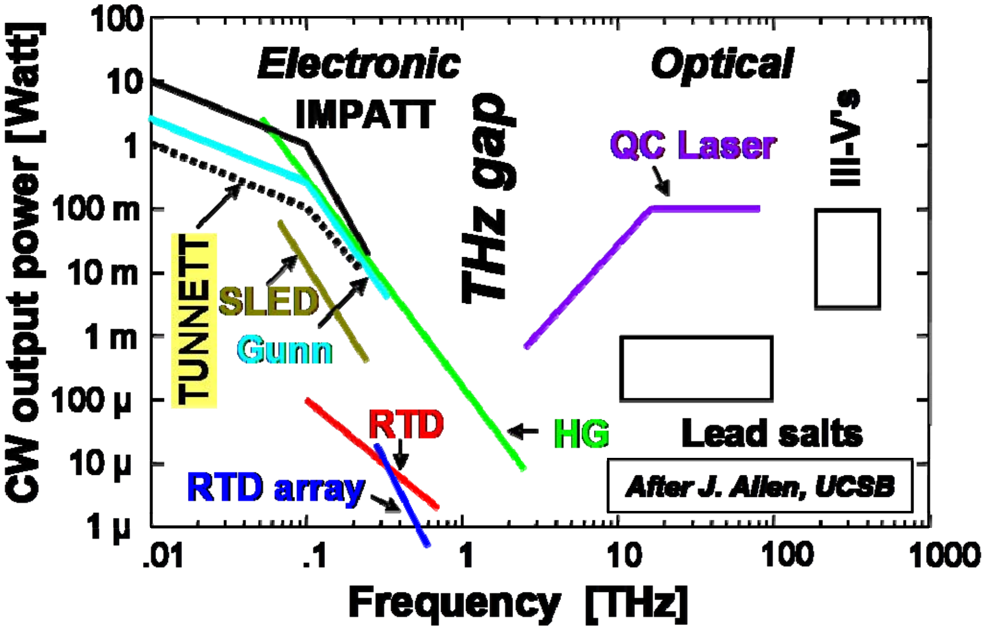

FIGURE 3-1 Available solid-state sources. NOTE: CW, continuous wave; TUNNETT, Tunnel Injection Transit Time; SLED, Super Luminescent Diode light source; RTD, Resonant Tunneling Diode; HG, harmonic generation; QC laser, Quantum Cascade laser; III-Vs, compounds from the periodic chart columns III and V (e.g., GaAs); IMPATT, Impact Ionization Avalanche Transit Time; and Gunn, electron drift velocity is decreasing as electric field in semiconductor is increasing above certain critical value. SOURCE: Courtesy of Heribert Eisele, University of Leeds, Leeds, UK.

A second point, somewhat less obvious, is that the power levels that are currently available (with some individual vacuum electronic device [VED] exceptions) above 100 GHz are below the power levels actually represented in Figure 3-2.

Backward wave oscillators have been a staple in the region of 100 GHz to 1,200 GHz as tunable sources for instrumentation. BWOs have been built by numerous concerns over the years but are now primarily available from the former Soviet Union. These sources have power ranging from tens of milliwatts at 100 GHz to a few milliwatts above 1 THz. While they operate at high voltages (above 2 kilovolts [kV]) and suffer from some tuning problems when using wideband cavities, they continue to be a useful tool for spectroscopy and diagnostics. The DARPA Terahertz Imaging Focal Plane Array Technology (TIFT) program is currently investing in improved designs for VEDs at 650 GHz that offer higher efficiencies and power levels that could reach 50 milliwatts. These designs are making use of micromachining techniques to improve the tolerances of the resonant structures. These structures that are being micromachined also have the potential of being used for traveling wave tubes. This development would result in potential coherent operation that should enhance resolution, both spatially and spectrally. By using these devices with multipliers, it should be possible to realize several milliwatts of power above 1 THz.

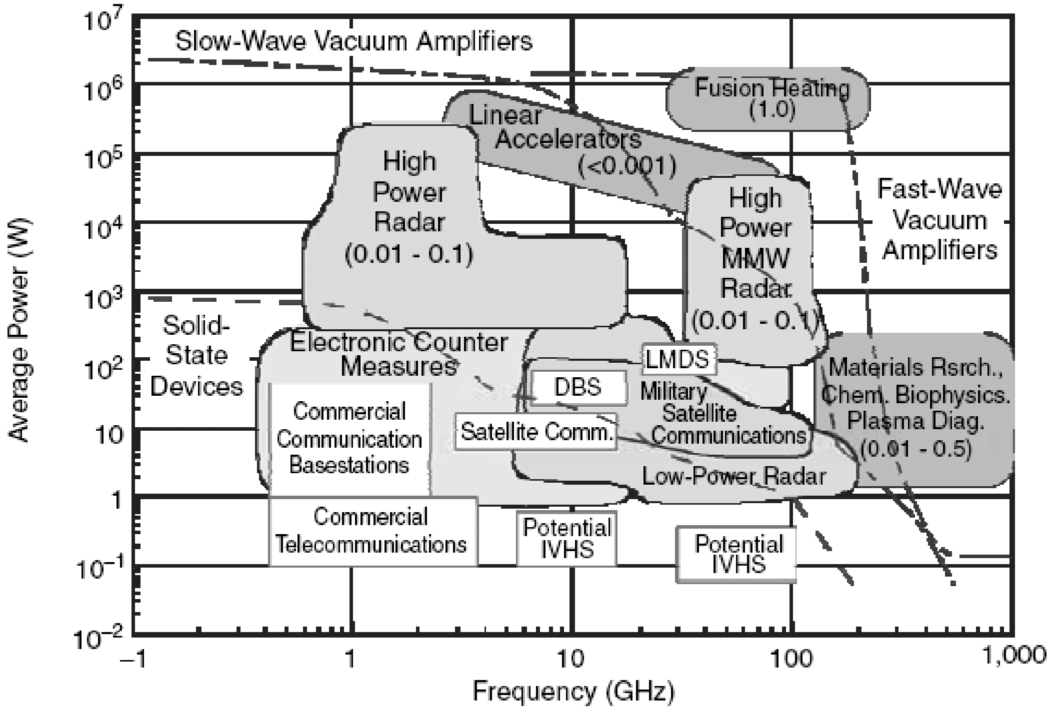

FIGURE 3-2 State-of-the-art radio-frequency sources (circa 2001). NOTE: IHVS and LMDS: Intelligent Highway Vehicle System and Local Multipoint Distribution System, respectively. SOURCE:R.H. Abrams, B. Levush, A. A. Mondelli, and R.K. Parker. 2001. Vacuum Electronics for the 21st Century. IEEE Microwave Magazine 2(3):61-72.

While numerous fundamental sources, such as Gunn,[2] Impact Ionization Avalanche Transit Time (IMPATT) diodes, or amplified phase-locked oscillators, can be found below 200 GHz, the most practical technique for generating coherent energy above 200 GHz is through multiplication. This is the primary technique for providing LO power to heterodyne receivers for radio astronomy or high-resolution spectroscopy. While in the past it was common to use whiskered Schottky diodes as multipliers, planar diodes have become readily available and offer suitable performance. Their output power levels can be limited by the maximum amount of input power that they can handle or by even the existence of a suitable source of RF that can be multiplied efficiently. Multipliers have been used successfully above 1 THz by chaining together a series to obtain the desired frequency. Power levels from various sources available from Virginia Diodes, a leading producer of the device to the community, is shown in Figure 3-3.

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[2] A form of diode that relies on the Gunn effect. Unlike other diodes, it consists only of N-doped semiconductor material.

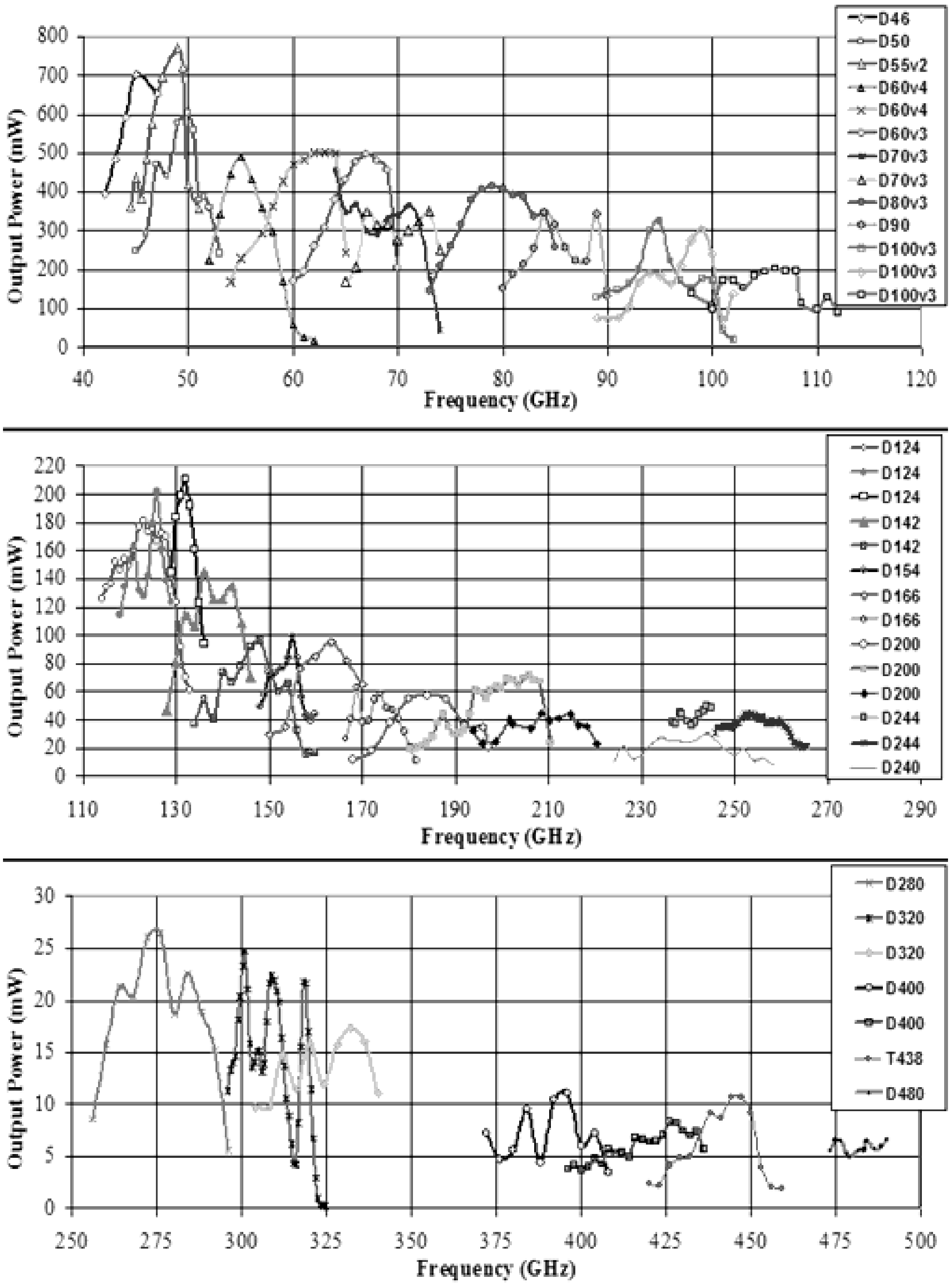

FIGURE 3-3 Power levels available from the various devices produced by Virginia Diodes. SOURCE: Courtesy of Virginia Diodes.

It can be seen that as frequencies increase to about 500 GHz, the power output capability drops to about 5 mW, which is generally sufficient as a source for spectroscopy that operates over short ranges or as an LO for heterodyne receivers.

Figure 3-4 summarizes the various choices for sources from Siegel[3] in the region from 500 GHz to 2,500 GHz. The trend for multipliers continues downward with power levels reaching a minimum at 2.5 THz, a level that is barely sufficient to provide LO power for receivers operating at cryogenic temperatures.

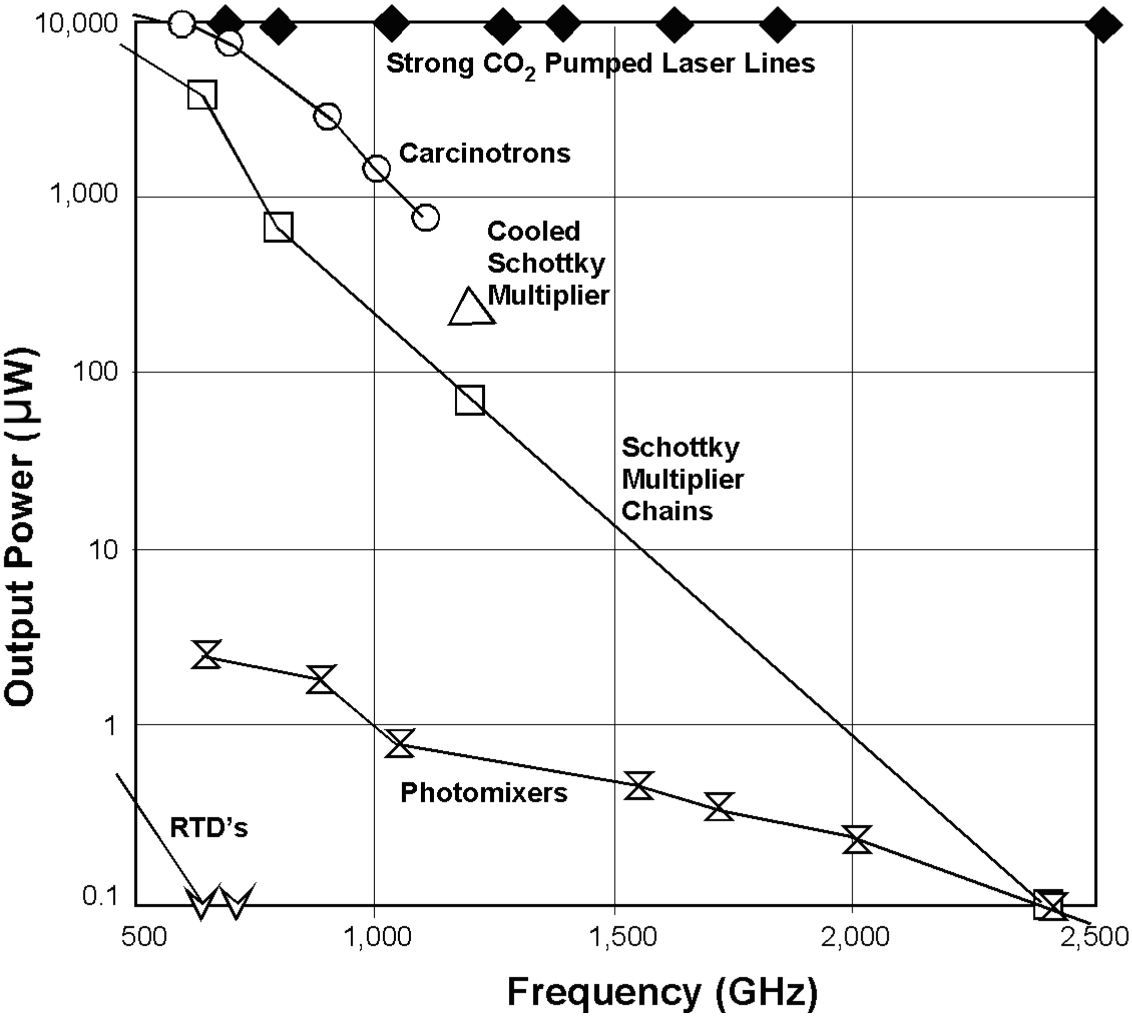

FIGURE 3-4 Power levels available for sources in the region from 500 GHz to 2,500 GHz. SOURCE: P.H. Siegel. 2002. Terahertz technology. IEEE Microwave Theory and Techniques 50(3): 910.

Time domain systems have evolved from first developing extremely short (pico- and femtosecond) pulsed lasers that can illuminate semiconductor material that illuminates a photoconductor, such as gallium arsenide, to generate carriers. The carriers then form a current in the material, which is radiated through an antenna. The radiated energy then has a frequency content equal to the Fourier content of the envelope of the

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[3] P.H. Siegel. 2002. Terahertz technology. IEEE Microwave Theory and Techniques 50(3): 910.

laser pulse. The spectrum would have peak power at a frequency commensurate with the inverse of the pulse-width and would consist of spectral lines separated by repetition rate. As an example, if the envelope of the laser pulse was very short and the repetition rate was great enough to form a square wave, the roll-off with increasing frequency would be 6 decibels (dB) every other harmonic of the peak frequency, reducing the efficiencies of harmonic generation. This, of course, assumes a perfect pulse shape, which is never true. Published data[4] for these types of sources typically show peak powers in the 100 GHz to 700 GHz region, with the submillimeter-wave and terahertz energy produced exhibiting this roll-off in power. The average power of the sources is not great, but by using a time-gated detector, instantaneous power is sufficient for applications where ranges are short, such as transmission through packages.

This energy can also be produced by illuminating a nonlinear material with two lasers whose difference frequency is in the region of interest. The nonlinear material then acts in a manner similar to an RF mixer and is called a photomixer. A key element of this technique is being able to couple the laser energy into the photomixer while at the same time being able to efficiently couple the RF energy out. Provided that the lasers are tunable and phase-lockable, very stable sources can be created over the operational range of the photomixer. A significant challenge remaining is to improve the efficiency of both the photomixer and the coupling structure to increase power output.

Lastly, investment continues in the development of quantum cascade lasers, which have demonstrated the generation of power in the 1 THz to 10 THz band. They are created by building tailored superlattices of semiconductors that form transition regions in the device. These devices currently operate at spot frequencies in the band, are usually pulsed, and require cooling in order to operate.

RECEIVERS

For any RF system, the maximum sensitivity will be achieved when the instantaneous bandwidth of the receiver is matched to the instantaneous bandwidth of the source. For a purely passive receiver, it is important to maximize the bandwidth of operation to obtain as much received energy from the emitting or reflecting field of observation as possible, since the source is essentially infinitely broad. For an active system, it is important to reduce the receiver bandwidth as much as possible to reduce the receiver-generated noise as much as possible while preserving the entire illumination signal. Some applications will also require that the phase of the illumination function be preserved so that advanced imaging techniques such as holography or sparse aperture array synthesis can be performed.

In the region of 30 GHz to 300 GHz, numerous types of receiver components are available commercially, so there can be systems trade-offs that include issues of cost and complexity as well as strict component performance. Typical receivers now use low-noise amplifiers as the first stage prior to either down conversion, for heterodyne systems, or diode detectors, for noncoherent receivers. The major difficulty with

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[4] The Johns Hopkins University Center for Materials Science and Detection. n.d. Terahertz (THz) Imaging and Spectroscopy. Available at http://www.wse.jhu.edu/~cmsd/Thz/. Accessed August 25, 2006.

performing imaging in this region is that of obtaining adequate spatial resolution with a simple aperture like an optical reflector or lens. On the positive side, because of the maturity of the components, more advanced techniques can be used for imaging scenes. Computed tomographic and holographic techniques can be applied to arrays of receivers or antennas used to image objects in close proximity. These techniques are dependent on having components or architectures that can measure or control the phase as well as the amplitude of the RF energy used. The Agilent and SafeView systems (described in Chapter 4) are examples of these classes of systems.

It can be shown that for passive techniques, the only suitable receivers are detectors cooled to liquid helium temperatures, to reduce noise, or heterodyne receivers. For active systems, room-temperature detectors may also be used as long as sufficient illumination power is available. An example of system performance is presented below.

The basic receiver most used by individuals trained in RF techniques is the heterodyne receiver, which is usually formed from a Schottky diode mixer and local oscillator that is followed by an intermediate-frequency amplifier and may be preceded by a low-noise amplifier (LNA). These components may all be operated at room temperature but may be temperature-stabilized for calibration or cooled to enhance performance. State-of-the-art noise figures are about 2.5 dB at 100 GHz for an LNA. At higher frequencies (above 300 GHz) where LNAs do not yet function, noise figures of 10 to 13 dB are typical.

As Siegel points out in the paper cited above, space-qualified heterodyne receivers have been fabricated for operation up to 2.5 THz. Whether the technology can be pushed to higher frequencies remains to be seen, but performance may still ultimately be limited by the availability of sources for LOs with power levels approaching 1 mW. Of course by cooling these receivers, performance can be enhanced by about 3 to 5 dB over performance at room temperature. Given the potential benefits in detection that come from cooling, further research into the cost and complexity of installing coolers is warranted. However, it is unlikely that this technology will have any near-term applications.

Looking beyond the classic Schottky diode as mixer, one finds other forms of heterodyne detectors which, while requiring cooling, have impressive performance. These include bolometers, hot electron bolometers (HEBs), Josephson effects devices, and the superconductor-insulator-superconductor device. While these devices do require cooling down to liquid helium temperatures, they also require reduced LO drive to obtain their best sensitivities. The performance of some of these devices approaches the quantum limit of performance. Figure 3-5 shows the performance of some of these devices compared with Schottky diodes.

A great deal of recent work has concentrated on developing direct detectors that can be used to replace heterodyne receivers in some applications. This has primarily been for active systems, but there have been attempts to use them for passive systems. As was pointed out above, direct detectors have yet to achieve the sensitivity of heterodyne receivers, but they are more viable for combining into arrays to perform imaging using architectures similar to what is used in the visible and infrared region. Other than sensitivity, limitations to date for uncooled detectors have included long output time constants, which is a detriment for video frame rate imaging. The TIFT program in DARPA is trying to overcome some of these problems, with different levels of success.

Ultimately, if cooling to very cold temperatures (~10 K) can be used, direct detectors may be able to achieve characteristics sufficient for security applications using spectroscopy, imaging, or both.

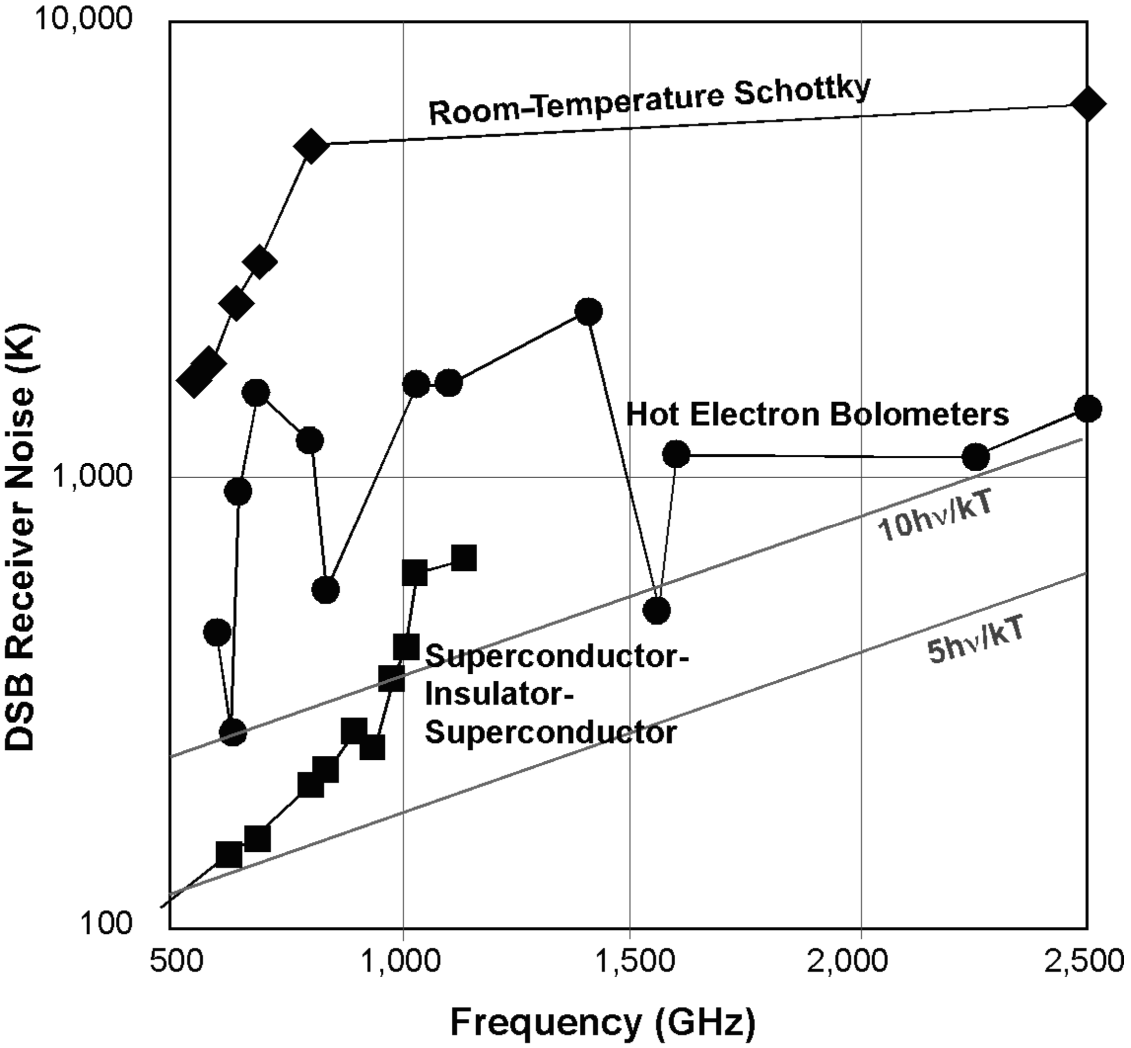

FIGURE 3-5 Heterodyne receiver noise temperatures (superconductor-insulator-superconductor, hot electron bolometers, and Schottky diodes) versus frequency in the millimeter-wavelength/terahertz range. NOTE: DSB, double sideband. SOURCE: P.H. Siegel. 2002. Terahertz technology. IEEE Microwave Theory and Techniques 50(3): 910.

Detectors can take on many forms, including those of Schottky diodes and bolometers. They are usually simple enough to be produced in arrays but must be integrated with micro antennas to efficiently couple RF energy into them. Since detectors are less sensitive than heterodyne receivers, they also must operate over a wide RF bandwidth, which makes the design of the micro antenna coupling more difficult. Some recent advances in detector technologies have been seen in the University of California at Santa Barbara (UCSB) work on unbiased metal-semimetal-semiconductor diodes that have good sensitivity and reduced 1/f noise, on zero bias backward tunnel diodes from HRL Laboratories, and on HEB devices that must be cooled to very low temperatures.

Some recent programs are also looking at other transition-edge bolometers that use the rapid transition in sensitivity of high-temperature superconductors, a nonlinear mechanism, for operation at liquid nitrogen temperatures.

SOURCES AND RECEIVERS: SUMMARY

In summary, the recent investment in component technology has been toward developing room-temperature sources and receivers that deliver performance required for the particular application. Sources and receivers that are cooled to low temperatures may exhibit performance that is reasonable for demonstrating imaging but have the potential burden of reliability and maintenance of vacuum and cooling systems.

The availability of millimeter-wave and terahertz components at a reasonable cost depends on the commercialization of the devices and systems based on those devices. While most millimeter-wave and terahertz devices over 100 GHz are handmade in small businesses and laboratories, DARPA has recently started a new program to push the state of the art of MMIC technologies beyond 300 GHz. Its Sub-Millimeter Wave Imaging Focal-Plane Technology program is intended to demonstrate an active subaperture operating at 340 GHz. Two key objectives will be the development of a coherent source capable of producing at least 50 mW from a single MMIC with a power-added efficiency of 5 percent and the development of an LNA having a noise figure of 8 dB operating at 340 GHz. If successful, these two MMIC components will not only raise the frequency of operational RF systems to 340 GHz but will also provide sources that can be used with multipliers to improve performance up into the terahertz region.

SYSTEM PERFORMANCE

Table 3-1 summarizes the performance trends of component technology as a function of increasing frequency or operating range that impact how well any millimeter-wavelength/terahertz system would be expected to perform.

While Table 3-1 only indicates trends, it does show how the phenomenological effects and component performance issues interact. In order to examine all of these effects on performance, a system model was developed to predict the performance of an imaging system designed to identify metal objects concealed underneath clothing in various weather conditions. The model is designed to predict the range at which a concealed object can be identified underneath clothing. The characteristics of the system, which were held constant, are delineated in the Table 3-2. This system is composed of a single detector and source pair that is scanned over the object being screened. It is not intended to describe any particular sensor architecture but rather to show the performance characteristics.

TABLE 3-1 Summary of Trends in Phenomenology and Component Technology

	Transmission Through Clothing	Transmission Through the Atmosphere	Resolution	Component Performance
Increasing frequency	↓	↓	↑	↓
Increasing distance	↔	↓	↓	↔

NOTE: ↑ = performance increases; ↓ = performance decreases; ↔ = no impact.

The component characteristics shown in Table 3-2 reflect the component goals of the DARPA TIFT program. The clothing material characteristics were developed by the Ohio State University and UCSB, as shown in Figure 2-4 in Chapter 2. The model was carried out under three different environmental conditions. The least challenging environment represented a winter condition at 25°F, which results in very low humidity and good atmospheric transmission. The most stringent condition represented what would be expected in the state of Maryland in August with conditions of high humidity: 95°F and 90 percent relative humidity. As the most critical component in the atmosphere is water vapor, these tests provide a good baseline for potential real-world operations.

TABLE 3-2 Parameters Used for Systems Analysis of Standoff Imaging Sensor

Model Component	Parameter
Transmitter and receiver antenna diameter	0.5 m
Transmitter power	10 mW
Receiver noise equivalent power	10-12 W/√(Hz)
Receiver bandwidth	5%
Frame rate	30 Hz
One-way path loss through clothing	1 dB per 100 GHz center frequency
Variation in clothing reflectivity	5%
Signal to clutter required for a good image	6:1
Size of object	75 mm
Resolution lines required for identification	7

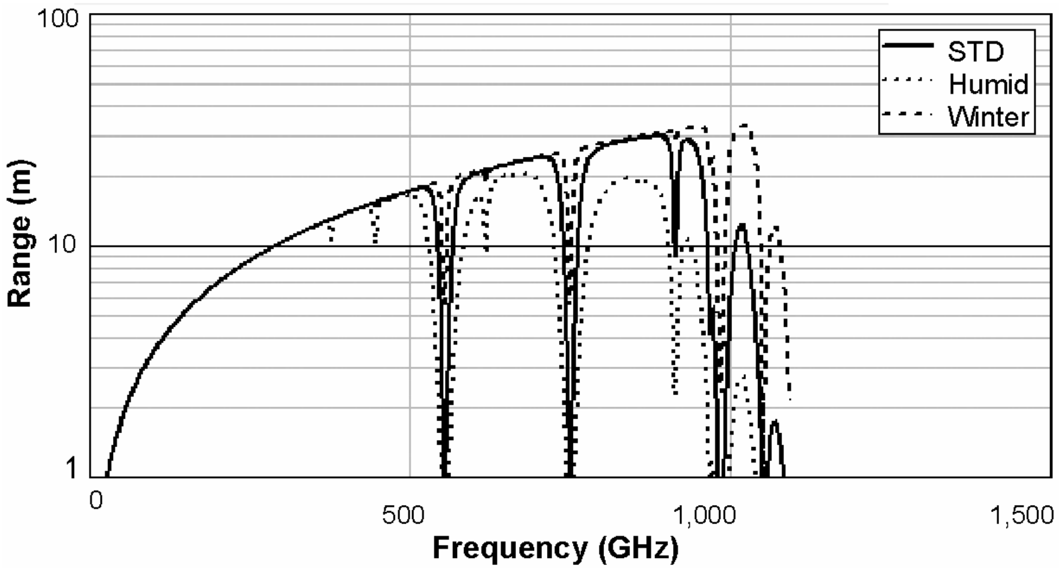

FIGURE 3-6 Predicted range to identify a concealed weapon using a single scanning spot sensor. NOTE: STD, standard.

There are three primary features to Figure 3-6. The first is that the range to achieve the required performance is first limited by the resolution of the system, which is a function of wavelength and antenna size; as previously shown for a given aperture (see Figure 2-1 in Chapter 2), higher frequency results in better resolution. If ranges of no greater than 10 m are desired to identify objects, according to the trends stated in Table 3-1, the atmosphere does not generally limit the range; resolution does.

The second feature visible in Figure 3-6 is the “dropouts” at various ranges. These are occurring at the frequencies where the atmosphere is so absorbing that negligible energy reaches the object to be imaged. Significant increases in system power or receiver sensitivity will have little impact on these features, as the attenuation is extremely high.

The third apparent feature in the figure is that the curves stop at approximately 1 THz. This is the point at which the variation in the reflection from the clothing covering the weapon is approaching the contrast of the clothing-covered object. At this point, the apparent contrast of the concealed object is competing with the variation in the reflections from the person, reducing performance below the desired 6:1 ratio. This effect is due to the increasing losses in the clothing as a function of frequency.

It has to be pointed out that there are very limited data on materials to accurately quantify the performance of systems in this region. Analysis of performance in this millimeter-wavelength/terahertz spectral region would benefit greatly from the extensive characterization of the reflectivities and losses of materials pertinent to the problem as well as the variability with aspect angle, surface roughness of materials, and environmental conditions. It is important to note that the components defined in the model have not yet been realized but are being developed, at fixed frequencies, under the DARPA TIFT program. Thus, at this point it is not prudent to develop applications based on more than one model.

Conclusion: The technology base for millimeter-wavelength/terahertz security screening is expanding rapidly internationally, yet there is insufficient technology available to develop a system capable of identifying concealed explosives.

Recommendation: To perform an accurate assessment of the applicability of millimeter-wavelength/terahertz-based technology to explosive detection, the Transportation Security Administration will need to do the following: (1) decide on the range of materials to be detected, (2) assess the state of knowledge of what chemical structures and/or features of the scope of materials lend themselves to detection by millimeter-wavelength/terahertz-based spectroscopy, (3) assess the presence of these features in other common materials (such as clothing) within the range of uncertainty for such features, and (4) assess the contribution of additives to explosives to the millimeter-wavelength/terahertz signature.

4

System Concepts

The design of imaging systems will certainly be driven by the performance requirements of specific applications. For example, a system designed to screen passengers in an airport for hidden weapons and explosives would focus on maximizing the contrast between threat materials and the human body with high resolution, but without placing too much emphasis on the ability to detect these weapons at high standoff distance. In a field application, resolution and contrast might be sacrificed for the ability to gather information when the subject is farther than a few meters away from the screener.

In this report, the committee focuses mainly on the screening of people in a controlled area such as an airport using a portal system, but it should be kept in mind that a change in the performance requirements also changes the importance and priority of the technology challenges.

SYSTEM-DEVELOPMENT REQUIREMENTS

The system-development requirements need to reflect the operational needs and validated threats and match the technology capabilities against those operational needs and threats.[1] The system-development requirements are to develop a technology that can accomplish the following:

1. Detect the presence, location, and identification of weapons (metallic and ceramic), explosive devices, and other proscribed items concealed underneath a person's clothing; and
2. Monitor a person for weapons (metallic and ceramic), explosive devices, and other proscribed items quickly and safely, without violating anyone's privacy.

An imaging system (or systems) is proposed because proscribed items and baggage now vary so broadly in terms of size and materials.

It is generally acknowledged that no single sensor technology has the capability to accomplish the entire mission. A millimeter-wavelength/terahertz imaging device is seen to be a critical subsystem in a layered system of complementary systems that can be dynamically reconfigured, combined, and deployed against an evolving terrorist threat to commercial transport. The most likely fielding of millimeter-wavelength/terahertz imaging systems will be accomplished as a part of an overall systems approach as an element of the passenger-screening checkpoint and baggage checkpoint, or as part of the access control to the secure areas of the facility or aircraft interior.

The principal imaging system components are these:

- A detector array and/or a scanning system,
- Image acquisition hardware and software,
- Image analysis and recognition computation,
- A database of key threat images and spectra,
- Display hardware, and
- A network interface with other elements of the layered system.

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[1] S. Mickan, D. Abbott, J. Munch, X.-C. Zhang, and T. van Doorn. 2000. Analysis of system trade-offs for terahertz imaging. Microelectronics Journal 31(7): 503-514.

SYSTEM CAPABILITIES AND DESIGN

The system-development requirements will drive the system design. Each requirement needs to be analyzed and validated to ensure that valid trade-offs between performance requirements and system design issues can be made.[2]

A comprehensive discussion of the screening technologies in various environments (indoor and outdoor, controlled and uncontrolled areas, day and night, and so on) and for various scenarios (pat-down search, surveillance, tracking, and so on) is found in a National Institute of Justice Guide 602-00, *Guide to the Technologies of Concealed Weapon and Contraband Imaging and Detection*.[3]

The goal of any millimeter-wavelength/terahertz imaging system will be not only to locate an object of concern but also to identify what it is. This process of identification begins with detection and progresses through processes variously described as recognition and classification. For this report, “detection” is defined as “the process for discriminating objects of possible interest from their surroundings.” An operator, however, may not know what type of object is detected but only that *something* was detected. Conventional walk-through metal detectors will let the operator know that metal objects have passed through the portal, but these systems do not provide the location or the identification of the type (gun versus keys) of the metal objects.

The next level of sophistication is to acquire images of the detection space and then to use image-recognition algorithms to convert the image into an indication (such as an audible or visual alarm). The imaging and image-recognition capability requires access to, or possession of, a large information (data) storage capability and significant computing power to provide the real-time detection capability of finding contraband hidden on individuals in a line of moving people.

The recognition process must follow a strict hierarchy of algorithms with ever-increasing thresholds in order to arrive at a positive indication with a high probability of recognition and low occurrence of false recognition. The algorithm taxonomy begins with the detection of an item or object of interest, followed by a decision on classification as threat or nonthreat. An item classified as threatening is further examined in order to recognize the threat, for example, a weapon or firearm. A package of explosives may be recognized as an anomaly in the body image because the reflective properties of the explosive differ from the reflective properties of a human body, as shown in Table 4-1. A further refinement is identification. The identification step may be necessary in order to reduce false positives generated by prosthetics, shoe shanks, and so on.

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[2] R.J. Hwu and D.L. Woolard, eds. 2003. Terahertz for military and security applications. Proceedings of SPIE [International Society for Optical Engineering], Vol. 5070; P.H. Siegel. 2002. Terahertz technology. IEEE Microwave Theory and Techniques 50(3): 910; E.R. Muller. 2003. Terahertz radiation: Applications and sources. The Industrial Physicist, August/September, p. 27; D.M. Mittleman, M. Gupta, R. Neelamani, R.G. Baraniuk, J.V. Rudd, and M. Koch. 1999. Recent advances in terahertz imaging. Applied Physics B: Lasers and Optics 68(6): 1085-1094.

[3] National Institute of Justice (NIJ). 2001. Guide to the Technologies of Concealed Weapon and Contraband Imaging and Detection. NIJ Guide 602-00. Prepared for NIJ, Office of Science and Technology, by Nicholas G. Paulter, Electricity Division, National Institute of Standards and Technology. Washington, D.C. February.

The task of developing an imaging system that is capable of identification is difficult at the onset and will require creative and innovative algorithm design. For the identification system to recognize a specific threat item, a catalog of images and spectral features is required, including the impact of unique orientations. Given that the set of all threats is extensive and the set of nonthreats is even more so, a method of learning must be implemented by which systems are networked and the catalog of threats and nonthreats can be updated continually.

Table 4-1 Reflectivity of Basic Explosives and Human Flesh

Substance	Name	Molecular Weight	Density (g/cm^3)	Dielectric Constant	Reflectivity R	Reflectivity −dB
TNT	2,4,6-Trinitrotoluene	227.13	1.65	2.7	−0.24	12.3
RDX	Hexahydro-1,3,5-trinitro-1,3,5-triazine	222.26	1.83	3.14	−0.28	11.1
HMX	Cyclotetramethylene-tetranitramine	296.16	1.96	3.08	−0.27	11.2
PETN	Pentaerythritol tetranitrate	316.2	1.78	2.72	−0.25	12.2
Tetryl	2,4,6-Trinitrophenyl-N-methylnitramine	287.15	1.73	2.9	−0.26	11.7
NG	Nitroglycerin	227.09	1.59	19	−0.63	4.1
AN	Ammonium nitrate	80.05	1.59	7.1	−0.45	6.9
Comp B	RDX TNT			2.9	−0.26	11.7
Comp C-4	RDX			3.14	−0.28	11.1
Detasheet	PETN			2.72	−0.25	12.2
Octol	HMX TNT			2.9	−0.26	11.7
Semtex-H	RDX-PETN			3	−0.27	11.4
Human flesh	H_2O + NaCl		0.93	88	−0.81	1.9

NOTE: R, reflectance; dB, decibel.

Screening Considerations

Imaging data that have been collected and processed and alarmed are typically passed to a human operator for final disposition. Thus, it is important to design the system and the human operator's role together if costly mistakes are to be avoided at the deployment stage. This applies in a situation in which the human role ranges from the unaided interpretation of a screen image to the interpretation of machine-suggested decisions. While this challenge is true for any security technology, imaging presents some unique problems, as the operator has direct, often visual, access to data about a passenger's body and clothing. This access raises both cultural issues of persons being under intimate observation and performance issues of interpretation of indications that may require subsequent physical access to the passenger's body. A question is whether operators and their managers will attempt to avoid specifying a hand search that the passenger is likely to find intrusive.

Conclusion: Millimeter-wavelength/terahertz image quality raises personal privacy issues that need to be addressed.

Recommendation: As with x-ray-based passenger imaging, the Transportation Security Administration needs to address issues associated with personal privacy raised by the millimeter-wavelength/terahertz imaging.

Human Operators

The most basic level of integration between the imaging system and the human operator is to ensure that the display provides an image that has sufficiently high spatial resolution and contrast to make a threat detectable with a high probability. This problem has largely been solved for other imaging systems by combining the modulation transfer function of the system with the contrast sensitivity function of the human eye. Unless requirements at this level are met, detection is not possible.

At the next level, the system must be able to search for and recognize the threats for which it is being deployed. Unaided human search is possible, but it is not considered highly reliable compared with a computer-augmented search for well-defined threat targets. The human visual search process is time-intensive, as it is a self-terminating, exhaustive search, albeit guided by expectations and experience—for example, knowing where to look first for potential targets. Search, whether of the unaided-human or machine-augmented type, ends in one of two ways: with the discovery of an indication or with the decision not to spend more time on a particular image and to move on to the next one.

The next logical function is recognition, that is, the classification of an indication as either a threat or a nonthreat. Note that this classification can be deferred by a demand for additional information from beyond the imaging system—for example, for a pat-down search. Human recognition depends strongly on both the orientation of the target and on the training of the human operator. Training programs that expose operators to a variety of views of each class of threat in a controlled manner have been highly effective in improving x-ray checkpoint screening.[4] These programs allow the operator to build up prototypical templates of each threat class, so that an unusual example of the threat class or an unusual view of the threat can be understood and recognized. At the level of human-and-system integration, the imaging system and the training program need to be designed together to optimize system performance.

At the highest level of human-and-system integration, the imaging system must be designed for the cultural background in which it will operate in the field. Privacy concerns need to be addressed, presumably by using the principle of choice: the passenger can choose between the imaging system and a currently fielded non-imaging approach, such as pat-down search. Where this has been tried—for example, in London Heathrow Airport (LHR)—passengers have overwhelmingly chosen the imaging

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[4] A. Schwanger. 2005. Increasing efficiency in airport security screening. WIT Transactions on the Built Environment: Safety and Security Engineering 82: 405-416. WIT Press, Southampton, United Kingdom.

alternative.[5] In other applications, such as area surveillance where people may not be passengers, less-revealing technologies may be more appropriate.

Cultural factors constitute only one in a larger set of factors influencing the bias that operators bring to a final decision. In any decision situation with serious consequences, and security decisions are certainly in that category, the operator chooses a balance between two errors: missing a threat and creating a false alarm. Signal detection theory (SDT) is the usual quantitative model for how the biases arise in such binary decisions. On the basis of the perceived costs and payoffs of the outcomes and the perceived prior probability of a true threat, the operator chooses a decision criterion for how much certainty is needed to report a threat. Any factors that might result in a cost of some kind are likely to influence the choice of criterion. For example, if operators perceive that their management wishes to avoid the embarrassment of calling for an unnecessary pat-down search with a sensitive passenger, an operator may not make that request, possibly resulting in a security breach.

Finally, as in all security applications, good human factors in the design of the equipment, its human interface, the physical ergonomics of the workplace, and the sociotechnical design of the organization play a part in ensuring that performance meets security needs. To cite an extreme example, even poor body posture can reduce the quality of performance in an inspection task.[6] Only by analyzing the operational situation and adapting the system for compatibility between the operational environment and the human physical, cognitive, and social functioning in that environment can any security system function as planned.

SECURITY SYSTEMS UNDER DEVELOPMENT

Passenger Portal Scanning

Active Millimeter-Wavelength Imaging—Pacific Northwest National Laboratory

Active millimeter-wave imaging technologies operate as short-range radar systems that project a narrow beam of millimeter-wave energy against a target and detect the reflected rays. The beam is scanned from head to toe or toe to head to produce an image of the subject. The U.S. Department of Energy's Pacific Northwest National Laboratory (PNNL) has developed a system for screening people that is based on active millimeter-wave technology. This method involves illuminating the subject with millimeter-wave radiation, but at a level low enough to prevent adverse health effects. However, the popular perception of the dangers of microwave radiation may cause public concern over this imaging technique.

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[5] Austin Considine. October 9, 2005. Will new x-rays invade privacy? The New York Times. Available at http://travel2.nytimes.com/2005/10/09/travel/09xray.html?pagewanted=1&ei=5070&en=ae024c7c386b9100&ex=1164344400. Accessed November 22, 2006.

[6] V. Bhatnager, C.G. Drury, and S.G. Schiro. 1985. Posture, postural discomfort and performance. Human Factors 27(2): 189-200.

Active millimeter-wave imaging bounces waves off the object being scanned, then reads and images the reflected waves. The image processor acts as the lens, focusing the millimeter waves to form the image. A vertical scanner and a 112-element horizontal linear array of antennas scan a person in 1 second. The radar array distributes the illuminating source from the transmitter over the length of the imaging aperture. At the same time, the array receives reflected millimeter-wave signals from the person under surveillance. A computer processes the data obtained from the scan and reconstructs it into high-resolution images. Unlike passive millimeter-wave systems that operate at 100 GHz, the PNNL scanner operates at between 12 GHz and 18 GHz. PNNL has entered into a commercial relationship with SafeView, Inc., of Santa Clara, California, to develop and market an entry portal based on the PNNL holographic imager.

25 GHz to 30 GHz Three-Dimensional Imager—SafeView

Using active millimeter-wave scanning technology developed at PNNL, SafeView has developed a line of next-generation security scanning portals[7] (Figure 4-1). These portals allow security personnel to determine safely and efficiently if people—whether visitors, employees, residents, guests, or passengers—are transporting undesirable objects onto or off the premises. This approach is an effective alternative to metal detectors, x-ray machines, and pat-down searches at security checkpoints. Airports using or in the process of conducting trials with millimeter-wave technology are Schiphol (Amsterdam), Mexico City, Jeddah (Saudi Arabia), Chiang Mai (Thailand), and Madrid (Spain), and the technology is under consideration in the United Kingdom, Italy, Australia, Russia, and Singapore.

FIGURE 4-1 SafeView security screening portal. SOURCE: Courtesy L-3 Communications, SafeView.

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[7] 3-D Holo Body Scanner: Description. Available at http://availabletechnologies.pnl.gov/securityelectronics/bodydescription.stm. Accessed August 25, 2006.

Millimeter-wave three-dimensional imagers have been deployed at several locations outside the United States. The results of these field trials indicate that a millimeter-wave imaging portal may be a compelling application for the detection of explosives hidden underneath clothing.[8] The results are published in press releases and on company Web pages, and thus the performance claims for detection and false-alarm rates tend to be anecdotal and optimistic. A well-designed field trial by an independent evaluator is needed to establish sound performance characteristics for millimeter-wave imaging systems.

For security applications, backscatter x-ray imagers and millimeter-wavelength/terahertz imagers produce images of quality and resolution similar to the quality and resolution from millimeter-wave three-dimensional imaging. X-ray photons have sufficient energy (100 electronvolts [eV] to 1 megaelectronvolt [MeV]) to penetrate dense materials, to cause chemical damage to molecules, and to knock particles out of atoms. Hence, they produce ionizing radiation.[9] Millimeter-wavelength/terahertz radiation is an electromagnetic wave with longer wavelengths and lower frequency than x-rays by several orders of magnitude. A millimeter-wavelength/terahertz photon does not have sufficient energy (~0.01 eV) to penetrate dense materials, cause chemical damage to molecules, or knock particles out of atoms.[10] Thus, it is non-ionizing radiation. The safety of millimeter-wavelength/terahertz energy has been established by a 2004 European Union study entitled *THz-BRIDGE—Tera-Hertz Radiation in Biological Research, Investigation on Diagnostics and Study of Potential Genotoxic Effects*.[11] Of note, this study has specific discussions on the little information that exists on corneal epithelial cells, which suggests that there are no adverse effects from exposure.

Conclusion: Millimeter-wavelength/terahertz technology and x-rays provide images of similar quality. However, millimeter-wavelength/terahertz energy has the safety benefit of being non-ionizing radiation, while x-rays are ionizing radiation. Millimeter-wavelength/terahertz energy cannot penetrate metal objects.

Recommendation: The Transportation Security Administration should examine how millimeter-wavelength/terahertz technology can be employed with other technologies to enhance the detection of weapons and explosives.

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[8] Shareholder Relations. 2006. Endwave Makes Initial Production Deliveries to L-3 SafeView for Phase II Switch Arrays: RF Designs Utilize Endwave's New Epsilon™ Packaging Technology. Available at http://www.shareholder.com/endwave/news/20060517-197245.cfm. Accessed August 25, 2006.

[9] National Institute of Standards and Technology. 1996. Table of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients. Available at http://physics.nist.gov/PhysRefData/XrayMassCoef/cover.html. Accessed August 28, 2006.

[10] By comparison: ultraviolet light is 50 eV, visible light is 2 eV, microwaves are 0.0001 eV, and radiowaves are 0.00000009 eV.

[11] G.P. Gallerano et al. 2004. THz-BRIDGE: Tera-Hertz Radiation in Biological Research, Investigation on Diagnostics and Study of Potential Genotoxic Effects. Available at http://www.frascati.enea.it/THz-BRIDGE/reports/THz-BRIDGE%20Final%20Report.pdf. Accessed August 28, 2006.

Standoff Scanning

Passive Millimeter-Wave Scanner—QinetiQ

The QinetiQ (pronounced like “kinetic”) passive millimeter-wave scanner[12] can scan large numbers of people and vehicles as they move in a continual stream through restricted or controlled areas, such as border checkpoints, airport terminals, or outdoor arenas. Most objects reflect radiation. As stated previously, the human body reflects about 35 percent of the incidental millimeter-wave radiation that it receives. At these levels, clothing and other materials appear transparent, giving the scanner operator a highly accurate and real-time image of the now-uncovered subject. The scanner sees guns, knives, and metal and ceramic devices through clothes and bags.

The scanner is completely passive, safe, and radiation-free. The QinetiQ system can operate covertly or overtly to give an instantly clear and comprehensive picture of the subjects, who need never know they have been scanned.

Millimeter-Wave Imaging System—Agilent Technologies

Agilent Technologies is developing a millimeter-wave imaging system based on a reflective, confocal millimeter-wave lens (see Figure 4-2). Agilent claims that the active millimeter-wave panel at less than 6 inches deep and under 30 pounds has demonstrated capabilities to locate concealed objects (explosive simulants,[13] metals, and ceramics) through typical clothing materials (wool, leather, cotton, and synthetics) as well as through plastics, commercial wallboard, and glass. This system was only recently announced, and as of this writing, limited information has been released by the company.

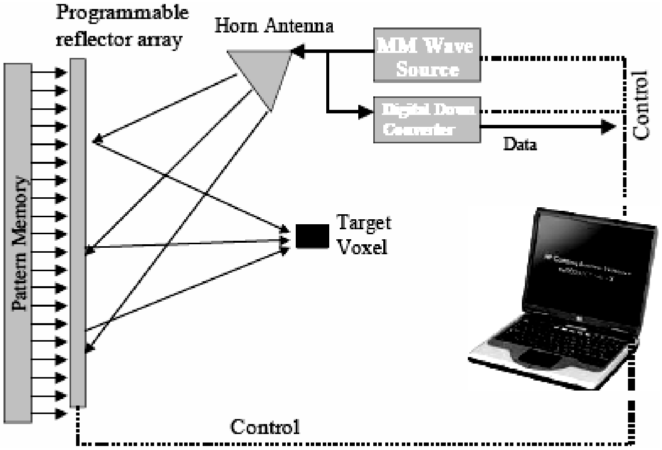

FIGURE 4-2 Agilent Technologies millimeter-wave imaging system based on a reflective, confocal millimeter-wave lens.

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[12] QinetiQ. 2005. Case Studies—Security. Available at http://www.qinetiq.com/home/case_studies/security/pmmw_scanning.html. Accessed August 28, 2006.

[13] Simulants are inert materials with densities and reflectivities similar to those of explosives (see Table 4-1 in this chapter).

Passive Millimeter-Wave Imaging—Millitech

Millitech, LLC, is developing a passive millimeter-wave (W-band) imaging sensor designed for use at a distance of up to 12 feet for the rapid and remote detection of metallic and nonmetallic weapons, plastic explosives, drugs, and other contraband concealed under multiple layers of clothing.[14]

When a person is scanned using this sensor, any concealed item shows up as a dark image against the lighter background image of the individual. This system was only recently announced, and as of this writing, limited information has been released by the company. Because this purely passive imaging technique relies solely on existing natural emissions from objects, it does not require human-made irradiation. To demonstrate the technology, Millitech is currently developing a proof-of-concept camera with a 300 millimeter aperture and monitoring console for fixed entranceway surveillance. Millitech has recently been acquired by Smiths Group.

Passive Millimeter-Wave Camera—Trex Enterprises Corporation

Under U.S. Army-sponsored development since 1992,[15] Trex Enterprises' Passive Millimeter-Wave Camera has demonstrated the ability to create thermal imagery at video frame rates, converting naturally occurring heat from the environment into monochromatic imagery in real time.[16] A prototype wide-field system has the following specifications:

- 77 GHz to 95 GHz real-time (30 Hz) imaging sensor,
- 2 ft aperture,
- 0.35° angular resolution,
- 1.7° temperature resolution at 30 Hz, and
- 30° by 24° field of view.

Trex Enterprises' Passive Millimeter-Wave Camera couples a planar millimeter-wave antenna with a low-noise phased-array receiver/processor and an array of millimeter-wave spectrum analyzers to realize a compact radiometer architecture for use in confined spaces.

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[14] Millitech, LLC. 2005. Microwave and Millimeter Wave Radiometry. Available at http://www.millitech.com/pdfs/Radiometer.pdf. Accessed August 28, 2006.

[15] Stuart E. Clark, John A. Lovberg, Christopher A. Martin, and Vladimir Kolinko. 2003. Passive millimeter-wave imaging for airborne and security applications. Passive Millimeter-Wave Imaging Technology VI and Radar Sensor Technology VII, Roger Appleby, David A. Wikner, Robert Trebits, and James L. Kurtz, eds. Proceedings of SPIE, Vol. 5077.

[16] Stuart E. Clark, John A. Lovberg, Christopher A. Martin, and Joseph A. Galliano. 2002. Passive millimeter-wave imaging for concealed object detection. Sensors, and Command, Control, Communications, and Intelligence (C3I) Technologies for Homeland Defense and Law Enforcement, Edward M. Carapezza, ed., Proceedings of SPIE, Vol. 4708.

Passive Millimeter-Wave Weapons-Detection System—Brijot

Brijot Imaging Systems, Inc.,[17] in conjunction with Lockheed Martin, is developing an automated target-recognition-based concealed-weapons-detection system to detect and identify weapons underneath a person's clothing. It consists of a millimeter-wave camera combined with a videocamera and special algorithm software. Outputs are a real-time video with visual identification of where a suspicious item is located on a person and electronic alarm notification signaling. The camera system is completely passive and is designed to operate at a range of up to 45 feet.

Millimeter-Wave Imaging—Millivision

The Millivision camera uses focal-plane-array technology, an imaging process that employs receiver elements positioned along the focal plane of the optical system. In addition to using a primary lens, optic filters, wave plates, and other elements, the Millivision imagers use a new class of optics employing arrays of wave-processing monolithic microwave integrated circuit (MMIC) chips from HRL (Malibu, California). The chips, which are made from indium phosphide, amplify the weak signals and perform the signal-processing functions on the electromagnetic waves. (The Millivision patents have been acquired by the L-3 Corporation.)

Conclusion: Millimeter-wavelength/terahertz technology in portal applications has been demonstrated for detecting and identifying objects concealed on people.

Recommendation: The Transportation Security Administration should commence developmental and operational testing of millimeter-wave-based portals to assess their effectiveness and suitability.

Conclusion: Universities, national laboratories, and the commercial sector (both national and international businesses) continue to increase investment in millimeter-wavelength/terahertz technologies for security, medical, nondestructive inspection, and manufacturing quality-control applications.

Recommendation: The Transportation Security Administration should actively pursue joint projects through agreements such as cooperative research and development agreements with industry, academia, the Department of Defense, and the national laboratories to benefit from their investments in millimeter-wavelength/terahertz technology and applications.

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[17] Brijot Imaging Systems, Inc. 2006. BIS-WDS™ Prime. Available at http://www.brijot.com/bis-wds.php. Accessed August 28, 2006.

Baggage Scanning

The current technologies employed to screen both carry-on and checked baggage are based on x-rays. The images produced result from density variations. The shape and size of items in the image are examined visually for carry-on baggage and with a computer for computed tomography images of checked baggage. Suspicious items are then examined manually for identification. A technique to reliably identify the chemical structure of a suspect item remotely would improve baggage throughput by resolving alarms. Mass spectroscopy systems to detect explosives by means of vapor analysis are currently going through field trial investigations.

As discussed in Chapter 2 of this report, there is a significant ongoing effort in examining terahertz time domain spectroscopy (TTDS) to detect spectral features of explosives. There have been numerous reports of TTDS being used for explosives detection in transmission mode. However, for real-field applications, reflection measurements are preferred, since most bulky targets are impossible to measure in a transmission mode, in which the targets will attenuate the incident energy completely. The reflection mode may be used in a standoff detection system, but it is not clear that individuals and vital assets could be outside the zone of severe damage of an explosive detonation.

Conclusion: Millimeter-wavelength/terahertz technology has potential for contributing to overall aviation security, but its limitations need to be recognized. It will be most effective when used in conjunction with sensor technologies that provide detection capabilities in additional frequency regions.

5

Implementation Strategy for the Deployment of Millimeter-Wavelength/Terahertz Technologies for Aviation Security

The millimeter-wavelength/terahertz spectral region has been the province of scientists and engineers for many years and has only recently been endowed with the label "hot research topic" with real business potential. Past applications have generally been for sophisticated experimentation or military use, and this work continues. Past commercial applications have been tried and/or discussed for four decades. These include the manufacture of power cables, the measurement of dehydration in plants and animals, imaging systems for environmental problems such as detection of oil spills, imaging for law enforcement, and a variety of proposals for remote detection of gaseous species.

Many of these past applications are sound concepts; they have not blossomed into commercial businesses for a variety of reasons.

The deployment of millimeter-wavelength/terahertz technologies in aviation security applications has to be made with a full appreciation of multiple past failed attempts and the realistic promise that newer work and concepts offer. It can be said that the past millimeter-wavelength/terahertz business case suffered from a “chicken-and-egg” problem. Promising applications depend on low cost and the availability of hardware; low cost and available hardware depend, in turn, on investments associated with applications. It can also be said that this “crossover spectral region” where the radiation is neither optical nor electronic[1] has created special challenges for the design engineer attempting to build hardware. Neither a compelling application nor a compelling breakthrough design concept has emerged to change the paradigm. Therefore, the committee is left with assessing the hardware and applications in an incremental or evolutionary sense, building on the current commercial progress.

First, there is no evidence for a current compelling application in the millimeter-wavelength/terahertz spectral region. There does seem to be new promise for a number of industrial or medical applications that are useful. Based on recent developments one can cite the following:

- Nondestructive inspection through dielectrics using TTDS pulse techniques,
- Medical use through skin or thin tissue for nonintrusive inspection, and
- Millimeter-wave imaging of people to detect contraband underneath clothing.

The committee notes that the imaging of people using millimeter-wave techniques is not really a compelling application, since x-ray techniques can also be used. The millimeter-wave techniques have one stand-out advantage. This radiation is non-ionizing and does not cause tissue damage, which trumps x-ray techniques if an individual is to be inspected repeatedly in a venue such as a prison. If one credits public perception as an important consideration (and this has certainly been the case in some screening applications), millimeter-wave trumps x-ray inspection for the general public. Still, the intrusive inspection of people may require extensive public relations campaigns for either technique to succeed. This may be a less prominent issue for government applications. Otherwise, cost and performance determine the usage.

A clear-cut case can be made for a millimeter-wave portal used for scanning people. Several businesses, Millitech, MilliVision, QinetiQ, SafeView, and Trex Enterprises, are building hardware and creating the production environment essential to successful portal performance, reliability, supportability, and cost reduction. Venture-capital investment is attracted by the business diversity of such a portal, which can operate to detect drugs and guns carried by people, for purposes of transportation security, security of government buildings, security of ports, customs, requirements of prisons, security of commercial buildings, and so on. Applications have been developed that use millimeter-wave imaging for the fitting of clothing as well as for the detection of the removal of contraband, such as computer hardware from industrial sites. All of these business opportunities are enhanced by the increasing global terrorist threat and the

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[1] That is, electron, neutron, x-ray, ultraviolet, infrared, and microwave radiation.

proliferation of drug trafficking. It would seem that aviation security could take advantage of this business base to fine-tune portal requirements for its use in a cost-effective manner.

Conclusion: A decision by the Transportation Security Administration to invest in an imaging portal depends on the potential threat posed by passengers carrying either weapons or explosives or other material. The cost of a system, the probability of detection, the false-alarm rate, and the throughput versus that of a competing x-ray system would impact the management decision.

This trade-off is, of course, influenced by the increasing sophistication of the perpetrator, who may use nonmetallic guns or knives or unconventional explosives. As a minimum, it would seem advisable to thoroughly test such a portal both technically and operationally to provide a firm basis for making deployment decisions.

Recommendation: The Transportation Security Administration should follow a two-pronged investment strategy:

- Focus on millimeter-wave imaging as a candidate system for evaluation and deployment in the near term, and
- Invest in research and development and track national technology developments in the terahertz region.

Inherent in all of the discussion above is the recognition that aviation, port, building, border, or prison security venues will surely require some tailoring of millimeter-wave portals to suit each individual application and its public acceptance. Serious contemplation of millimeter-wave portal use needs to include these costs in the strategic plan for evaluation and deployment.

TEST AND EVALUATION

Privacy Issues

Operational trade-offs among the level of automation, manual operation with a highly trained operator to interpret images, false-alarm rate, and throughput performance will drive the ultimate design of a millimeter-wavelength/terahertz-based detection system. The performance criterion will be the probability of detection achieved versus the rate of false positives at a specified throughput.

For systems that provide detailed images of anatomical features, other factors such as privacy and modesty issues need to be considered. In general, displaying detailed anatomical features of a person is considered a violation of that individual's privacy. The issue of whether it is or is not a violation of privacy to acquire an image with anatomical detail even though the image is never displayed needs be addressed rigorously by experts in the legal, human factors, and psychological areas.

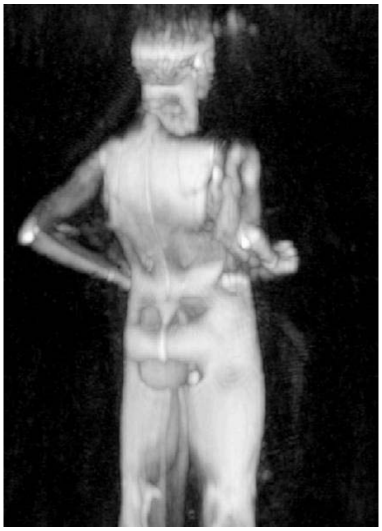

FIGURE 5-1 Millimeter-wave image—Pacific Northwest National Laboratory.

The image in Figure 5-1 has a resolution of less than 1 cm, and when displayed on a monitor shows sufficient detail to be offensive or embarrassing to many people. Legal challenges are likely from privacy groups. The following is a statement of Timothy D. Sparapani, American Civil Liberties Union legislative counsel, at a hearing regarding the U.S. Transportation Security Administration's physical screening of airline passengers and related cargo screening before the U.S. Senate Committee on Commerce, Science, and Transportation on April 4, 2006:

> Passengers expect privacy underneath their clothing and should not be required to display highly personal details of their bodies—such as evidence of mastectomies, colostomy appliances, penile implants, catheter tubes, and the size of their breasts or genitals—as a prerequisite to boarding a plane. However, X-ray backscatter technology has tremendous potential to screen carry-on bags, luggage, and cargo.[2]

The National Research Council report entitled *Airline Passenger Security Screening: New Technologies and Implementation Issues* includes a complete and thorough presentation on the key issues of health, convenience, privacy, and comfort that will determine the acceptance or rejection of imaging technologies. To address privacy concerns about and obtain public acceptance of full-body imaging will require careful and extensive public education to preclude the spread of "urban legends" and false or misleading information. The report states:

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[2] Statement of Timothy D. Sparapani, American Civil Liberties Union Legislative Counsel, at a Hearing Regarding the U.S. Transportation Security Administration's Physical Screening of Airline Passengers and Related Cargo Screening Before the U.S. Senate Committee on Commerce, Science, and Transportation. 2006. Available at www.aclu.org/privacy/gen/24856leg20060404.html. Accessed August 28, 2006.

> The panel concluded that the images produced by these technologies are of sufficiently high quality to make them effective for screening passengers. However, when the perceived level of threat is low, passengers, crews, and others passing through screening checkpoints are likely to object to having images of their bodies displayed. There are also likely to be concerns about the use and storage of the data used to generate images. Procedures, such as having operators of the same sex view the images or moving operators away from the screening checkpoints, could allay concerns. However, for financial and logistical reasons, these procedures are likely to make imaging technologies extremely unattractive for use as primary screening systems at all checkpoints. Quantifying the level of threat at which people are likely to accept this kind of invasion of privacy is difficult but necessary prior to mandating the use of any imaging technology for screening passengers at airports.[3]

The resolution of privacy issues in other countries is not likely to be relevant to the resolution of these issues in the United States because local attitudes and perceptions determine the issues of privacy to be addressed. In practice to date, many of these issues are solved via the operational protocols adopted by various countries. For example, only male operators screen males, and females screen females. The person screening is remote and does not see the subject, and vice versa. Also, software allows for various measures of privacy and automatic target detection. Finally, imaging allows for “directed search,” which means that in place of a full pat-down, the person has to explain or show only what is in a specific area, typically a pocket.

Decisions on such issues will have to be made prior to a deployment of these imaging technologies. For this report, the committee limited its review to the technical issues that would move these technologies closer to implementation, without considering the public’s acceptance of the deployed technology.

A field trial to gauge both feasibility and public acceptance of such technology was conducted by QinetiQ at Gatwick Airport and summarized as follows: “The results of this trial indicated that public reaction to the possible introduction of this technology into UK airports has been favorable, and that the performance of this imager in detecting specific threat items concealed on passengers, such as metal or ceramic weapons has been very encouraging.”[4]

Cost Issues

In the past decade, the cost reductions and performance improvements of devices to generate, control, and detect radiation in the spectral region millimeter-wavelength/terahertz made detection systems viable for checking baggage and scanning people. However, a reasonable and affordable initial cost is only part of the total life-cycle cost of a deployed operating system. There are other recurring and nonrecurring costs over the lifetime of the system that will likely exceed the initial purchase price. The following are

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[3] National Research Council. 1996. Airline Passenger Security Screening: New Technologies and Implementation Issues. National Academy Press, Washington, D.C.

[4] H. Oman, ed. 2003. Conference Report: 36th International Canahan Conference on Security Technology. IEEE AESS Systems Magazine 18(4): 28-40.

other issues that should be considered in the life-cycle cost analysis and evaluation of millimeter-wavelength/terahertz imaging systems:

- *Installation*—time, footprint, and skill requirements for installation personnel;
- *Integration*—interconnectivity and interoperability implementation costs;
- *Reliability*—expected lifetime before replacement, MTBF (mean time before failure) statistics, and unscheduled downtime costs;
- *Scheduled downtime*—calibration or scheduled maintenance costs;
- *Repairs*—MTTR (mean time to repair) statistics, availability of repair parts, warranty, onsite or offsite, and skill requirements;
- *Environmental*—Occupational Safety and Health Administration requirements; and
- *Training*—initial and update training, operator skill-level requirements.

A valid life-cycle cost analysis needs sound data input. These data (1) can be developed using widely acceptable reliability predictor models, or (2) be gathered from operations of similar systems and complete logs maintained during the pilot demonstration phase of system deployment. Industrial experience has shown that initial cost may comprise only 10 to 15 percent of the total cost.[5]

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[5] J.T. Bailey and S.R. Heidt. 2003. Why Is Total Cost of Ownership (TCO) Important? If You Want to Know Where Your Money Goes, Get Ready to Master the Concept of TCO. Available at http://www.darwinmag.com/read/110103/question74.html. Accessed August 28, 2006.

6

Conclusions and Recommendations

This chapter is a compilation of all of the conclusions and recommendations presented throughout the report.

CONCLUSIONS

1. The technology base for millimeter-wavelength/terahertz security screening is expanding rapidly internationally, yet there is insufficient technology available to develop a system capable of identifying concealed explosives.

2. Millimeter-wavelength/terahertz technology has potential for contributing to overall aviation security, but its limitations need to be recognized. It will be most effective when used in conjunction with sensor technologies that provide detection capabilities in additional frequency regions.
3. Millimeter-wavelength/terahertz technology in portal applications has been demonstrated for detecting and identifying objects concealed on people.
4. Millimeter-wavelength/terahertz image quality raises personal privacy issues that need to be addressed.
5. Millimeter-wavelength/terahertz technology and x-rays provide images of similar quality. However, millimeter-wavelength/terahertz energy has the safety benefit of being non-ionizing radiation, while x-rays are ionizing radiation. Millimeter-wavelength/terahertz energy cannot penetrate metal objects.
6. Universities, national laboratories, and the commercial sector (both national and international businesses) continue to increase investment in millimeter-wavelength/terahertz technologies for security, medical, nondestructive inspection, and manufacturing quality-control applications.
7. A decision by the Transportation Security Administration (TSA) to invest in an imaging portal depends on the potential threat posed by passengers carrying either weapons or explosives or other material. The cost of a system, the probability of detection, the false-alarm rate, and the throughput versus that of a competing x-ray system would impact the management decision.

RECOMMENDATIONS

1. To perform an accurate assessment of the applicability of millimeter-wavelength/terahertz-based technology to explosive detection, the TSA will need to do the following: (1) decide on the range of materials to be detected, (2) assess the state of knowledge of what chemical structures and/or features of the scope of materials lend themselves to detection by millimeter-wavelength/terahertz-based spectroscopy, (3) assess the presence of these features in other common materials (such as clothing) within the range of uncertainty for such features, and (4) assess the contribution of additives to explosives to the millimeter-wavelength/terahertz signature.
2. The TSA should examine how millimeter-wavelength/terahertz technology can be employed with other technologies to enhance the detection of weapons and explosives.
3. The TSA should commence developmental and operational testing of millimeter-wave-based portals to assess their effectiveness and suitability.
4. As with x-ray-based passenger imaging, the TSA needs to address issues associated with personal privacy raised by millimeter-wave/terahertz imaging.
5. The TSA should actively pursue joint projects through agreements such as cooperative research and development agreements with industry, academia, the Department of Defense, and the national laboratories to benefit from their

investments in millimeter-wavelength/terahertz technology and applications.

6. The TSA should follow a two-pronged investment strategy:
   - Focus on millimeter-wave imaging as a candidate system for evaluation and deployment in the near term, and
   - Invest in research and development and track national technology developments in the terahertz region.

Appendixes

Appendix A

Acronyms

ATSA	Aviation and Transportation Security Act
BWO	backward wave oscillator
DARPA	Defense Advanced Research Projects Agency
DSB	double sideband
EDS	explosive detection system
EM	electromagnetic
GHz	gigahertz

HEB	hot electron bolometer
HMX	cyclotetramethylene-tetranitramine
IEEE	Institute of Electrical and Electronics Engineers
IHVS	Intelligent Highway Vehicle System
IMPATT	Impact Ionization Avalanche Transit Time
LHR	London Heathrow Airport
LMDS	Local Multipoint Distribution System
LNA	low-noise amplifier
LO	local oscillator
MMIC	monolithic microwave integrated circuit
MTBF	mean time before failure
NaCl	sodium chloride
NRC	National Research Council
OSU	Ohio State University
PE4	plastic explosive
PETN	pentaerythritol tetranitrate
PNNL	Pacific Northwest National Laboratory
PSI	Physical Sciences, Inc.
QC	Quantum Cascade
RDX	cyclotrimethylene-trinitramine
RF	radio frequency
RTD	Resonant Tunneling Diode
SDT	signal detection theory
SLED	Super Luminescent Diode
STD	standard
TIFT	Terahertz Imaging Focal Plane Array Technology
TNT	trinitrotoluene
TSA	Transportation Security Administration
TSL	Transportation Security Laboratory
TTDS	terahertz time domain spectroscopy
TUNNETT	Tunnel Injection Transit Time
UCSB	University of California at Santa Barbara
VED	vacuum electronic device

Appendix B

Committee Biographies

James F. O'Bryon (*Chair*) served as Deputy Assistant Secretary of Defense until his retirement in 2001. During his 15 years in the Pentagon, he served under seven Secretaries of Defense as director, live fire testing, and deputy director, operational test and evaluation. Mr. O'Bryon also worked in various positions within the office of the Director of Defense Research and Engineering, Undersecretary of Defense for Acquisition and Technology, overseeing and directing testing and evaluation activities for the Secretary of Defense, including examining test plan adequacy, test execution, vulnerability, lethality, and survivability of the nation's major defense systems, and application of tactics and doctrine to these issues. He has testified before various committees of the U.S. Congress on defense and homeland security issues as well as drafting the Secretary of Defense's reports on system survivability, vulnerability, and lethality. He has served on more than a dozen committees addressing such issues as directed energy, ozone-depleting compounds, and modeling and simulation. His degrees are from The King's College, George Washington University, and the MIT. He has also served for nearly 20 years as a mathematician, ballistician, and weapon systems analyst at the Ballistic Research Laboratories and the Army's Materiel Systems Analysis Activity. He currently works as an independent defense consultant for several government, not-for-profit, and defense industries and serves as president of The O'Bryon Group.

Sandra Hyland (*Vice Chair*) is Etching System Group Manager, Tokyo Electron (TEL) Technology Center America, responsible for TEL's etch process development at the Albany Nanotechnology Center at the University of Albany. She supports oxide and low-k film etch for integrated development projects for TEL and IBM, as well as for other members of the Nanotechnology Center. Formerly, she was East Coast manager for TEL Etch Systems, analyzing technology trends and customer data to determine hardware and process needs for manufacturing current and next-generation computer chips, including both capability and cost-reduction considerations. Dr. Hyland was previously an integration engineer for IBM's radiation-hardened computer chip manufacturing facility, and she managed a processing facility for the Jet Propulsion Laboratory to assess various materials for their potential as solar-cell substrates. She was also a staff officer for the National Materials Advisory Board, where she managed committees on aviation security and the design of the U.S. paper money. She has a Ph.D. in materials science from Cornell University, and M.S. and B.S. degrees in electrical engineering, from Rutgers, the State University of New Jersey, and from Rensselaer Polytechnic Institute, respectively.

Cheryl A. Bitner is vice president of programs for Pioneer UAV, Inc., responsible for program execution for the Pioneer unmanned air vehicle programs. Ms. Bitner also worked in various capacities at AAI Corporation, including as director of quality systems, program director for fire fighter trainers, electronic warfare trainers, maintenance trainers, gunnery system trainers, and on-board (embedded) trainers. She has more than 28 years of industry experience in providing products and services for the Department of Defense as well as commercial customers and has a strong background in cost- and schedule-control techniques. Her responsibilities include ensuring positive program performance, strategic planning, manpower management, and personnel development. Ms. Bitner is a certified project management professional, certified quality manager, certified software quality engineer, and is a member of the National Training and Simulation Association and the American Society for Quality. She has published a cost-and-benefit analysis of piloting and navigational team trainers and contributes to the AAI Training Systems Newsletter. Ms. Bitner completed the Advanced Program Management Course at the Defense Systems Management College in 1989 and holds an M.S. in engineering science and a B.S. in computer science from Loyola College.

Donald E. Brown is chair of the Department of Systems Engineering of the University of Virginia. His research focuses on data fusion and simulation optimization with applications to intelligence, security, logistics, and transportation. He has developed decision-support systems for several U.S. intelligence agencies and was previously an intelligence operations officer for the U.S. Army. Dr. Brown is coeditor of *Operations Research and Artificial Intelligence: The Integration of Problem Solving Strategies* and *Intelligent Scheduling Systems* and is an associate editor for the journal *International Abstracts in Operations Research*. He has been president, vice president, and secretary of the Systems, Man, and Cybernetics Society of the Institute of Electrical and Electronics Engineers. He is past chair of the Technical Section on Artificial Intelligence of the Institute for Operations Research and Management Science and was awarded that society's Outstanding Service Award.

John B. Daly (*deceased*) retired from the Department of Transportation (DOT) in the summer of 2004. He worked in the Office of Intelligence and Security, part of the immediate staff of the Secretary of Transportation, from its inception in 1990 in the aftermath of the terrorist bomb that led to the crash of Pan Am Flight 103, and he served as the associate director for security policy from 1994 until his retirement. From the beginning of his work in the Office of Intelligence and Security, security research and development was a major focus of his work, particularly explosives and weapons detection. He was the founding chair of the Gordon Research Conference on Illicit Substance Detection. This conference meets annually to review and stimulate research at the frontiers of science and national policy on the detection of explosives, narcotics, and chemical/biological agents. He was the founding chair of the Transportation Security Experts Group in APEC's Transportation Working Group (TPT-WG). This group was established in 2000 at the eighteenth meeting of the TPT-WG in Miyazaki, Japan, to address security in all modes of transportation—land, sea, and air. The press of events, however, has focused its work thus far primarily on aviation security. From 1975 to 1990, he worked for the U.S. Coast Guard in strategic planning for the enforcement of laws and treaties, dealing primarily with the interdiction of drugs and illegal aliens, rising to be Chief of the Plans and Policies Branch in the Office of the Chief of Staff. He was a graduate of Georgetown University's School of Foreign Service (B.S.F.S.), the University of Southern California's School of Public Administration (M.P.A.), and the U.S. Naval War College (Graduate Diploma in Naval Warfare).

Colin G. Drury is a professor of industrial engineering at the State University of New York, Buffalo, and executive director of The Center for Industrial Effectiveness, where he has worked extensively in the integration of ergonomics/human factors into company operations, resulting in increased competitiveness and job growth for regional industry and two National Association of Management and Technical Assistance Centers' Project of the Year awards. Since 1990, he has headed a team applying human factors to the inspection and maintenance of civil aircraft, with the goal being error reduction. Dr. Drury performed a study for the Air Transport Association evaluating the Federal Aviation Administration's modular bomb set and the use of this bomb set in training and testing security screeners. Dr. Drury is a fellow of the Human Factors and Ergonomics Society, the Institute of Industrial Engineers, and the Ergonomics Society. In 1981, he received the Bartlett Medal from the Ergonomics Society, and in 1992 the Paul Fitts Award from the Human Factors and Ergonomics Society. He has a Ph.D. in production engineering from Birmingham University, specializing in work design and ergonomics.

Dr. Drury served on the National Research Council (NRC) Panel on Assessment of Technologies Deployed to Improve Aviation Security.

Patrick Griffin is a senior member of the technical staff at Sandia National Laboratories and was chair of the NRC Panel on Assessment of Practicality of Pulsed Fast Neutron Analysis for Aviation Security. At Sandia National Laboratories, he performs research in the areas of radiation modeling and simulation, neutron effects testing, radiation dosimetry, and radiation damage to materials. He is active in the standardization community and is the current chair of the American Society of Testing and Materials Subcommittee E10.05 on Nuclear Radiation Metrology.

Harry E. Martz, Jr., is the nondestructive evaluation research and development thrust area leader for the Lawrence Livermore National Laboratory. Dr. Martz has extensive background in the use of computed tomography and x-ray radiography (technologies commonly used in explosives detection) to perform nondestructive evaluation. His current projects include the use of nonintrusive x- and gamma-ray computed tomography techniques as three-dimensional imaging tools to understand material properties and to assay radioactive waste forms. Dr. Martz has served on several NRC committees and panels dealing with the general topic of aviation security, including chairing the Committee on Technical Regulation of Explosives Detection Systems.

Richard McGee is a retired electronics engineer with 35 years at the Ballistic/Army Research Laboratory, Aberdeen Proving Ground. He is currently working part time as a senior scientist contractor at Army Research Laboratory. Mr. McGee is an experienced researcher with extensive expertise in millimeter wave, infrared, radiometry, radar, smart munitions, and sensor-based systems engineering and integration. He possesses solid understanding of the procedures and tasks required to transfer technology from the research laboratory to the field, and conducted field experiments to characterize near-Earth propagation of millimeter waves (10 mm to 1 mm wavelength) in turbid and tactically hostile environments. Mr. McGee designed, fabricated, and field-tested smart munitions sensors as well as instrumentation to measure millimeter radiometric and radar signatures of red and blue combat vehicles and various terrains. Other projects in which he has been involved are microwave and millimeter-wave holography, multispectral fusion target recognition algorithm development, and synthetic aperture radar and inverse synthetic-aperture radar high-resolution instrumentation radars.

Richard L. Rowe is retired chief executive officer of MCMS (a $550 million electronics contract manufacturing company). His experience includes sensor technologies applied to aviation security. His expertise includes new technologies in optics and radio frequency, electronic sensors, and switch products. He has more than 20 years of experience in the electronic sensors and switch products industry. Prior to his work in the electronics industry, he was with the U.S. Army for 6 years. He has a master's degree in engineering administration from the George Washington University and a bachelor's degree in engineering and applied sciences from the U.S. Military Academy, West Point, New York. He has served on the board of various electronics industries and was awarded the Honeywell Lund Award (a major leadership award) in 1987.

H. Bruce Wallace is president of MMW Concepts LLC, a firm he established to provide consultative expertise in He retired as a Department of the Army civilian employee where he was most recently acting as deputy and director of the Weapons and Materials Research Directorate of the Army Research Laboratory. Previous to that he spent 7 years as chief of the RF and Electronics Division, where he was responsible for the Army's basic and applied research in RF technologies. His primary area of research involved investigating the application of millimeter-wave techniques to weapon systems. This included studies in electronic components, atmospheric and near-Earth propagation, active and passive system designs, and high-resolution polarimetric imaging. Key outcomes from his work was the development of Sense and Destroy Armor millimeter-wave sensor system, the Army's High Resolution Radar Imaging facility, which provides state-of-the-art imaging of ground platforms, and the Multifunction Radio Frequency System, which has become a key electronic component in the Army's Future Combat Systems. He is author of more than 60 government and open-literature publications. Mr. Wallace has served on multiple Department of Defense and North Atlantic Treaty Organization panels as chair or Army lead and as lead investigator on several trade studies of Department of Defense radar systems and capabilities. He was a member of two NASA review panels providing technical and managerial review of basic research program and a member of the Independent Review Team examining the performance of the Phoenix Mars landing radar. He is a fellow of the IEEE Geosciences and Remote Sensing Society.