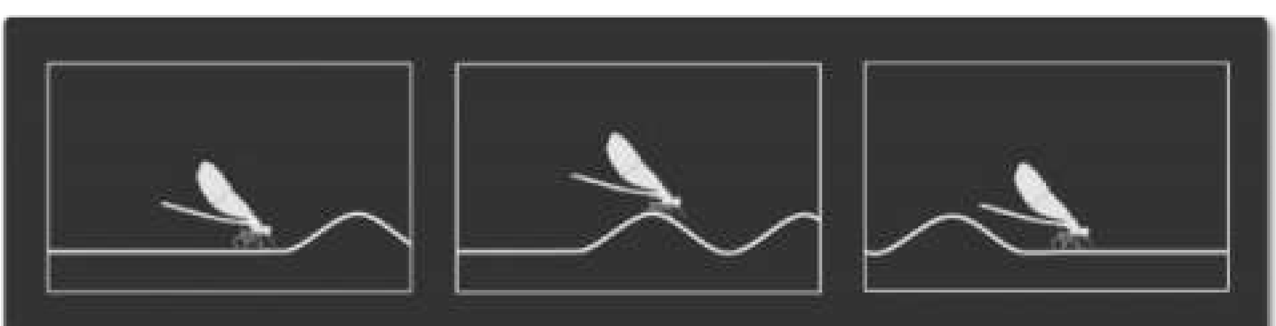
Anatomy of an Electromagnetic Wave

Energy, a measure of the ability to do work, comes in many forms and can transform from one type to another. Examples of stored or potential energy include batteries and water behind a dam. Objects in motion are examples of kinetic energy. Charged particles—such as electrons and protons—create electromagnetic fields when they move, and these fields transport the type of energy we call electromagnetic radiation, or light.

What are Electromagnetic and Mechanical waves?

Mechanical waves and electromagnetic waves are two important ways that energy is transported in the world around us. Waves in water and sound waves in air are two examples of mechanical waves. Mechanical waves are caused by a disturbance or vibration in matter, whether solid, gas, liquid, or plasma. Matter that waves are traveling through is called a medium. Water waves are formed by vibrations in a liquid and sound waves are formed by vibrations in a gas (air). These mechanical waves travel through a medium by causing the molecules to bump into each other, like falling dominoes transferring energy from one to the next. Sound waves cannot travel in the vacuum of space because there is no medium to transmit these mechanical waves.



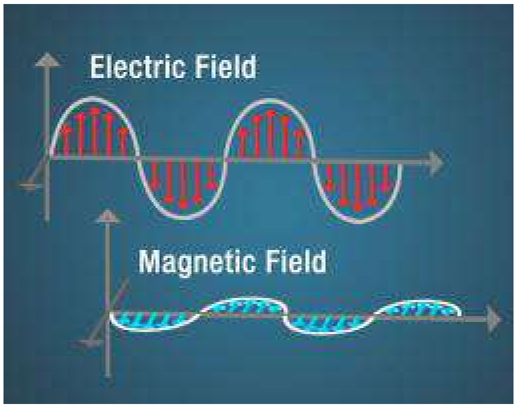
Classical waves transfer energy without transporting matter through the medium. Waves in a pond do not carry the water molecules from place to place; rather the wave's energy travels through the water, leaving the water molecules in place, much like a bug bobbing on top of ripples in water.

When a balloon is rubbed against a head of hair, astatic electric charge is created causing their individual hairs to repel one another. Credit: Ginger Butcher

ELECTROMAGNETIC WAVES

Electricity can be static, like the energy that can make your hair stand on end. Magnetism can also be static, as it is in a refrigerator magnet. A changing magnetic field will induce a changing electric field and vice-versa—the two are linked. These changing fields form electromagnetic waves. Electromagnetic waves differ from mechanical waves in that they do not require a medium to propagate. This means that electromagnetic waves can travel not only through air and solid materials, but also through the vacuum of space.

In the 1860's and 1870's, a Scottish scientist named James Clerk Maxwell developed a scientific theory to explain electromagnetic waves. He noticed that electrical fields and magnetic fields can couple together to form electromagnetic waves. He summarized this relationship between electricity and magnetism into what are now referred to as "Maxwell's Equations."



Heinrich Hertz, a German physicist, applied Maxwell's theories to the production and reception of radio waves. The unit of frequency of a radio wave -- one cycle per second -- is named the hertz, in honor of Heinrich Hertz.

His experiment with radio waves solved two problems. First, he had demonstrated in the concrete, what Maxwell had only theorized — that the velocity of radio waves was equal to the velocity of light! This proved that radio waves were a form of light! Second, Hertz found out how to make the electric and magnetic fields detach themselves from wires and go free as Maxwell's waves — electromagnetic waves.

WAVES OR PARTICLES? YES!

Light is made of discrete packets of energy called photons. Photons carry momentum, have no mass, and travel at the speed of light. All light has both particle-like and wave-like properties. How an instrument is designed to sense the light influences which of these properties are observed. An instrument that diffracts light into a spectrum for analysis is an example of observing the wave-like property of light. The particle-like nature of light is observed by detectors used in digital cameras—individual photons liberate electrons that are used for the detection and storage of the image data.

POLARIZATION

One of the physical properties of light is that it can be polarized. Polarization is a measurement of the electromagnetic field's alignment. In the figure above, the electric field (in red) is vertically polarized. Think of a throwing a Frisbee at a picket fence. In one orientation it will pass through, in another it will be rejected. This is similar to how sunglasses are able to eliminate glare by absorbing the polarized portion of the light.

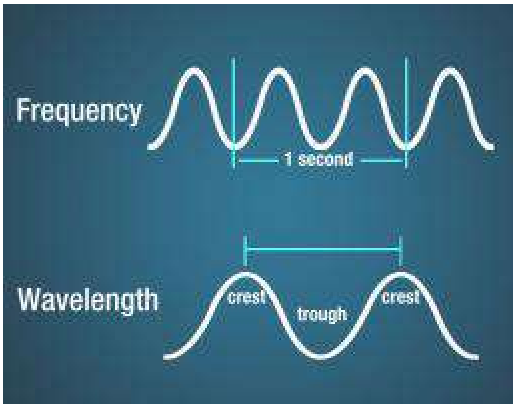
DESCRIBING ELECTROMAGNETIC ENERGY

The terms light, electromagnetic waves, and radiation all refer to the same physical phenomenon: electromagnetic energy. This energy can be described by frequency, wavelength, or energy. All three are related mathematically such that if you know one, you can calculate the other two. Radio and microwaves are usually described in terms of frequency (Hertz), infrared and visible light in terms of wavelength (meters), and x-rays and gamma rays in terms of energy (electron volts). This is a scientific convention that allows the convenient use of units that have numbers that are neither too large nor too small.

FREQUENCY

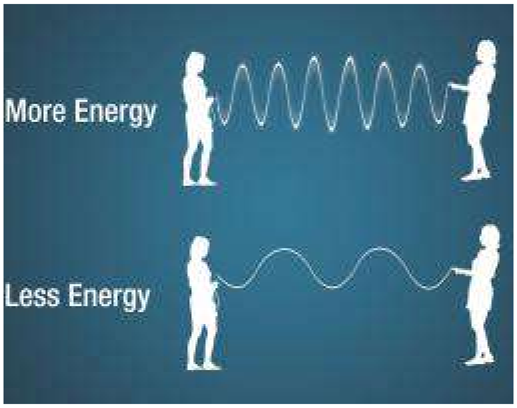
The number of crests that pass a given point within one second is described as the frequency of the wave. One wave—or cycle—per second is called a Hertz (Hz), after Heinrich Hertz who established the existence of radio waves. A wave with two cycles that pass a point in one second has a frequency of 2 Hz.

WAVELENGTH



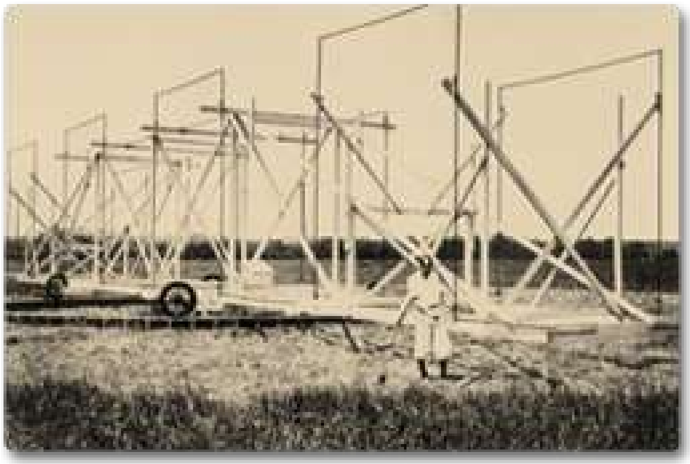
Electromagnetic waves have crests and troughs similar to those of ocean waves. The distance between crests is the wavelength. The shortest wavelengths are just fractions of the size of an atom, while the longest wavelengths scientists currently study can be larger than the diameter of our planet!

ENERGY



An electromagnetic wave can also be described in terms of its energy—in units of measure called electron volts (eV). An electron volt is the amount of kinetic energy needed to move an electron through one volt potential. Moving along the spectrum from long to short wavelengths, energy increases as the wavelength shortens. Consider a jump rope with its ends being pulled up and down. More energy is needed to make the rope have more waves.

WHAT ARE RADIO WAVES?



In 1932, Karl Jansky at Bell Labs revealed that stars and other objects in space radiated radio waves. Credit: NRAO/AUI

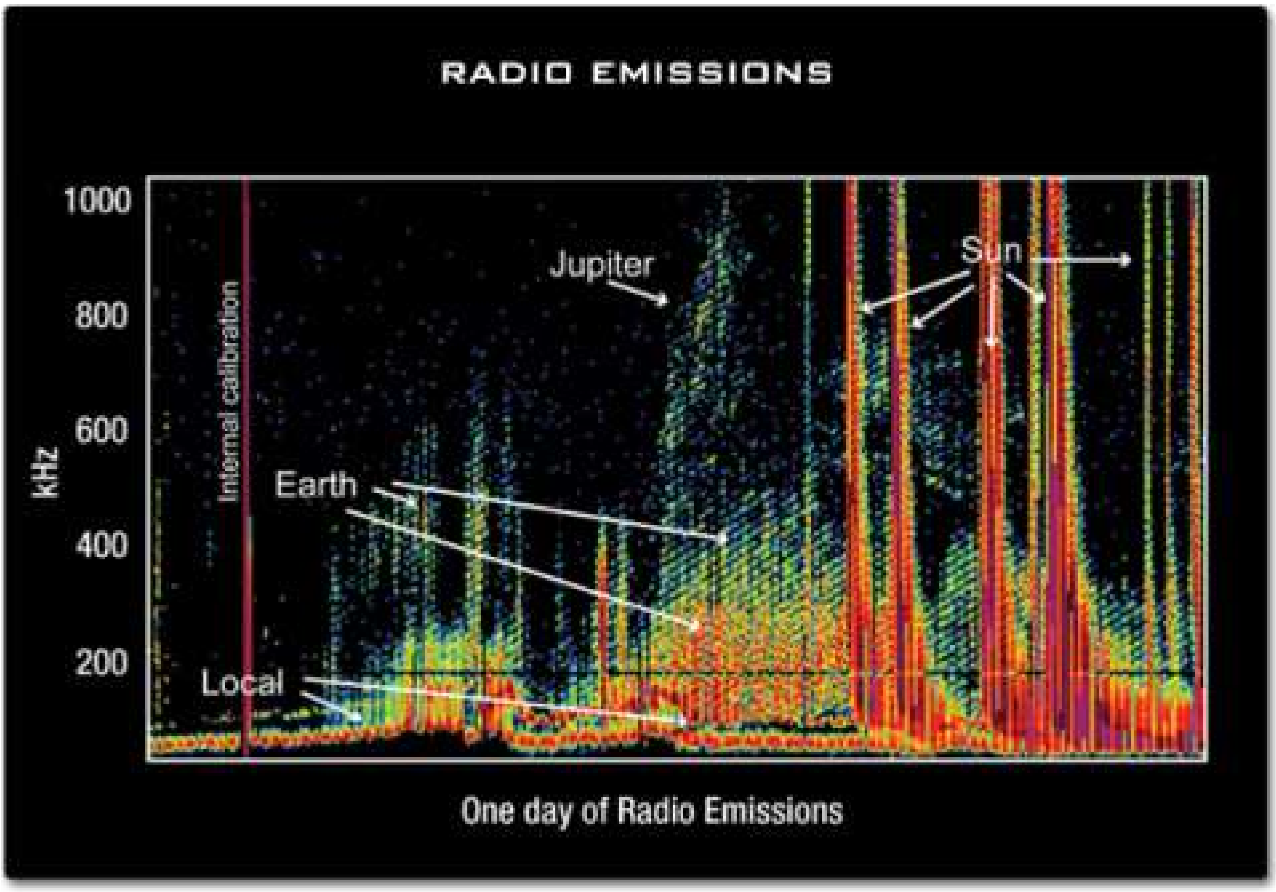
Radio waves have the longest wavelengths in the electromagnetic spectrum. They range from the length of a football to larger than our planet. Heinrich Hertz proved the existence of radio waves in the late 1880s. He used a spark gap attached to an induction coil and a separate spark gap on a receiving 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.



Credit: NASA/GSFC Wind Waves Michael L. Kaiser

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!

Credit: Ian Sutton

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).

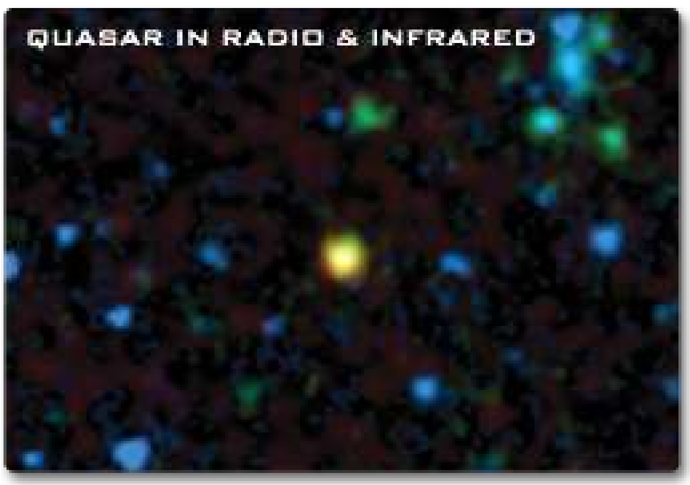
The techniques used in radio astronomy at long wavelengths can sometimes be applied at the shorter end of the radio spectrum—the microwave portion. The VLA image below captured 21-centimeter energy emissions around a black hole in the lower right and magnetic field lines pulling gas around in the upper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

Credit: VLA & NRAO, FarhadYusef-Zedehet al. Northwestern

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.



Credit: NASA/JPL-Caltech/A.Martinez-Sansigre

Astronomers identified the quasars with the help of radio data from the VLA radio telescope because many galaxies with quasars appear bright when viewed with radio telescopes. In the false-color image below, infrared data from the Spitzer space telescope is colored both blue and green, and radio data from the VLA telescope is shown in red. The quasar-bearing galaxy stands out in yellow because it emits both infrared and radio light.

MICROWAVES

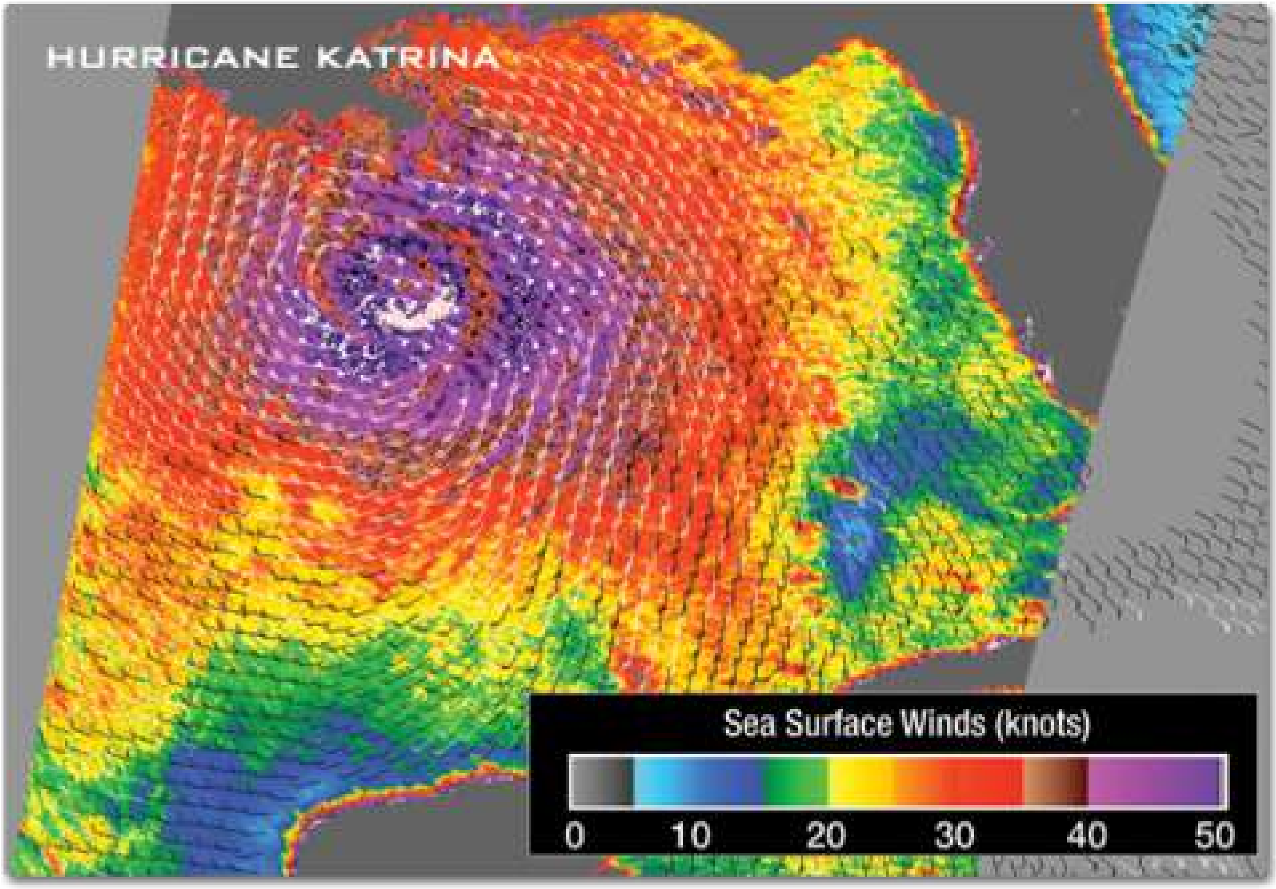
You may be familiar with microwave images as they are used on TV weather news and you can even use microwaves to cook your food. Microwave ovens work by using microwave about 12 centimeters in length to force water and fat molecules in food to rotate. The interaction of these molecules undergoing forced rotation creates heat, and the food is cooked.

MICROWAVE BANDS

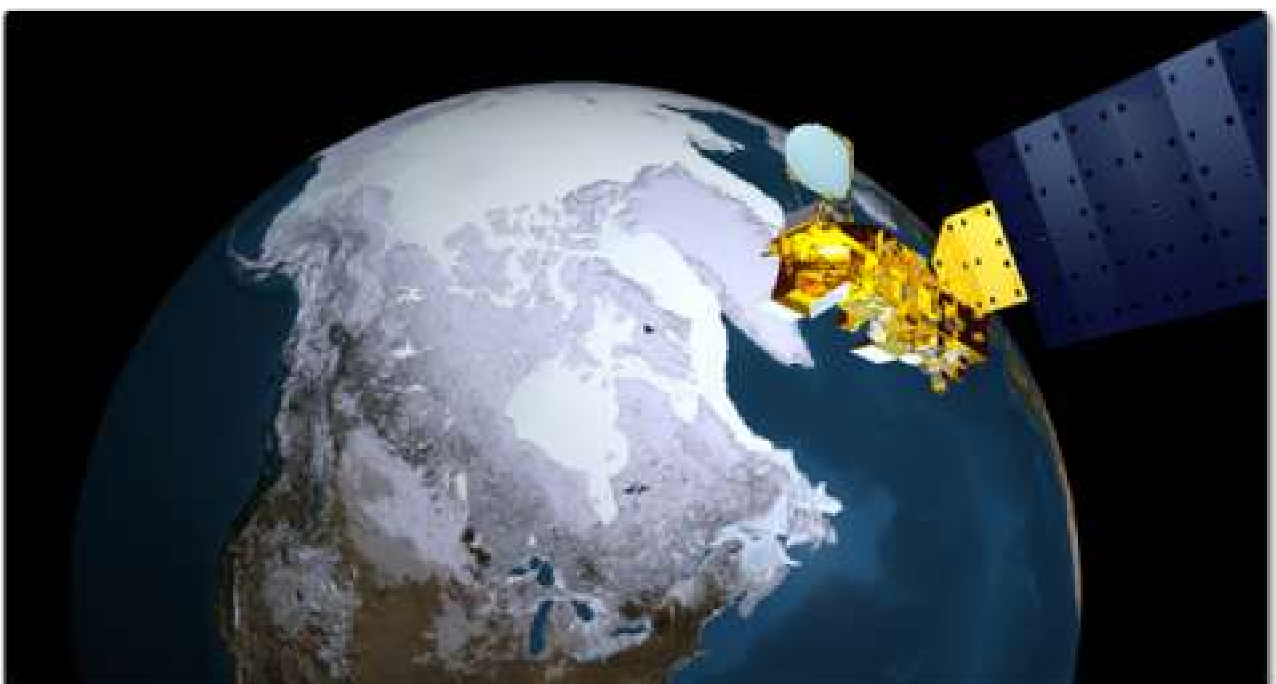
Microwaves are a portion or "band" found at the higher frequency end of the radio spectrum, but they are commonly distinguished from radio waves because of the technologies used to access them. Different wavelengths of microwaves (grouped into "sub-bands") provide different information to scientists. Medium-length (C-band) microwaves penetrate through clouds, dust, smoke, snow, and rain to reveal the Earth's surface. L-band microwaves, like those used by a Global Positioning System (GPS) receiver in your car, can also penetrate the canopy cover of forests to measure the soil moisture of rain forests. Most communication satellites use C-, X-, and Ku-bands to send signals to a ground station.

LEFT: *The ERS-1 satellite sends out wavelengths about 5.7 cm long (C-band).This image shows sea ice breaking off the shores of Alaska.* ***CENTER***: *The JERS satellite uses wavelengths about 20 cm in length (L-band).This is an image of the Amazon River in Brazil.* ***RIGHT***: *This is a radar image acquired from the Space Shuttle. It also used awavelengthin the L-band of the microwave spectrum. Here we see a computerenhanced radarimage of some mountains on the edge of Salt Lake City, Utah.*

Microwaves that penetrate haze, light rain and snow, clouds, and smoke are beneficial for satellite communication and studying the Earth from space. The SeaWinds instrument onboard the Quick Scatterometer (QuikSCAT) satellite uses radar pulses in the Ku-band of the microwave spectrum. This scatterometer measures changes in the energy of the microwave pulses and can determine speed and direction of wind near the ocean surface. The ability of microwaves to pass through clouds enables scientists to monitor conditions underneath a hurricane.



Credit: NASA image courtesy the QuikSCAT Science Team at the Jet Propulsion Laboratory

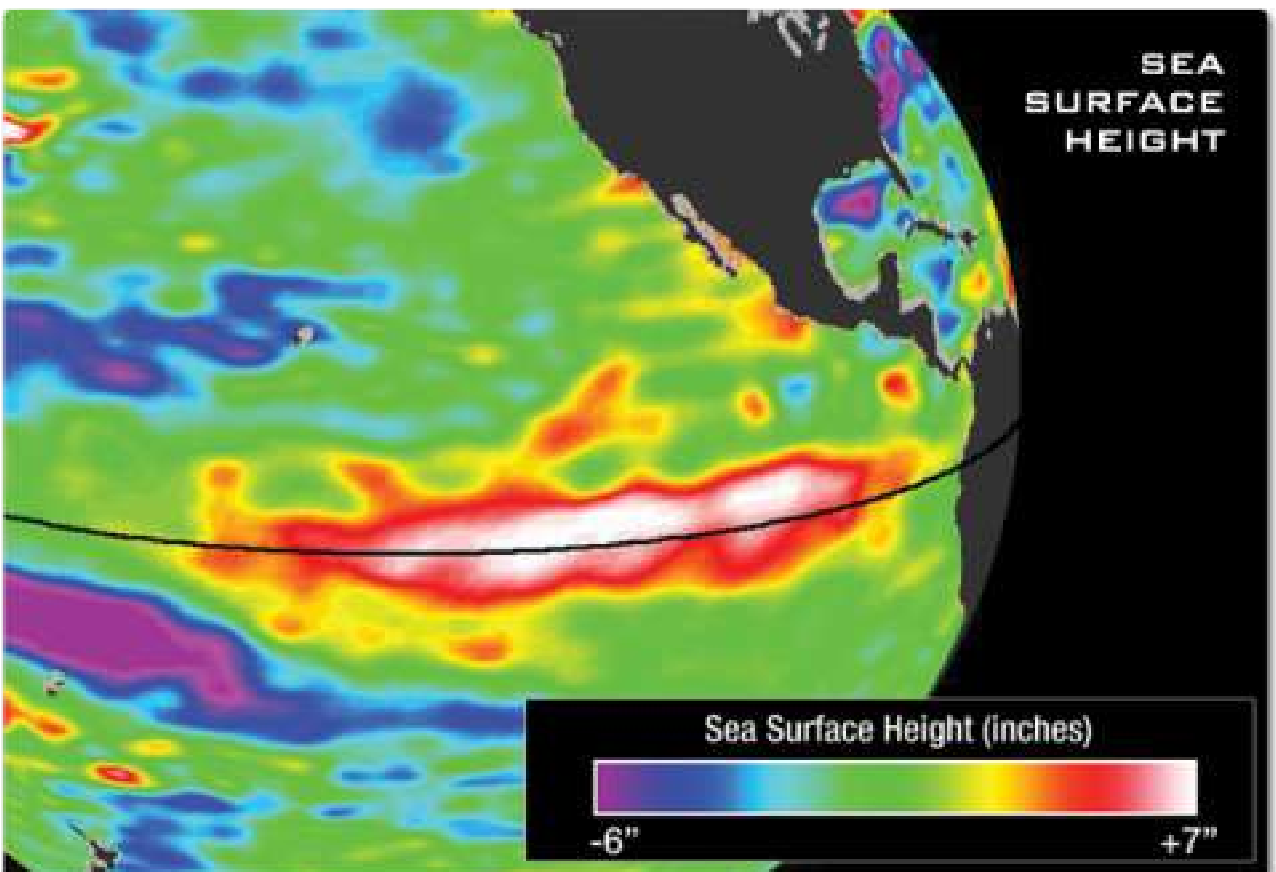


The Japanese Advanced Microwave Scanning Radiometer for EOS (AMSR-E) instrument onboard NASA's Aqua satellite can acquire high-resolution microwave measurements of the entire polar region every day, even through clouds and snowfall. Credit: NASA/Goddard Space Flight Center Scientific Visualization Studio

ACTIVE REMOTE SENSING

Radar technology is considered an active remote sensing system because it actively sends a microwave pulse and senses the energy reflected back. Doppler Radar, Scatterometers, and Radar Altimeters are examples of active remote sensing instruments that use microwave frequencies.

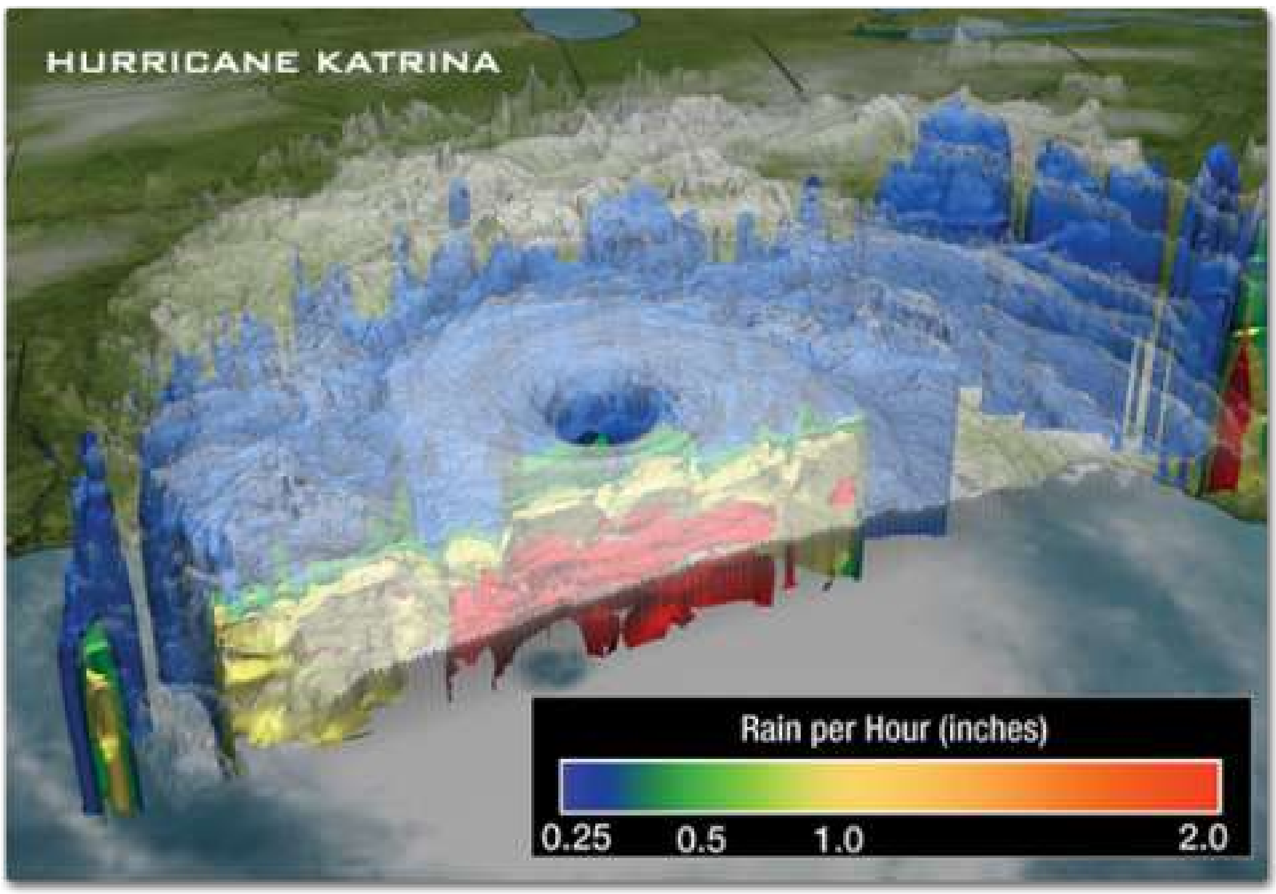
The radar altimeter onboard the joint NASA/CNES (French space agency) Ocean Surface Topography Mission (OSTM)/Jason-2 satellite can determine the height of the sea surface. This radar altimeter beams microwaves at two different frequencies (13.6 and 5.3 GHz) at the sea surface and measures the time it takes the pulses to return to the spacecraft. Combining data from other instruments that calculate the spacecraft's precise altitude and correct for the effect of water vapor on the pulse can determine the sea surface height within just a few centimeters!



Scientists monitor the changes in sea surface height around the world to help measurethe amount of heat stored in the ocean and predict global weather and climate eventssuch as El Niño. Since warm water is less dense than cold water, areas with a highersea surface tend to be warmer than lower areas. The sea surface height image(page 12) shows an area of warm water in the central and *eastern Pacific Ocean thatis about 10 to 18 centimeters higher than normal. Such conditions can signify anEl Niño.Credit: NASA/JPL Ocean Surface Topography Team.*

PASSIVE REMOTE SENSING

Passive remote sensing refers to the sensing of electromagnetic waves that did not originate from the satellite or instrument itself. The sensor is merely a passive observer collecting electromagnetic radiation. Passive remote sensing instruments onboard satellites have revolutionized weather forecasting by providing a global view of weather patterns and surface temperatures. A microwave imager onboard NASA's Tropical Rainfall Measuring Mission (TRMM) can capture data from underneath storm clouds to reveal the underlying rain structure.

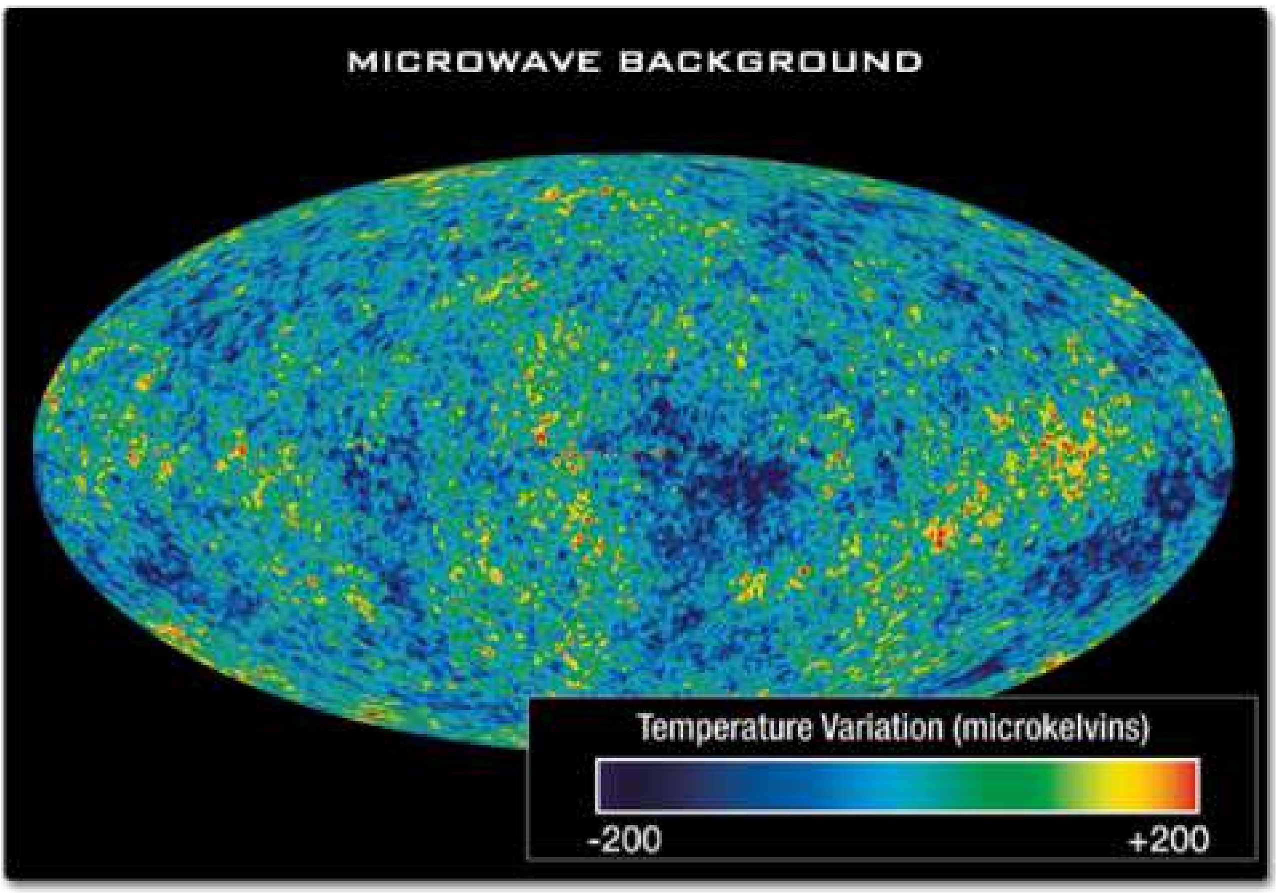


Credit: NASA/Goddard Space Flight Center Scientific Visualization Studio

CLUES TO THE BIG BANG

In 1965, using long, L-band microwaves, Arno Penzias and Robert Wilson, scientists at Bell Labs, made an incredible discovery quite by accident: they detected background noise using a special lownoise antenna. The strange thing about the noise was that it was coming from every direction and did not seem to vary in intensity much at all. If this static were from something on our planet, such as radio transmissions from a nearby airport control tower, it would come only from one direction, not everywhere. The Bell Lab scientists soon realized that they had serendipitously discovered the cosmic microwave background radiation. This radiation, which fills the entire universe, is a clue to its beginning, known as the Big Bang.

The image below from the Wilkinson Microwave Anisotropy Probe (WMAP) shows a detailed, all-sky picture of the infant universe at 380,000 years of age. This light, emitted 13.7 billon-years ago, is ~2.7 Kelvin today. The observed +/-200 microKelvin temperature fluctuations, shown as color differences in the image, are the seeds that grew to become clusters of galaxies.



Credit: NASA/WMAP Science Team