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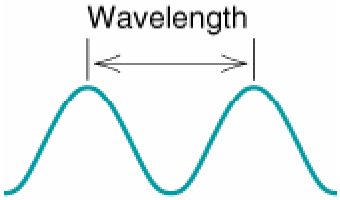
ELECTROMAGNETIC WAVES

ЭЛЕКТРОМАГНИТНЫЕ ВОЛНЫ

Electromagnetic Spectrum.

Light consists of electromagnetic (EM) waves. An EM wave is composed of an electric field and a magnetic field that are oscillating together. The fields are oriented perpendicular to each other, and the wave travels in a direction perpendicular to both of the fields. These waves can also be thought of as particles called photons: massless packets of energy that travel at the speed of light. In fact, EM radiation behaves as both a particle and a wave at the same time. EM waves can be characterized by any of three properties: wavelength (λ) - the distance between two adjacent crests of the wave, frequency (f) - the number of wave oscillations per second, or the energy (E) of the individual photons in the wave. For all types of EM radiation, the simple relationships between wavelength, frequency, and energy are:

$$\lambda = \frac{c}{f} = \frac{hc}{E}$$



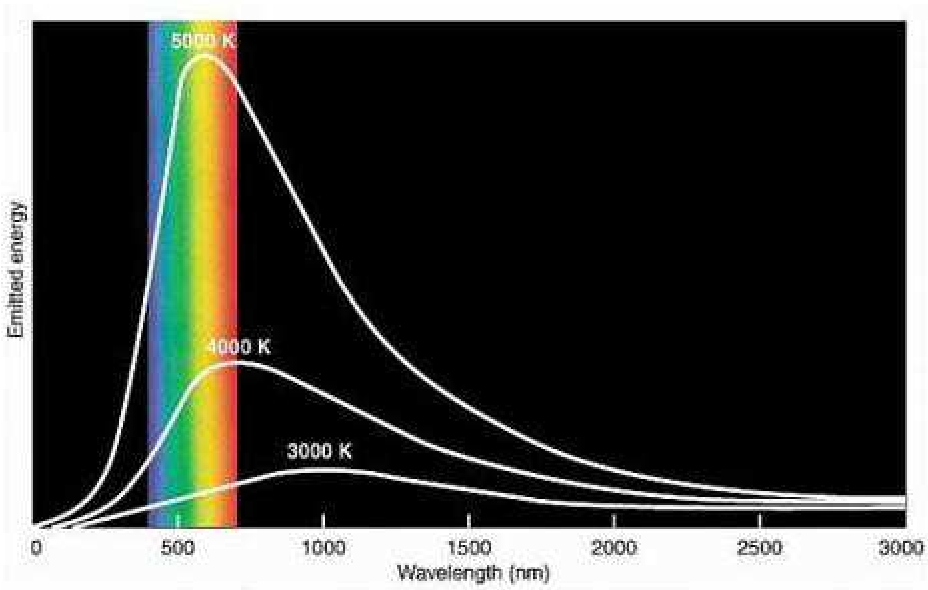
where wavelength is measured in units of length such as meters (where 1 cm = 10^{-2} meters, 1 micrometer = 10^{-6} meters, etc.), frequency is measured in units of Hertz (Hz), where 1 Hz = 1 wave crest per second (e.g. 1 MHz = 10^{6} Hz, 1 GHz = 10^{9} Hz); c is the speed of light, which is about 3 x 10^{8} meters per second (or 186,000 miles per second); and h is Planck's constant, which is equal to 6.63 x 10^{-27} erg/s, where an erg is a unit of energy. Remarkably, all forms of EM radiation (visible light, x-rays, radio waves, etc.) travel at the speed of light, regardless of their energy. Since the energy of an EM wave is directly proportional to its frequency and inversely proportional to its wavelength, the higher the energy of the wave, the higher the frequency, and the shorter the wavelength.The different wavelengths of EM radiation cause the radiation to react differently with different materials, such as our eyes or detectors in telescopes. The way visible light of different wavelengths interacts with our eyes gives rise to "colors", with the shorter wavelengths (about 0.0004 mm) appearing as blue light and the longer wavelengths (about 0.0007 mm) appearing as red light. Even shorter wavelengths of EM radiation (such as x-rays) can pass right through tissues in our bodies. Radiation at longer wavelengths (e.g. infrared) cannot be seen by our eyes, but can be felt as heat. Radio waves are EM waves with the longest wavelengths, from 1 mm - 100 km.

Just as the EM spectrum is divided up into different regions depending on wavelength, the radio region of the EM spectrum can also be divided up into different regions or "bands". These are the bands in which astronomers use radio telescopes to observe the radio waves emitted by astronomical objects. Astronomers must build special telescopes and detectors in order to detect EM radiation of different wavelengths. For example, optical telescopes are designed similar to the human eye, with a lens to focus incoming light onto a detector. Since radio waves have a much longer wavelength than optical light, radio telescopes are designed much differently, although the basic principles are the same. Electromagnetic radiation is emitted by charged particles such as electrons when they change speed or direction (or accelerate). In general, electromagnetic radiation is emitted by one of two means, eitherthermal or non-thermal mechanisms. Thermal emission, which depends only on the temperature of the emitting object, includes blackbody radiation,free-free emission in an ionized gas, and spectral line emission. Non-thermal emission, which does not depend on the temperature of the emitting object, includes synchrotron radiation, gyrosynchrotron emission, and amplified emission from masers in space.

Thermal Emission.

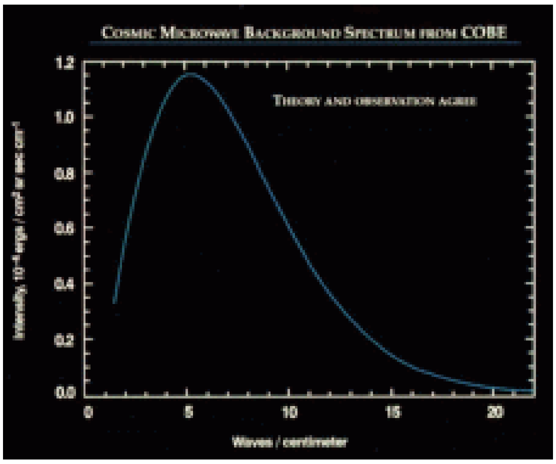
Blackbody Radiation.

Thermal emission is perhaps the most basic form of emission for EM radiation. Any object or particle that has a temperature above absolute zero emits thermal radiation. The temperature of the object causes the atoms and molecules within the object to move around. For example, the molecules of a gas, as in a planet's atmosphere, spin around and bump into one another. When the molecules bump into each other, they change direction. A change in direction is equivalent to acceleration. As stated above, when charged particles accelerate, they emit electromagnetic radiation. So each time a molecule changes direction, it emits radiation across the spectrum, just not equally. As a result, the amount of motion within an object is directly related to its temperature.



You can explore this for yourself by placing a cast-iron pan on a stove, heating it for a few minutes, and then placing it to the side. It is hot enough to be emitting a noticeable amount of infrared radiation (or heat), which you can detect by placing your hands near it. If you were to put more heat into the iron, it would eventually emit higher and higher energy wavelengths, until it would glow on its own, emitting visible light as well as infrared radiation. Scientists call this blackbody radiation. A blackbody is a hypothetical object that completely absorbs all of the radiation that hits it, and reflects nothing. The object reaches an equilibrium temperature and re-radiates energy in a characteristic pattern (or spectrum). The spectrum peaks at a wavelength that depends only on the object's temperature. All objects in the universe behave this way. The image shows blackbody spectra for objects at three different temperatures: 5000 K, 4000 K, and 3000 K. It is apparent from the image that objects at lower temperatures emit more radiation at longer wavelengths. The objects in the image emit at or near the visible range of the electromagnetic spectrum; in order for an object to emit thermal radiation at radio wavelengths, it must be much colder than these objects. The unit of temperature that astronomers typically use is called the Kelvin, and its symbol is K (no degree symbol is used). To convert from degrees Celsius to Kelvin, add 273 to the temperature in Celsius. So, if an object has a temperature of 100° C, its temperature in Kelvin is 100+273 = 373 K. Objects that are cooler than about 1000

K emit more infrared than visible light, such as the Earth orbrown dwarfs (dim, cool objects too massive to be planets but not massive enough to be stars). Hotter objects, like stars, emit mostly optical light. Very hot objects emit mostly ultraviolet radiation, such as white dwarfs (dying stars that have burned up all of the hydrogen in their cores). The major difference in the type of energy emitted by these objects is their temperature.

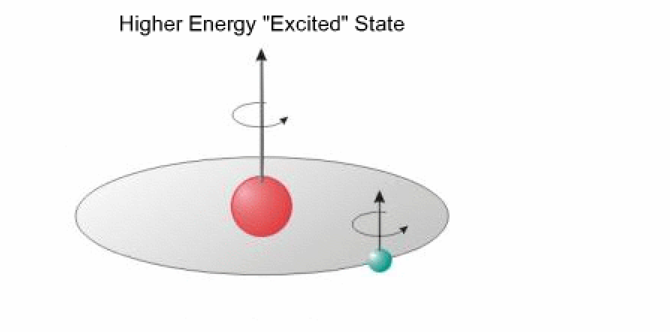


The Sun and other stars are, for all intents and purposes, considered blackbody radiators. By looking at the frequency or "color" of the radiation they emit, scientists can learn about the temperature of these bodies. For example, cooler stars appear red and hotter stars appear bluish-white. One of the most famous examples of a "perfect" blackbody is known as the Cosmic Microwave Background (CMB) radiation. This is the radiation permeating the entire Universe that was released during the Big Bang explosion and has been cooling for the last 15 billion years. Today the CMB radiation is so cold (only 2.725 K, or -270° C), that most of the radiation is emitted at radio wavelengths of a few centimeters (also called "microwave" radiation; see image at right). Astronomers were able to obtain the spectrum of the microwave background using a specially designed satellite called the Cosmic Background Explorer (COBE). The blackbody nature of the microwave background spectrum matches the predictions of the Big Bang theory extremely accurately, thus confirming the theory that the microwave background radiation was created in the Big Bang explosion. The Wilkinson Microwave Anisotropy Probe (WMAP), launched in 2001, has observed the microwave background to an even higher level of sensitivity, giving astronomers greater insights into the origin and evolution of the Universe.

Free-Free Emission.

Another form of thermal emission comes from gas which has been ionized. Atoms in the gas become ionized when their electrons become stripped or dislodged. This results in charged particles moving around in an ionized gas or "plasma", which is a fourth state of matter, after solid, liquid, and gas. As this happens, the electrons are accelerated by the charged particles, and the gas cloud emits radiation continuously. This type of radiation is called "free-free" emission or "bremsstrahlung". The image at left shows the emission of a photon when a negatively charged electron (green particle) changes direction or accelerates due to the presence of a nearby positively charged ion (red particle). Some sources of free-free emission in the radio region of the EM spectrum include ionized gas near star-forming regions or Active Galactic Nuclei (AGN).

Spectral Line Emission.



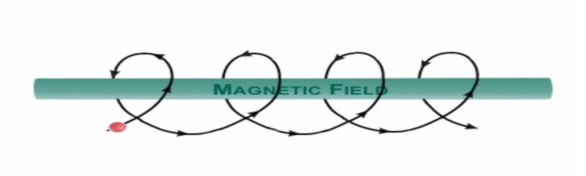
Spectral line emission involves the transition of electrons in atoms from a higher energy level to lower energy level. When this happens, a photon is emitted with the same energy as the energy difference between the two levels. The emission of this photon at a certain discrete energy shows up as a discrete "line" or wavelength in the electromagnetic spectrum.

An important spectral line that radio astronomers study is the 21-cm line of neutral hydrogen. This line is emitted by the following transition: the hydrogen atom consists of one electron orbiting one proton in the nucleus. Both the electron and the proton have a "spin". In the lowest energy state, or "ground" state, the spins of both particles are in opposite directions. When the atom becomes excited, either by absorbing a photon of energy, or by bumping into other atoms, the electron absorbs a small amount of energy, and the spin of the electron "flips," so that the spins of both particles are in the same direction. When the atom reverts back to its natural state, it loses this energy by emitting a photon with a wavelength of 21 cm, in the radio region of the electromagnetic spectrum.

Non-thermal Emission.

Synchrotron Emission.

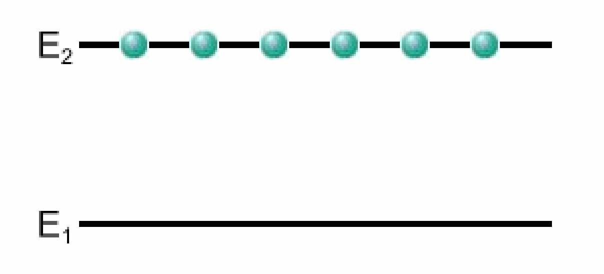
Non-thermal emission does not have the characteristic signature curve of blackbody radiation. In fact, it is quite the opposite, with emission increasing at longer wavelengths. The most common form of non-thermal emission found in astrophysics is called synchrotron emission. Basically, synchrotron emission arises by the acceleration of charged particles within a magnetic field. Most commonly, the charged particles are electrons. Compared to protons, electrons have relatively little mass and are easier to accelerate and can therefore more easily respond to magnetic fields.



As the energetic electrons encounter a magnetic field, they spiral around it rather than move across it. Since the spiral is continuously changing the direction of the electron, it is in effect accelerating, and emitting radiation. The frequency of the emission is directly related to how fast the electron is traveling. This can be related to the initial velocity of the electron, or it can be due to the strength of the magnetic field. A stronger field creates a tighter spiral and therefore greater acceleration. For this emission to be strong enough to have any astronomical value, the electrons must be traveling at nearly the speed of light when they encounter a magnetic field; these are known as "relativistic" electrons. (Lower-speed interactions do happen, and are called cyclotron emission, but they are of considerably lower power, and are virtually non-detectable astronomically). As the electron travels around the magnetic field, it gives up energy as it emits photons. The longer it is in the magnetic field, the more energy it loses. As a result, the electron makes a wider spiral around the magnetic field, and emits EM radiation at a longer wavelength. To maintain synchrotron radiation, a continual supply of relativistic electrons is necessary. Typically, these are supplied by very powerful energy sources such as supernova remnants, quasars, or other forms of active galactic nuclei (AGN). It is important to note that, unlike thermal emission, synchrotron emission is polarized. As the emitting electron is viewed side-on in its spiral motion, it appears to move back-and-forth in straight lines. Its synchrotron emission has its waves aligned in more or less the same plane. At visible wavelengths this phenomenon can be viewed with polarized lenses (as in certain sunglasses, and in modern 3-D movie systems).

Masers.

Another form of non-thermal emission comes from masers. A maser, which stands for "microwave amplification by stimulated emission of radiation", is similar to a laser (which amplifies radiation at or near visible wavelengths). Masers are usually associated with molecules, and in space masers occur naturally in molecular clouds and in the envelopes of old stars. Maser action amplifies otherwise faint emission lines at a specific frequency. In some cases the luminosity from a given source in a single maser line can equal the entire energy output of the Sun from its whole spectrum.



Masers require that a group of molecules be pumped to an energized state (labeled E_2 in the diagram at right), like compressed springs ready to uncoil. When the energized molecules are exposed to a small amount of radiation at just the right frequency, they uncoil, dropping to a lower energy level (labeled E_1 in the diagram), and emit a radio photon. The process entices other nearby molecules to do the same, and an avalanche of emission ensues, resulting in the bright, monochromatic maser line. Masers rely on an external energy source, such as a nearby, hot star, to pump the molecules back into their excited state (E_2), and then the whole process starts again. The first masers to be discovered came from the hydroxl radical (OH), silicon oxide (SiO), and water (H_2O). Other masers have been discovered from molecules such as methanol (CH_3OH), ammonia (NH_3), and formaldehyde (H_2CO).

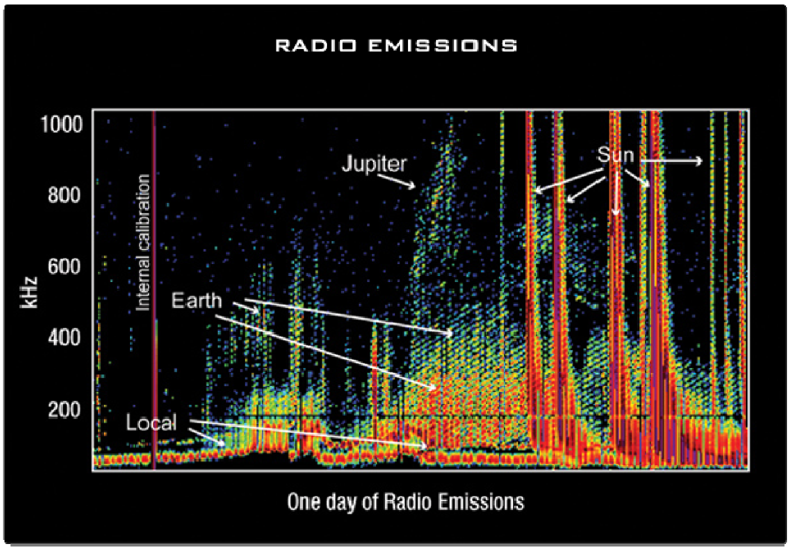
What are radio waves?

In 1932, Karl Jansky at Bell Labs revealed that stars and other objects in space radiated radio waves. Radio waves have the longest wavelengths in the electromagnetic spectrum. They range from the length of a football to larger than our planet. Heinrich Hertz proved the existence of radio waves in the late 1880s. He used a spark gap attached to an induction coil and a separate spark gap on a receiving antenna. When waves created by the sparks of the coil transmitter were picked up by the receiving antenna, sparks would jump its gap as well. Hertz showed in his experiments that these signals possessed all the properties of electromagnetic waves.

You can tune a radio to a specific wavelength—or frequency—and listen to your favorite music. The radio "receives" these electromagnetic radio waves and converts them to mechanical vibrations in the speaker to create the sound waves you can hear.

Radio emissions in the solar system.

Astronomical objects that have a changing magnetic field can produce radio waves. The radio astronomy instrument called WAVES on the WIND spacecraft recorded a day of bursts of radio waves from the Sun's corona and planets in our solar system. Data pictured below show emissions from a variety of sources including radio bursts from the Sun, the Earth, and even from Jupiter's ionosphere whose wavelengths measure about fifteen meters in length. The far right of this graph shows radio bursts from the Sun caused by electrons that have been ejected into space during solar flares moving at 20% of the speed of light.



Radio telescopes.

Radio telescopes look toward the heavens to view planets, comets, giant clouds of gas and dust, stars, and galaxies. By studying the radio waves originating from these sources, astronomers can learn about their composition, structure, and motion. Radio astronomy has the advantage that sunlight, clouds, and rain do not affect observations.Since radio waves are longer than optical waves, radio telescopes are made differently than the telescopes used for visible light. Radio telescopes must be physically larger than an optical telescopes in order to make images of comparable resolution. But they can be made lighter with millions of small holes cut through the dish since the long radio waves are too big to "see" them. The Parkes radio telescope, which has a dish 64 meters wide, cannot yield an image any clearer than a small backyard optical telescope!

A very large telescope.

In order to make a clearer, or higher resolution, radio image, radio astronomers often combine several smaller telescopes, or receiving dishes, into an array. Together, these dishes can act as one large telescope whose resolution is set by the maximum size of the area. The National Radio Astronomy Observatory's Very Large Array (VLA) radio telescope in New Mexico is one of the world's premier astronomical radio observatories. The VLA consists of 27 antennas arranged in a huge "Y" pattern up to 36 km across (roughly one-and-one-half times the size of Washington, DC).

The techniques used in radio astronomy at long wavelengths can sometimes be applied at the shorter end of the radio spectrum—the microwave portion. The VLA image below captured 21-centimeter energy emissions around a black hole in the lower right and magnetic field lines pulling gas around in the upper left.

The radio sky.

If we were to look at the sky with a radio telescope tuned to 408 MHz, the sky would appear radically different from what we see in visible light. Instead of seeing point-like stars, we would see distant pulsars, star-forming regions, and supernova remnants would dominate the night sky. Radio telescopes can also detect quasars. The term quasar is short for quasi-stellar radio source. The name comes from the fact that the first quasars identified emit mostly radio energy and look much like stars. Quasars are very energetic, with some emitting 1,000 times as much energy as the entire Milky Way. However, most quasars are blocked from view in visible light by dust in their surrounding galaxies.

Radio waves 'see' through walls.

In Mathematics and Economics University of Utah engineers showed that a wireless network of radio transmitters can track people moving behind solid walls. The system could help police, firefighters and others nab intruders, and rescue hostages, fire victims and elderly people who fall in their homes. It also might help retail marketing and border control. "By showing the locations of people within a building during hostage situations, fires or other emergencies, radio tomography can help law enforcement and emergency responders to know where they should focus their attention," Joey Wilson and Neal Patwari wrote in one of two new studies of the method. Both researchers are in the university's Department of Electrical and Computer Engineering – Patwari as an assistant professor and Wilson as a doctoral student. Their method uses radio tomographic imaging (RTI), which can "see," locate and track moving people or objects in an area surrounded by inexpensive radio transceivers that send and receive signals. People don't need to wear radio-transmitting ID tags.One of the studies – which outlines the method and tests it in an indoor atrium and a grassy area with trees – is awaiting publication soon in IEEE Transactions on Mobile Computing, a journal of the Institute of Electrical and Electronics Engineers. The study involved placing a wireless network of 28 inexpensive radio transceivers – called nodes – around a square-shaped portion of the atrium and a similar part of the lawn. In the atrium, each side of the square was almost 14 feet long and had eight nodes spaced 2 feet apart. On the lawn, the square was about 21 feet on each side and nodes were 3 feet apart. The transceivers were placed on 4-foot-tall stands made of plastic pipe so they would make measurements at human torso level. Radio signal strengths between all nodes were measured as a person walked in each area. Processed radio signal strength data were displayed on a computer screen, producing a bird's-eye-view, blob-like image of the person.A second study detailed a test of an improved method that allows "tracking through walls." The study details how variations in radio signal strength within a wireless network of 34 nodes allowed tracking of moving people behind a brick wall. The method was tested around an addition to Patwari's Salt Lake City home. Variations in radio waves were measured as Wilson walked around inside. The system successfully tracked Wilson's location to within 3 feet. The wireless system used in the experiments was not a Wi-Fi network like those that link home computers, printers and other devices. Patwari says the system is known as a Zigbee network – the kind of network often used by wireless home thermostats and other home or factory automation. Wilson demonstrated radio tomographic imaging during a mobile communication conference last year, and won the MobiCom 2008 Student Research Demo Competition. The researchers now have a patent pending on the method. "I have aspirations to commercialize this," says Wilson, who has founded a spinoff company named Xandem Technology LLC in Salt Lake City. The research was funded by the National Science Foundation.

How it works.

Radio tomographic imaging (RTI) is different and much less expensive than radar, in which radar or radio signals are bounced off targets and the returning echoes or reflections provide the target's location and speed. RTI instead measures "shadows" in radio waves created when they pass through a moving person or object. RTI measures radio signal strengths on numerous paths as the radio waves pass through a person or other target. In that sense, it is quite similar to medical CT (computerized tomographic) scanning, which uses X-rays to make pictures of the human body, and seismic imaging, in which waves from earthquakes or explosions are used to look for oil, minerals and rock structures underground. In each method, measurements of the radio waves, X-rays or seismic waves are made along many different paths through the target, and those measurements are used to construct a computer image. In their indoor, outdoor and through-the-wall experiments, Wilson and Patwari obtained radio signal strength measurements from all the transceivers – first when the rectangle was empty and then when a person walked through it. They developed math formulas and used them in a computer program to convert weaker or "attenuated" signals – which occur when someone creates "shadows" by walking through the radio signals – into a blob-like, bird's-eye-view image of that person walking. RTI has advantages. "RF [radio frequency] signals can travel through obstructions such as walls, trees and smoke, while optical and infrared imaging systems cannot," the engineers wrote. "RF imaging will also work in the dark, where video cameras will fail." Even "where video cameras could work, privacy concerns may prevent their deployment," Wilson and Patwari wrote. "An RTI system provides current images of the location of people and their movements, but cannot be used to identify a person." Would bombardment by radio waves pose a hazard? Wilson says the devices "transmit radio waves at powers 500 times less than a typical cell phone." "And you don't hold it against your head," Patwari adds.

Radio 'Eyes' to the Rescue.

Patwari says the system still needs improvements, "but the plan is that when there is a hostage situation, for example, or some kind of event that makes it dangerous for police or firefighters to enter a building, then instead of entering the building first, they would throw dozens of these radios around the building and immediately they would be able to see a computer image showing where people are moving inside the building." "They are reusable and you can pick them up afterwards," he says. The technique cannot distinguish good guys from bad guys, but at least will tell emergency personnel where people are located, he adds. Patwari says radio tomography probably can be improved to detect people in a burning building, but also would "see" moving flames. "You may be able to look at the image and say this is a spreading fire and these are people," says Patwari.

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