

Lecture 8: Microwave and Radio Wave Imaging

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- ◆ Radio Waves and Microwaves
- ◆ Radioastronomy
- ◆ Radar
- ◆ Terahertz Imaging

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Microwaves and Radio Waves (1)

Microwaves and Radio Waves

Radiation

Low-energy electromagnetic radiation.

- ◆ *Radio Waves:*
Frequency between 3×10^4 and 3×10^9 Hz.
Wavelength between 10 cm and 10 km.
 - *Long Waves (LW):* approx. 30–300 kHz
 - *Medium Waves (MW):* approx. 300–3000 kHz
 - *Short Waves (SW):* approx. 3–30 MHz
 - *Ultra-short Waves:* approx. 30–3000 MHz
- ◆ *Microwaves:* Frequency between 10^8 and 10^{12} Hz.
Wavelength between 0.3 mm and 3 m.
Some overlap with infrared and with radio waves.
- ◆ *Terahertz Radiation:* Frequency between 0.1 and 30 THz (10^{11} and 3×10^{13} Hz)
i.e. in the range of short microwaves and far infrared.

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Microwaves and Radio Waves (2)



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Interaction with Matter

The frequency/wavelength range of these types of radiation is tremendous (factor 30,000,000), thus their physical properties differ widely.

- ◆ *Long and medium waves* easily penetrate the atmosphere. Most solid objects on the ground are too small to be an obstacle (below 1/10 wavelength). They are diffracted at very large objects, including the Earth.
- ◆ *Short waves* behave similar but are less diffracted by the earth. Additionally, they are reflected at the ionosphere.
- ◆ *Ultra-short waves* are blocked by many objects because of their short wavelength. They display a *quasi-optical* propagation with little diffraction.
- ◆ Damage in biological tissue caused by high doses of radio waves is under dispute.
- ◆ *Microwaves* typically penetrate solid and liquid matter over short distances before being absorbed depending on the chemical composition of the material. Since water efficiently absorbs certain spectral ranges of microwaves, microwaves can introduce high energy doses into biological tissues.

Microwaves and Radio Waves (3)



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Radio Frequencies

One typical use of radio waves, though not in imaging, are radio transmissions. The propagation behaviour determines the use of the different frequencies.

- ◆ LW, MW and SW are used for radio transmissions in *amplitude modulation (AM)*. Medium waves are propagated over several hundred kilometres, long waves up to approx. 1,500 km. Short waves allow long-distance transmissions over 10,000 km and more during the night because of reflection at the ionosphere.
- ◆ Ultra-short waves contain
 - *very high frequency (VHF)* and *ultra-high frequency (UHF)* bands used for television,
 - a radio band used for transmissions in *frequency modulation (FM)*,
 - bands for cellular phones and other applications.

The quasi-optical propagation implies that senders cover only small areas (radius below 100 km for TV and FM radio, a few kilometres for cellular phones).

Dipole Antennas

- ◆ Frequencies of radio waves and microwaves can be achieved by electronic circuits. Moreover, wavelengths are in the order of magnitude of technical devices. Radio waves and microwaves can therefore be directly emitted and absorbed by electronic equipment.
- ◆ *Dipole antennas* consist of elongated conductors (e.g. wire). Combined with electronic oscillators they allow to directly generate and detect the oscillating electrical field of the electromagnetic wave.



Left: Heinrich Hertz (1857–1894)
Used in 1886 dipoles to generate and detect electromagnetic waves.
(Image: Spektrum-Verlag, 1999)

Right: Television tower of Canberra, Australia.
(Image: Nucolorvue, 1988)



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Paraboloid Antennas

- ◆ Radio waves can also be reflected by mirrors consisting of electrical conducting materials. This is mostly used to bundle waves by *paraboloid reflectors*.
- ◆ *Paraboloid antennas* consist of a paraboloid reflector and a dipole antenna. They can detect waves from a specific (axial) direction with reasonable spatial resolution.



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Radio Astronomy

Radio Telescopes

- ◆ *Radio telescopes* are used to image radio waves emitted by space objects. Emission of radio waves by space objects has been discovered in 1932 by Karl Guthe Jansky.
- ◆ Main components of most radio telescopes are large parabolic antennas which can measure radiation from one specific direction at one time. To obtain images of entire sky regions, the telescope is moved, or the Earth's daily movement is used.

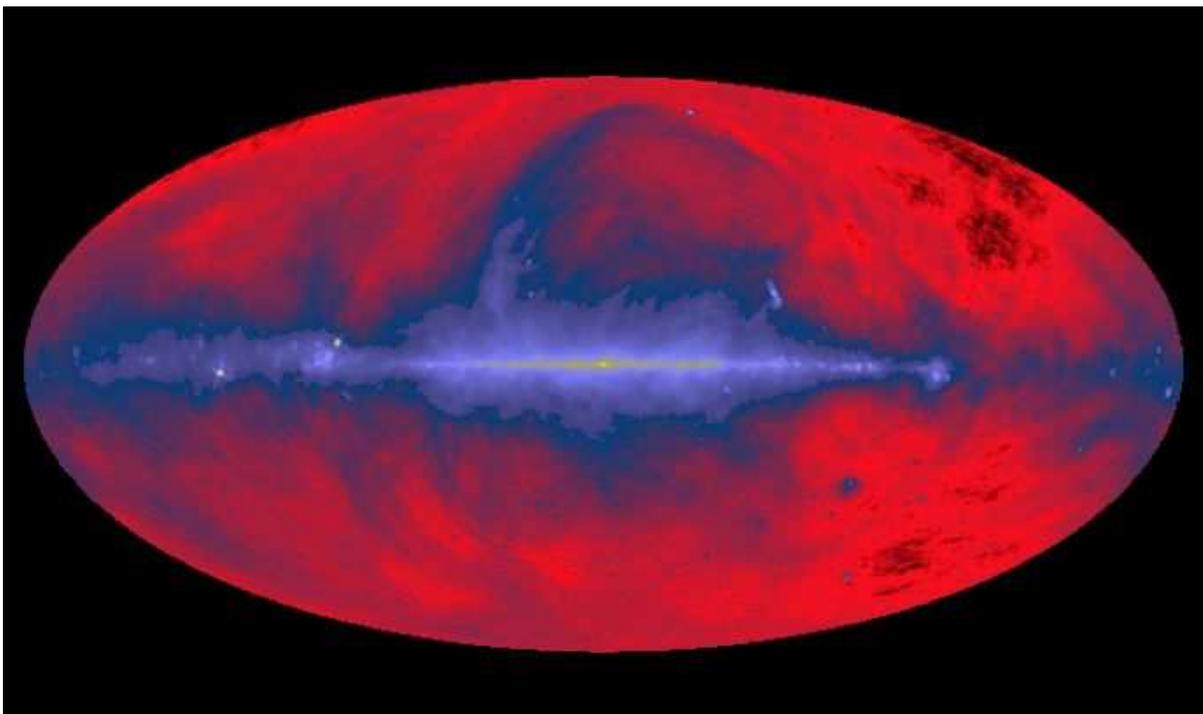


Left to right: Karl Guthe Jansky (1905–1950) – 32 m radio telescope at Toruń, Poland – 100 m radio telescope at Effelsberg, Germany – 300 m radio telescope at Arecibo, Puerto Rico.

Images: Wikipedia / <http://vlab.psnc.pl/news/03.html> / http://www.skynet.com.pl/~rzezniak/galeria_radioteleskopy_1.htm / <http://www.evlbi.org/evlbi/te024/arecibo.jpg>

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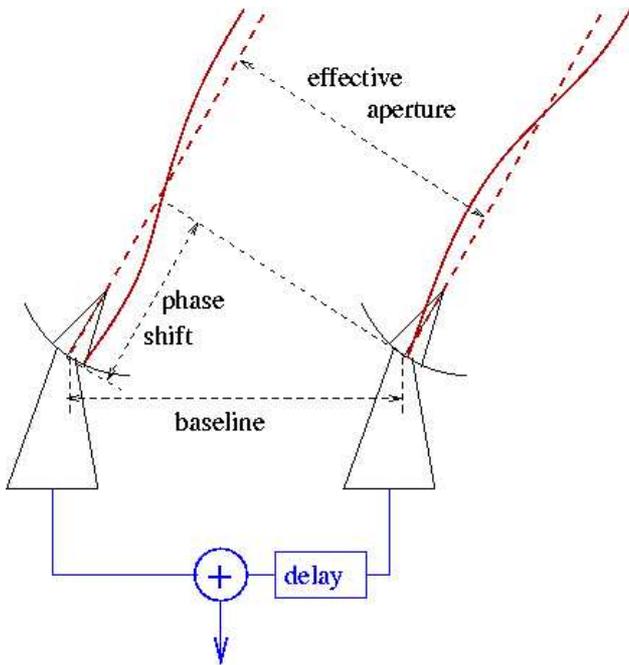
Example



Survey of the entire sky, composed from data taken at the radiotelescopes of Jodrell Bank (USA), Effelsberg (Germany) and Parkes (Australia), 1982. (C. Haslam et al., Max Planck Institute for Radio Astronomy, SkyView)

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Radio Interferometry



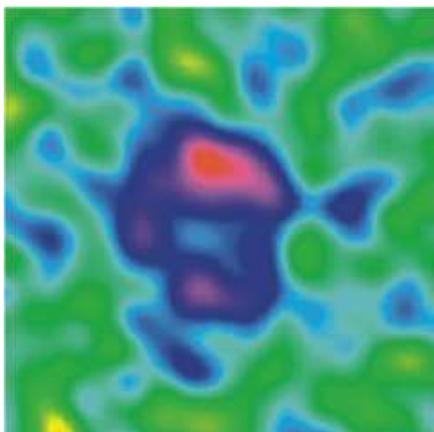
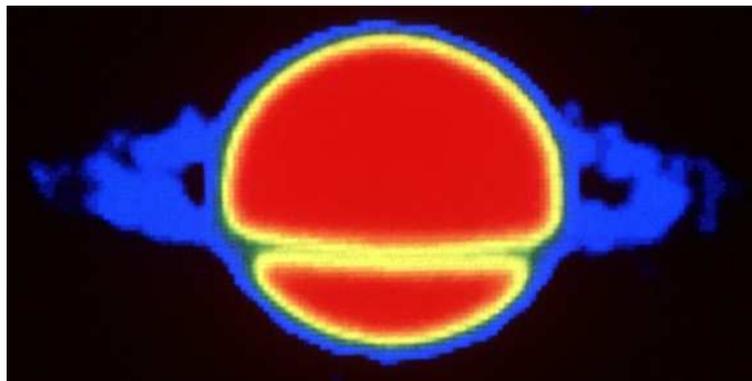
The *spatial resolution* of radio telescopes is limited by the diameter of the paraboloid antenna, compare Abbe's formula for optical microscopes (Lecture 5).

A remedy is to superpose electronically the signals from two radio antennas such that they can interfere.

This *interferometer* setting improves the resolution in direction of the baseline between the telescopes.

It reaches that of a single antenna whose aperture (diameter) equals the projection of the baseline onto the plane perpendicular to the object direction.

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Top left: The *Very Large Array (VLA)*, New Mexico, USA, an interferometric radioobservatory with 27 paraboloid antennas. (Image: Wikipedia)

Top right: VLA radio image of Saturn. (Image courtesy of NRAO/AUI)

Bottom left: VLA image of the quasar PSS J2322. (Image: NRAO/Chris Carilli – from <http://www.weltderphysik.de>)

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Very Long Baseline Interferometry

- ◆ Deterioration of signals by transmission restricts extensions of baseline.
- ◆ To circumvent these limitations, signals can be recorded separately together with synchronised atomic clock ticks and the superposition computed later.
- ◆ In this way, baselines of many thousand kilometres can be realised.

Image Quality

- ◆ Image resolution is limited by directional characteristics of antennas. Interferometry is the main way to reduce these problems.
- ◆ Noise in images may be caused by terrestrial sources of radio waves.

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Radar

- ◆ *Radar* (**r**adio **d**etection **a**nd **r**anging) is a technique to detect objects and measure the distance to them by reflection of radio waves.
- ◆ In the standard setting, the radar equipment emits radio waves in a directed beam and receives the reflected waves.
- ◆ If the emitted beam is pulsed, the same antenna can be used for emission and reception.
- ◆ The *intensity* of reflected beams indicates reflectivity of objects.
- ◆ The *time of flight* of reflected beams indicates the distance to objects.
- ◆ *Frequency differences* between emitted and received waves (*Doppler effect*) allow also to measure velocities (used in speed cameras).

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Radar History

Christian Hülsmayer (1881–1957).
 Inventor of radar: He proposed in 1904 the use of radio waves to detect ships in fog.
 (Image: <http://www.100-jahre-radar.de>)



Albert Hoyt Taylor (1874–1961).
 Constructor of first radar system: Together with Leo C. Young, he demonstrated experimentally in 1922 the radar principle by detecting a wooden ship. (Image: <http://www.todayinsci.com>)

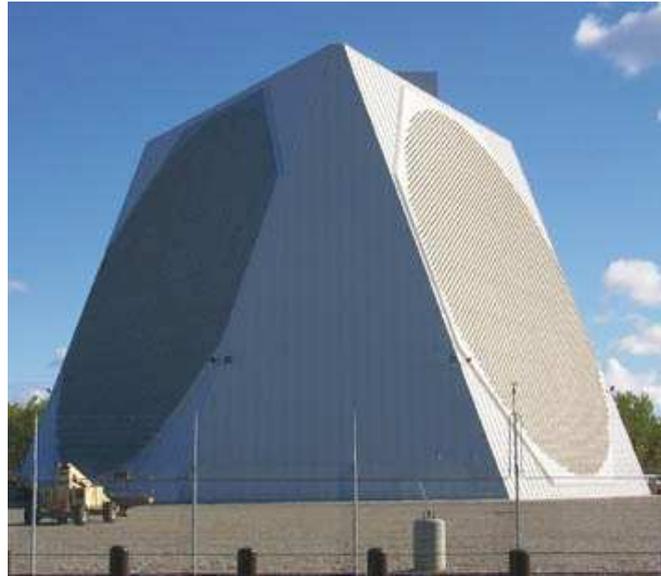
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Radar Antennas

- ◆ **Paraboloid antennas** allow directed emission and reception subject to the previously described limitations concerning aperture and resolution. Paraboloid antennas have to be moved to scan different directions.
- ◆ **Phased array antennas** consist of large arrays of dipoles which allow directed emission and reception by the interferometric principle. Phased array antennas don't involve moving parts.
- ◆ **Synthetic aperture radar (SAR)** is used e.g. in aircrafts or remote sensing satellites. It uses a small antenna with broad emission/detection angle. Information gathered during the movement of the antenna allows to compute an image with high angular resolution. The resulting 2D images are easy to interpret and resemble photographic images.

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Radar (4)



Left: Rotable radar antenna for airspace surveillance. Note the small vertical extension since little vertical resolution is required. (Image: http://ed-thelen.org/hipar_fan.jpg)

Right: Phased array radar antenna without moving components. (Image download source: Wikipedia. Image credits: This image is a work of an U.S. Army Corps of Engineers employee, taken or made during the course of the person's official duties. As a work of the U.S. federal government, the image is in the public domain.)

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Radar (5)

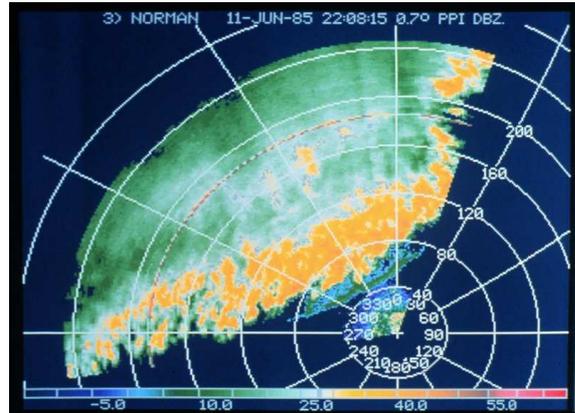
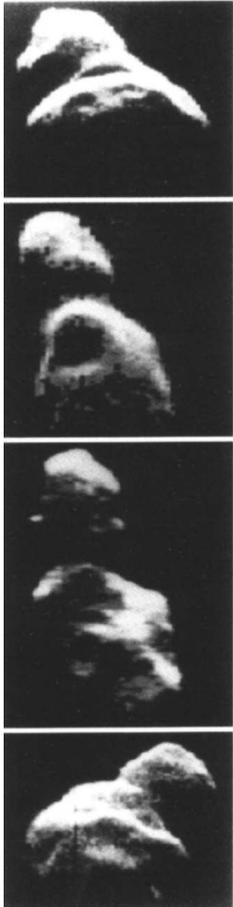
Radar Imaging

- ◆ 2-D images in the plane perpendicular to the beams can be obtained using the intensity information from antennas with reasonable resolution in two directions.
Example: Radar astronomy.
- ◆ 2-D images in a plane containing the radar system can be obtained by using intensity and time-of-flight information from antennas with good resolution in one direction.
Examples: Air traffic surveillance, marine radar, adaptive cruise control in cars (under development), meteorologic radar.
- ◆ 3-D images can be obtained by using intensity and time-of-flight information from antennas with good resolution in two directions.
Example: Air traffic control, with altitude information.

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Radar Imaging Examples



Left: Radar images of the asteroid Toutatis. (Image: Spektrum-Verlag, 1999.)

Top middle: Doppler radar image from cloud radar, depicting a stormy front. Colours indicate velocities. (Image: National Oceanic and Atmospheric Administration/Department of Commerce. Public domain. Download source: Wikipedia.)

Top right: Synthetic aperture radar (SAR) image of Venus, obtained by the Magellan satellite. (Image: NASA, download source: Wikipedia)

Terahertz Imaging (1)

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Terahertz Imaging

The Terahertz Gap

- ◆ Imaging technology has neglected for a long time the electromagnetic spectrum section between 100 GHz (in the short microwave range) and 30 THz (in the far infrared).
- ◆ The reason was the lack of suitable sources and detectors for radiation of such frequencies.
- ◆ This “Terahertz gap” has recently been closed by new technology, allowing intensive investigation of the properties of Terahertz radiation and its possible application.
- ◆ Terahertz imaging techniques have arisen mainly in the last decade, gaining increasing attention in medical imaging and security scanning. They are also expected to be useful in astronomical imaging. However, most techniques are still experimental.

Terahertz Imaging (2)



Direct Terahertz Sources

- ◆ *Electronic generators* can only work in the microwave range, up to approx. 300 GHz ... 1 THz.
- ◆ *Lasers* for this spectral range are large and costly.

Indirect Terahertz Sources

Most viable sources for Terahertz radiation use generators for other spectral ranges followed by frequency transformations, upward or downward. Examples:

- ◆ *Beat*, a special type of mixing between coherent waves of different frequencies: Mixing light of two optical laser diodes lets radiation of the *difference* frequency emerge. This can be tuned to be in the THz range.
- ◆ *Optical rectification* in certain crystals can remove the high-frequency oscillation from a short laser pulse, leaving a Terahertz oscillation.

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Terahertz Imaging (3)



Terahertz Detectors

For advanced imaging methods, one is interested in detectors that are able to capture both amplitude (intensity) and phase of incoming Terahertz waves.

- ◆ *CCD arrays* can be designed to detect Terahertz radiation.
- ◆ *Electrooptic detection*: The Terahertz electrical field modifies the optical properties of some transparent crystals which can be read out by polarised light.

Resolution is relatively low.

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Terahertz Imaging (4)

Interaction of Terahertz Radiation with Matter

- ◆ *Water* attenuates Terahertz radiation.
- ◆ *Biological tissue*, particularly skin, is penetrated by Terahertz radiation over several millimetres, i.e. considerably deeper than pure water.
- ◆ *Dry materials* (plastics, cardboard, paper, cloth, wound dressings) are mostly transparent.
- ◆ Terahertz transparency depends sensitively on water contents but apparently also on other chemical components.
- ◆ Refraction and reflection are possible and allow the use of lens and mirror optics.
- ◆ Terahertz imaging can be done by transmitted light (for sufficiently thin objects) or reflected light.

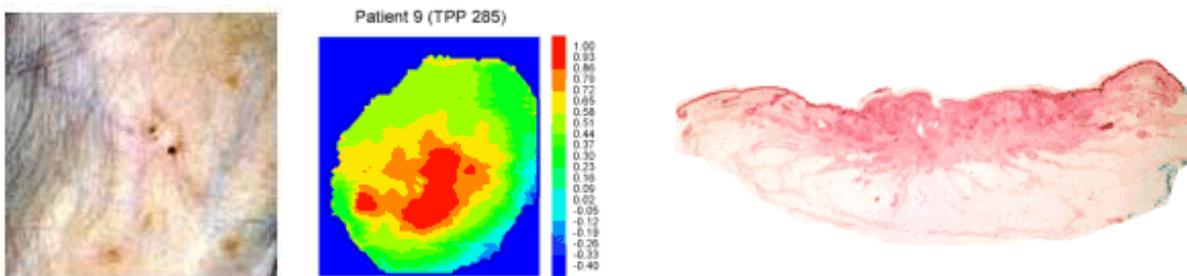
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Terahertz Imaging (5)

Medical Applications

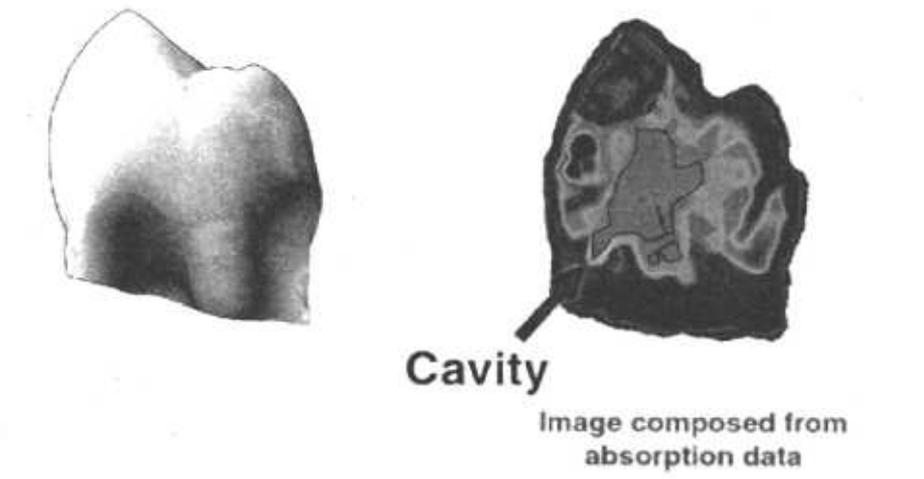
- ◆ Main application areas are skin imaging and dentistry.
- ◆ Cancer cells display a (surprisingly) high contrast to healthy cells which can not be ascribed to water contents since it is conserved even when water is removed in preparation.
- ◆ Possible diagnosis fields: skin cancer, caries.

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Left to right: Visual image of human skin – Terahertz image indicating melanoma – Histological image confirming diagnosis. (Images: TeraView, <http://www.teraview.com>)

Visible image of human tooth Terahertz image of cavity in human tooth

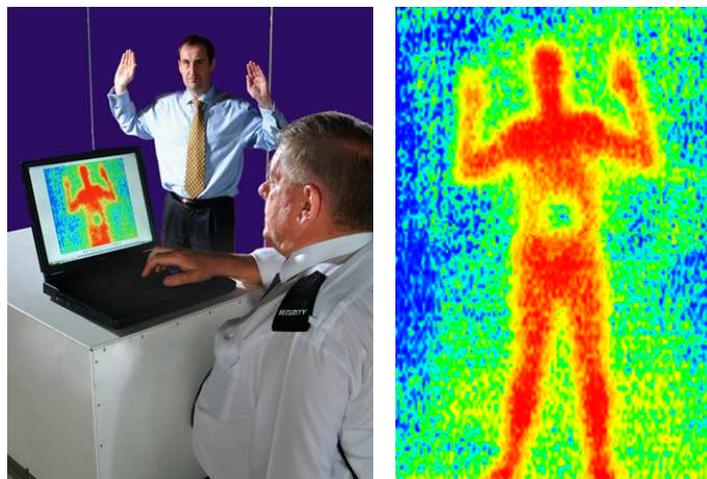


Visual and Terahertz image of a human tooth. *D. Arnone 1999, reproduced from Siegel 2002.*

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Imaging with Emitted Terahertz Radiation

- ◆ The human body itself is a source of Terahertz radiation.
- ◆ Detecting this radiation allows imaging applications that promise to become useful for security checking, e.g. at airports.



Terahertz screening of a person with concealed plastic explosives. The Terahertz radiation used is emitted by the human body itself. *(Images: ThruVision, <http://www.thruvision.com>)*

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Summary

- ◆ Radio waves, micro waves and terahertz waves are low energy electromagnetic radiation with wavelengths between 0.01 mm and 10 km.
- ◆ Radio waves can be easily created and detected with antennas.
- ◆ Radio telescopes image radio waves emitted by space objects. Radio interferometry helps to increase the patial resolution.
- ◆ Radar detects objects and measures their distance and speed using reflection of radio waves.
- ◆ Terahertz imaging is an emerging research area. Terahertz radiation is difficult to generate and to detect. However, it offers interesting potential applications in medical imaging and security scanning.

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