Final Publishable JRP Summary for NEW07 THz Security
Microwave and terahertz metrology for homeland security

Overview

Microwave and terahertz detection devices have great potential for use in homeland security. But the development and use of these devices was being held back as important performance properties could not be reliably measured – limiting their effectiveness, and preventing an accurate assessment of the effects of exposure to the radiation they emit. This project developed methods to calibrate microwave and terahertz instrumentation against SI unit definitions, and validated an approach to assess the effects of the radiation. The techniques are being used to develop the next generation of security scanners, offering dramatically improved, fast, safe and non-invasive scanning.

Need for the project

Microwave (millimetre) and terahertz (THz) (sub-millimetre) radiation has the potential to transform defence and homeland security. Personal scanning devices operating at these wavelengths can quickly and non-invasively image through clothing, to identify concealed weapons, explosives, drugs and other contraband items. Whilst THz spectrometers can analyse substances in real-time to determine their composition, such as analysing liquids to identify the presence of explosives, drugs, or chemical or biological weapons. These technologies offer the potential of better detection and increased security, coupled with faster and more comfortable security checks.

Microwave scanning technology is already in development, and the first commercial scanners are currently being trialled in airports worldwide. The use of higher-performance THz scanners and spectrometers has been demonstrated in the laboratory, and they represent the future of security scanning devices. However, the development and use of microwave and THz detection was hampered by a lack of certainty in their performance. Different devices reported varying results in identical tests, and measurements could not be traced back to the SI unit definitions, so levels of accuracy and uncertainty could not be determined reliably. Techniques were needed to calibrate important performance parameters against SI definitions, such as frequency, amplitude and power. And, to satisfy existing and future safety requirements, methods were needed for assessing the effects of exposure to microwave and THz radiation for people being scanned, and for people operating the devices.

Scientific and technical objectives

Four objectives were identified to achieve the overall goal of developing measurement capabilities to support the development of reliable and accurate microwave and THz detection devices. Objective 1 developed a suite of complementary techniques to calibrate microwave and THz detectors. Objective 2 used the results of objective 1 to develop specific techniques to calibrate THz spectrometers. These techniques were then used in objective 3 to compare the performance of THz spectrometers and to accurately determine measurement uncertainty. Objective 4 validated modelling approaches for assessing the effects of exposure to the microwave and THz radiation.

1. <u>To extend existing capabilities for characterisation and calibration of sources and detectors, traceable to the SI units, from the existing single frequency capability of 2.52 THz, to a wide frequency range from 20 GHz and 5 THz.</u> This includes both the extension of calibration facilities at National Metrology Institutes, as well as the development of new detectors suitable for transfer and dissemination of the calibration to customers from science, industry and regulation authorities.

2. <u>To establish traceability of amplitude, phase and frequency for pulsed time-domain, vector network analysis (VNA) based and Fourier-Transform Infrared (FTIR) spectrometers and to develop reference materials for spectrometer validation.</u> This is the basis for the evaluation of the measurement uncertainty of THz spectrometers.

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3. To assess the performance of pulsed time-domain, VNA-based and FTIR spectrometers, by comparison of their uncertainty. This will result in an evaluation of the measurement uncertainty which is a prerequisite for meaningful results.

4. To assess the radiated power flux densities of different types of microwave and THz scanners, and to use the results for realistic dosimetry, by development of numerical skin models and phantoms, as a basis both for performance and safety evaluation of such systems. This will enable regulation authorities to base their evaluation concerning the harmfulness of THz radiation on validated facts.

Results

1. To extend existing capabilities for characterisation and calibration of sources and detectors, traceable to the SI units, from the existing single frequency capability of 2.52 THz, to a wide frequency range from 20 GHz and 5 THz.

A range of complementary methods for calibrating microwave and THz detectors were developed to ensure measurements could be traced back to SI unit definitions:

For the first time, the properties of THz and microwave beams were characterised in such a way that their contribution to measurement uncertainty could be established, enabling full traceability for detectors. A comparison of measurements between three different laboratories, each using more than one detector type, showed that the measurement uncertainties specified by the laboratories were consistent and realistic. This allowed the existing calibration facility at the German National Measurement Institute PTB, to be extended from a single frequency to five frequencies, covering the THz spectrum from 20 GHz to 5 THz. This service is now available for industrial users and calibration laboratories to send detectors for the highest standard of calibration accuracy.

In order to disseminate this traceability, pyro-electric detectors and microbolometers were developed to allow industrial users to transfer calibration from PTB to their own detectors. In cooperation with the commercial project partner SLT GmbH, new pyro-electric detectors were developed as transfer standards. These detectors allow developers of microwave and THz technology to easily calibrate devices, providing sufficient accuracy for activities like production quality management. These pyro-electric detectors are now available for sale through SLT. Functional room-temperature microbolometers were also developed, fabricated and tested as an alternative to the pyro-electric detectors for lower-power measurements. The microbolometers are more sensitive than the pyro-electric detectors, and are currently in the experimental stage of development.

A portable room-temperature radiometer has also been built and tested, to enable laboratories to establish traceability of their THz measurements without relying on the calibration service. It is commercially available for customers at SFI Davos, and although less accurate than the calibration service, it allows traceable THz measurements for laboratories engaged in applied research.

2. To establish traceability of amplitude, phase and frequency for pulsed time-domain, vector network analysis (VNA) based and Fourier-Transform Infrared (FTIR) spectrometers and to develop reference materials for spectrometer validation.

Results from the first objective were used to develop methods to calibrate amplitude, phase and frequency for the three most common spectrometer types; pulsed time-domain, FTIR and VNA based spectrometers.

Experimental procedures were established to test the three spectrometer types in the THz spectral region. New methods for calibration and data extraction were developed and published. A variety of dielectric materials for spectrometer verification were selected, tested and measured. Calibration methods for amplitude, phase and frequency were successfully established for each spectrometer type, for use in objective 3.

3. To assess the performance of pulsed time-domain, VNA-based and FTIR spectrometers, by comparison of their uncertainty.

After methods were developed to calibrate amplitude, phase and frequency for THz spectrometers in objective 2, measurement uncertainty analysis could be developed for the absorption and reflection coefficients, the two quantities measured by spectrometers. Traceability of these coefficients allowed the measurement uncertainty of spectrometers to be assessed at THz frequencies for the first time.

THz pulsed time-domain, FTIR and VNA-based spectrometers were built, capable of measuring both transmission and reflection coefficients. Data analysis methods were developed, including techniques for uncertainty analysis, and analysis software was written and tested. Measurement comparisons were then made between spectrometers in the German and Italian National Measurement Institutes, PTB and INRIM. The comparison exercise was successful. The results were comparable in all considered frequency bands, and demonstrated that reliable and comparable THz measurements can be made, when traceability to the SI units is implemented and measurement uncertainty is determined. Each spectrometer type was suited to different sample properties, such as sample thickness and absorption spectrum.

4. To assess the radiated power flux densities of different types of microwave and THz scanners, and to use the results for realistic dosimetry, by development of numerical skin models and phantoms, as a basis both for performance and safety evaluation of such systems

Microwave and THz radiation is non-ionising radiation, so does not cause damage by breaking molecular structures with high-energy waves. But, radiation at these wavelengths can be absorbed by skin, and could potentially cause damage by heating the skin of scanner users and subjects. Using the results from objective 1, which allow the accurate measurement of radiated power, the radiated emission of the scanners (power flux density) can be reliably measured. The effects of this radiation on subjects and users can then be assessed, to be used in current safety standards, and to set future safety guidelines.

Detectors were selected and calibrated to measure the power flux densities of a range of microwave and THz scanners. The effects of the levels of radiation energy measured on human skin were investigated through developing a numerical model, which simulated the propagation of electromagnetic waves through stratified skin layers. The accuracy of this model was then validated through developing skin phantoms, gel-based solutions based on optimised recipes found in the scientific literature, which replicated the thermal and electrical properties of human skin.

The objective was achieved, as the validation demonstrated that the modelling approach yielded realistic results, and is thus an appropriate method for estimating the amount of heating that occurs in human skin from microwave and THz radiation.

Actual and potential impact

This project has substantially improved microwave and THz measurement accuracy and reliability, making these technologies readily accessible for security applications.

Dissemination of results

To ensure the uptake of the project's achievements, results have been shared with scientific and industrial end-users through the publication of 34 papers in international journals (listed in the next section), and 70 conference contributions, including plenary talks during the International Conference on Infrared, Millimeter, and THz Waves, and the Conference on Precision Electromagnetic Measurements. A training workshop "Security Scanners – Adequate Methods to Measure the Exposure" was held at Rohde & Schwarz GmbH & Co. KG in Munich, with participants from industry, research organisations and authorities. A best practice guide based on the workshop results is available on the project webpage and EURAMET repository, and enables producers, users and regulators to reliably measure the performance of THz security scanners. Results were presented at the final project workshop to stakeholders in industry, universities and regulatory authorities, focusing on the detector technology and calibration, and the use and validation of THz spectrometers.

Impact on standards

This project is among the first standardisation activities performed for scanners and spectrometers in the microwave to THz region. Results may contribute to two overarching standards, IEC/EN 62479 and IEC/EN 62311, which govern the protection of people exposed to electromagnetic fields when using novel devices for which product standards have not yet been established. These standards are a prerequisite for new hardware development, and are essential for securing the public acceptance of new technologies that use electromagnetic radiation. The techniques developed during this project will also be used to demonstrate compliance with European Directive 2004/40/EC “Physical Agents Directive”, which sets exposure limits for personnel working with high-frequency radiation, as well as for other applicable national and international guidelines, such as that of the International Commission on Non-Ionising Radiation Protection (ICNIRP). The PTB service has been used to perform a pilot comparison of THz detector calibration capabilities from Germany, China and the USA, an important first step in harmonising international standards.

Early impact on industry

For the first time, a range of methods are now available for industrial users and research laboratories to calibrate THz instruments against measurement unit definitions. The THz detector calibration service offered by PTB was used more than 20 times by the end of the project, by manufacturers and research institutions from China, Japan, USA, Russia, France and Germany. The new pyro-electric detectors, to be used as calibration transfer standards, can be purchased from SLT GmbH. The room-temperature radiometer developed at SFI Davos is available for customers, such as small research laboratories, to establish traceability to measurement definitions outside of the calibration service.

Potential future impact on industry

This project has made fundamental contributions to improving the accuracy and reliability of microwave and THz measurements, paving the way for their development and commercialisation in Europe. The measurement and calibration methods developed will be used to more effectively design, manufacture and test high-performance security devices, and to ensure that the devices are used safely. Microwave and THz radiation can now be harnessed to deliver a new level in non-invasive scanning and detection, with faster and more comfortable security checks.

List of publications

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