Remote Sensing
& its Technological Applications

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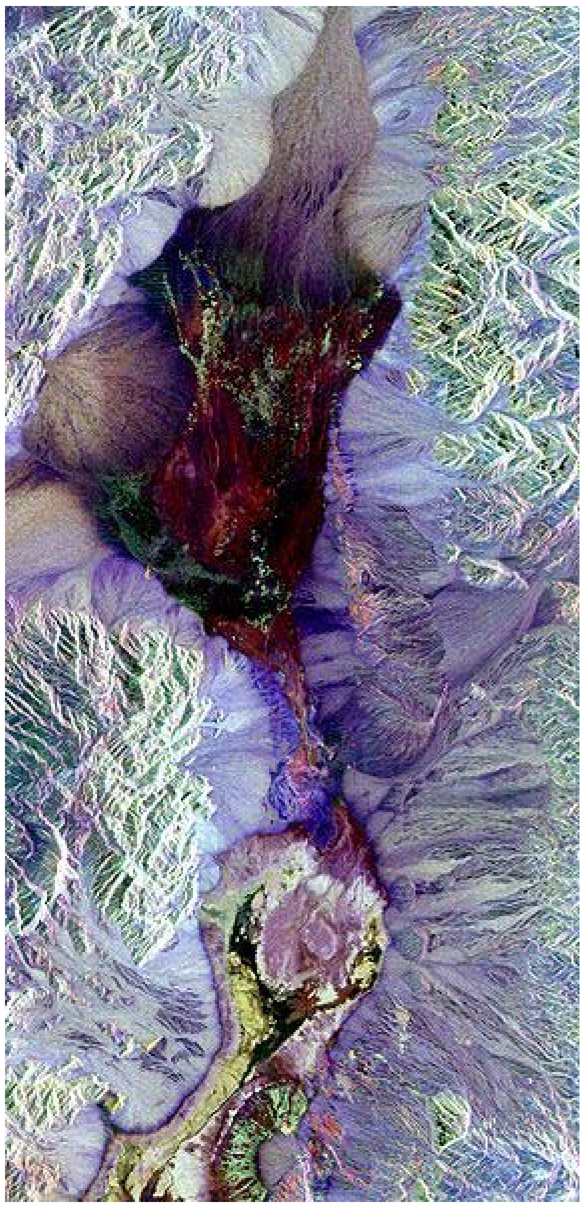
Remote Sensing



Synthetic aperture radar image of Death Valley colored using polarimetry.

Remote sensing is the acquisition of information about an object or phenomenon, without making physical contact with the object. In modern usage, the term generally refers to the use of aerial sensor technologies to detect and classify objects on Earth (both on the surface, and in the atmosphere and oceans) by means of propagated signals (e.g. electromagnetic radiation emitted from aircraft or satellites).

Overview

There are two main types of remote sensing: passive remote sensing and active remote sensing. Passive sensors detect natural radiation that is emitted or reflected by the object or surrounding area being observed. Reflected sunlight is the most common source of radiation measured by passive sensors. Examples of passive remote sensors include film photography, infrared, charge-coupled devices, and radiometers. Active collection, on the other hand, emits energy in order to scan objects and areas whereupon a sensor then detects and measures the radiation that is reflected or backscattered from the target. RADAR is an example of active remote sensing where the time delay between emission and return is measured, establishing the location, height, speed and direction of an object.

Remote sensing makes it possible to collect data on dangerous or inaccessible areas. Remote sensing applications include monitoring deforestation in areas such as the Amazon Basin, glacial features in Arctic and Antarctic regions, and depth sounding of coastal and ocean depths. Military collection during the cold war made use of stand-off collection of data about dangerous border areas. Remote sensing also replaces costly and slow data collection on the ground, ensuring in the process that areas or objects are not disturbed.

Orbital platforms collect and transmit data from different parts of the electromagnetic spectrum, which in conjunction with larger scale aerial or ground-based sensing and analysis, provides researchers with enough information to monitor trends such as El Niño and other natural long and short term phenomena. Other uses include different areas of the earth sciences such as natural resource management, agricultural fields such as land usage and conservation, and national security and overhead, ground-based and stand-off collection on border areas.

By satellite, aircraft, spacecraft, buoy, ship, and helicopter images, data is created to analyze and compare things like vegetation rates, erosion, pollution, forestry, weather, and land use. These things can be mapped, imaged, tracked and observed. The process of remote sensing is also helpful for city planning, archaeological investigations, military observation and geomorphological surveying.

Data acquisition techniques

The basis for multispectral collection and analysis is that of examined areas or objects that reflect or emit radiation that stand out from surrounding areas.

Applications of remote sensing data

- Conventional radar is mostly associated with aerial traffic control, early warning, and certain large scale meteorological data. Doppler radar is used by local law enforcements' monitoring of speed limits and in enhanced meteorological collection such as wind speed and direction within weather systems. Other types of active collection includes plasmas in the ionosphere. Interferometric synthetic aperture radar is used to produce precise digital elevation models of large scale terrain.
- Laser and radar altimeters on satellites have provided a wide range of data. By measuring the bulges of water caused by gravity, they map features on the seafloor to a resolution of a mile or so. By measuring the height and wave-length of ocean waves, the altimeters measure wind speeds and direction, and surface ocean currents and directions.
- Light detection and ranging (LIDAR) is well known in examples of weapon ranging, laser illuminated homing of projectiles. LIDAR is used to detect and measure the concentration of various chemicals in the atmosphere, while airborne LIDAR can be used to measure heights of objects and features on the ground more accurately than with radar technology. Vegetation remote sensing is a principal application of LIDAR.
- Radiometers and photometers are the most common instrument in use, collecting reflected and emitted radiation in a wide range of frequencies. The most common are visible and infrared sensors, followed by microwave, gamma ray and rarely, ultraviolet. They may also be used to detect the emission spectra of various chemicals, providing data on chemical concentrations in the atmosphere.
- Stereographic pairs of aerial photographs have often been used to make topographic maps by imagery and terrain analysts in trafficability and highway departments for potential routes.
- Simultaneous multi-spectral platforms such as Landsat have been in use since the 70's. These thematic mappers take images in multiple wavelengths of electro-magnetic radiation (multi-spectral) and are usually found on Earth observation satellites, including (for example) the Landsat program or the IKONOS satellite. Maps of land cover and land use from thematic mapping can be used to prospect for minerals, detect or monitor land usage, deforestation, and examine the health of indigenous plants and crops, including entire farming regions or forests.
- Within the scope of the combat against desertification, remote sensing allows to follow-up and monitor risk areas in the long term, to determine desertification factors, to support decision-makers in defining relevant measures of environmental management, and to assess their impacts.

Geodetic

- Overhead geodetic collection was first used in aerial submarine detection and gravitational data used in military maps. This data revealed minute perturbations in the Earth's gravitational field (geodesy) that may be used to determine changes in the mass distribution of the Earth, which in turn may be used for geological studies.

Acoustic and near-acoustic

- Sonar: *passive sonar*, listening for the sound made by another object (a vessel, a whale etc); *active sonar*, emitting pulses of sounds and listening for echoes, used for detecting, ranging and measurements of underwater objects and terrain.

- Seismograms taken at different locations can locate and measure earthquakes (after they occur) by comparing the relative intensity and precise timing.

To coordinate a series of large-scale observations, most sensing systems depend on the following: platform location, what time it is, and the rotation and orientation of the sensor. High-end instruments now often use positional information from satellite navigation systems. The rotation and orientation is often provided within a degree or two with electronic compasses. Compasses can measure not just azimuth (i. e. degrees to magnetic north), but also altitude (degrees above the horizon), since the magnetic field curves into the Earth at different angles at different latitudes. More exact orientations require gyroscopic-aided orientation, periodically realigned by different methods including navigation from stars or known benchmarks.

Resolution impacts collection and is best explained with the following relationship: less resolution=less detail & larger coverage, More resolution=more detail, less coverage. The skilled management of collection results in cost-effective collection and avoid situations such as the use of multiple high resolution data which tends to clog transmission and storage infrastructure.

Data processing

Generally speaking, remote sensing works on the principle of the *inverse problem*. While the object or phenomenon of interest (the **state**) may not be directly measured, there exists some other variable that can be detected and measured (the **observation**), which may be related to the object of interest through the use of a data-derived computer model. The common analogy given to describe this is trying to determine the type of animal from its footprints. For example, while it is impossible to directly measure temperatures in the upper atmosphere, it is possible to measure the spectral emissions from a known chemical species (such as carbon dioxide) in that region. The frequency of the emission may then be related to the temperature in that region via various thermodynamic relations.

The quality of remote sensing data consists of its spatial, spectral, radiometric and temporal resolutions.

Spatial resolution

> The size of a pixel that is recorded in a raster image – typically pixels may correspond to square areas ranging in side length from 1 to 1,000 metres (3.3 to 3,300 ft).

Spectral resolution

> The wavelength width of the different frequency bands recorded – usually, this is related to the number of frequency bands recorded by the platform. Current Landsat collection is that of seven bands, including several in the infra-red spectrum, ranging from a spectral resolution of 0.07 to 2.1 μm. The Hyperion sensor on Earth Observing-1 resolves 220 bands from 0.4 to 2.5 μm, with a spectral resolution of 0.10 to 0.11 μm per band.

Radiometric resolution

> The number of different intensities of radiation the sensor is able to distinguish. Typically, this ranges from 8 to 14 bits, corresponding to 256 levels of the gray scale and up to 16,384 intensities or "shades" of colour, in each band. It also depends on the instrument noise.

Temporal resolution

> The frequency of flyovers by the satellite or plane, and is only relevant in time-series studies or those requiring an averaged or mosaic image as in deforesting monitoring. This was first used by the intelligence community where repeated coverage revealed changes in infrastructure, the deployment of units or the modification/introduction of equipment. Cloud cover over a given area or object makes it necessary to repeat the collection of said location.

In order to create sensor-based maps, most remote sensing systems expect to extrapolate sensor data in relation to a reference point including distances between known points on the ground. This depends on the type of sensor used. For example, in conventional photographs, distances are accurate in the center of the image, with the distortion of measurements increasing the farther you get from the center. Another factor is that of the platen against which the film is pressed can cause severe errors when photographs are used to measure ground distances. The step in which this problem is resolved is called georeferencing, and involves computer-aided matching up of points in the image (typically 30 or more points per image) which is extrapolated with the use of an established benchmark, "warping" the image to produce accurate spatial data. As of the early 1990s, most satellite images are sold fully georeferenced.

In addition, images may need to be radiometrically and atmospherically corrected.

Radiometric correction

> gives a scale to the pixel values, e. g. the monochromatic scale of 0 to 255 will be converted to actual radiance values.

Atmospheric correction

> eliminates atmospheric haze by rescaling each frequency band so that its minimum value (usually realised in water bodies) corresponds to a pixel value of 0. The digitizing of data also make possible to manipulate the data by changing gray-scale values.

Interpretation is the critical process of making sense of the data. The first application was that of aerial photographic collection which used the following process; spatial measurement through the use of a light table in both conventional single or stereographic coverage, added skills such as the use of photogrammetry, the use of photomosaics, repeat coverage, Making use of objects' known dimensions in order to detect modifications. Image Analysis is the recently developed automated computer-aided application which is in increasing use.

Object-Based Image Analysis (OBIA) is a sub-discipline of GIScience devoted to partitioning remote sensing (RS) imagery into meaningful image-objects, and assessing their characteristics through spatial, spectral and temporal scale.

Old data from remote sensing is often valuable because it may provide the only long-term data for a large extent of geography. At the same time, the data is often complex to interpret, and bulky to store. Modern systems tend to store the data digitally, often with lossless compression. The difficulty with this approach is that the data is fragile, the format may be archaic, and the data may be easy to falsify. One of the best systems for archiving data series is as computer-generated machine-readable ultrafiche, usually in typefonts such as OCR-B, or as digitized half-tone images. Ultrafiches survive well in standard libraries, with lifetimes of several centuries. They can be created, copied, filed and retrieved by automated systems. They are about as compact as archival magnetic media, and yet can be read by human beings with minimal, standardized equipment.

Data processing levels

To facilitate the discussion of data processing in practice, several processing "levels" were first defined in 1986 by NASA as part of its Earth Observing System and steadily adopted since then, both internally at NASA (e. g.,) and elsewhere (e. g.,); these definitions are:

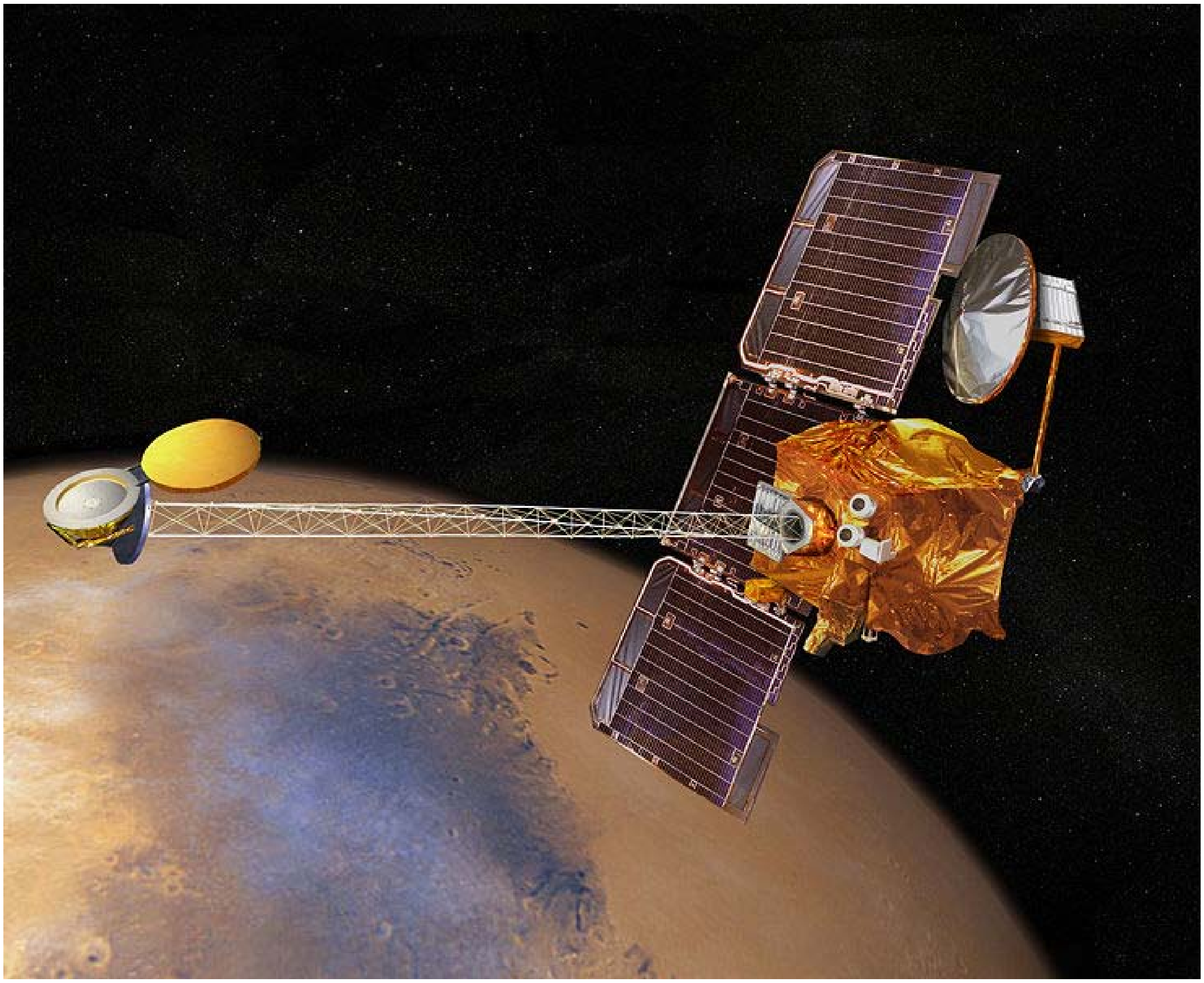
Level	Description
0	Reconstructed, unprocessed instrument and payload data at full resolution, with any and all communications artifacts (e. g., synchronization frames, communications headers, duplicate data) removed.
1a	Reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric calibration coefficients and georeferencing parameters (e. g., platform ephemeris) computed and appended but not applied to the Level 0 data (or if applied, in a manner that level 0 is fully recoverable from level 1a data).
1b	Level 1a data that have been processed to sensor units (e. g., radar backscatter cross section, brightness temperature, etc.); not all instruments have Level 1b data; level 0 data is not recoverable from level 1b data.
2	Derived geophysical variables (e. g., ocean wave height, soil moisture, ice concentration) at the same resolution and location as Level 1 source data.
3	Variables mapped on uniform spacetime grid scales, usually with some completeness and consistency (e. g., missing points interpolated, complete regions mosaicked together from multiple orbits, etc).

4	Model output or results from analyses of lower level data (i. e., variables that were not measured by the instruments but instead are derived from these measurements).

A Level 1 data record is the most fundamental (i. e., highest reversible level) data record that has significant scientific utility, and is the foundation upon which all subsequent data sets are produced. Level 2 is the first level that is directly usable for most scientific applications; its value is much greater than the lower levels. Level 2 data sets tend to be less voluminous than Level 1 data because they have been reduced temporally, spatially, or spectrally. Level 3 data sets are generally smaller than lower level data sets and thus can be dealt with without incurring a great deal of data handling overhead. These data tend to be generally more useful for many applications. The regular spatial and temporal organization of Level 3 datasets makes it feasible to readily combine data from different sources.

History

The TR-1 reconnaissance/surveillance aircraft.



The *2001 Mars Odyssey* used spectrometers and imagers to hunt for evidence of past or present water and volcanic activity on Mars.

The modern discipline of remote sensing arose with the development of flight. The balloonist G. Tournachon (alias Nadar) made photographs of Paris from his balloon in 1858. Messenger pigeons, kites, rockets and unmanned balloons were also used for early images. With the exception of balloons, these first, individual images were not particularly useful for map making or for scientific purposes.

Systematic aerial photography was developed for military surveillance and reconnaissance purposes beginning in World War I and reaching a climax during the Cold War with the use of modified combat aircraft such as the P-51, P-38, RB-66 and the F-4C, or specifically designed collection platforms such as the U2/TR-1, SR-71, A-5 and the OV-1 series both in overhead and stand-off collection. A more recent development is that of increasingly smaller sensor pods such as those used by law enforcement and the military, in both manned and unmanned platforms. The advantage of this approach is that this requires minimal modification to a given airframe. Later imaging technologies would include Infra-red, conventional, doppler and synthetic aperture radar.

The development of artificial satellites in the latter half of the 20th century allowed remote sensing to progress to a global scale as of the end of the Cold War. Instrumentation aboard various Earth observing and weather satellites such as Landsat, the Nimbus and more recent missions such as RADARSAT and UARS provided global measurements of various data for civil, research, and military purposes. Space probes to other planets have also provided the opportunity to conduct remote sensing studies in extraterrestrial environments, synthetic aperture radar aboard the Magellan spacecraft provided detailed topographic maps of Venus, while instruments aboard SOHO allowed studies to be performed on the Sun and the solar wind, just to name a few examples.

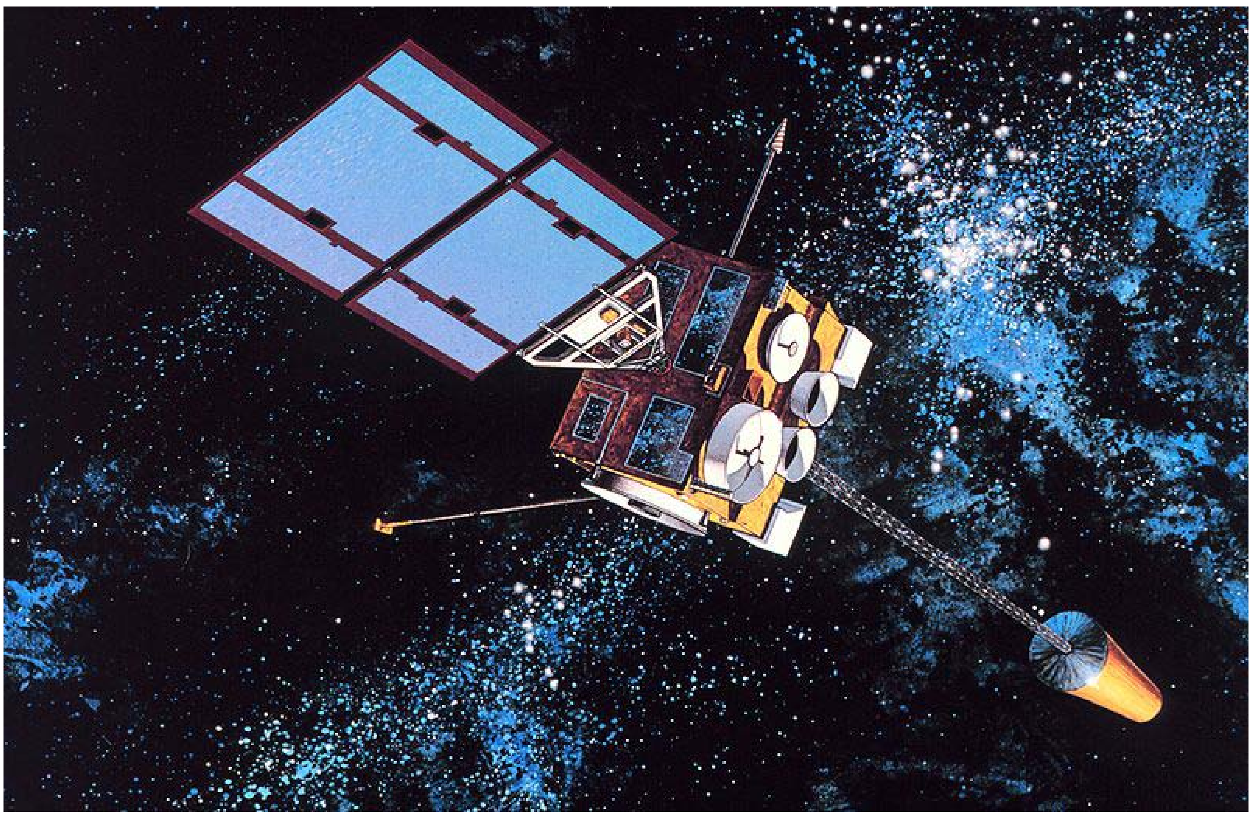
Recent developments include, beginning in the 1960s and 1970s with the development of image processing of satellite imagery. Several research groups in Silicon Valley including NASA Ames Research Center, GTE and ESL Inc. developed Fourier transform techniques leading to the first notable enhancement of imagery data.

Remote Sensing software

Remote Sensing data is processed and analyzed with computer software, known as a remote sensing application. A large number of proprietary and open source applications exist to process remote sensing data. According to an NOAA Sponsored Research by Global Marketing Insights, Inc. the most used applications among Asian academic groups involved in remote sensing are as follows: ERDAS 36% (ERDAS IMAGINE 25% & ERMapper 11%); ESRI 30%; ITT Visual Information Solutions ENVI 17%; MapInfo 17%. Among Western Academic respondents as follows: ESRI 39%, ERDAS IMAGINE 27%, MapInfo 9%, AutoDesk 7%, ITT Visual Information Solutions ENVI 17%. Other important Remote Sensing Software packages include: TNTmips from MicroImages, PCI Geomatica made by PCI Geomatics, the leading remote sensing software package in Canada, IDRISI from Clark Labs, Image Analyst from Intergraph, RemoteView made by Overwatch Textron Systems, and the original object based image analysis software eCognition from Definiens. Dragon/ips is one of the oldest remote sensing packages still available, and is in some cases free. Open source remote sensing software includes GRASS GIS, ILWIS, QGIS, OSSIM, Opticks (software) and Orfeo toolbox.

Chapter 2

Weather Satellite



GOES-8, a United States weather satellite

The **weather satellite** is a type of satellite that is primarily used to monitor the weather and climate of the Earth. Satellites can be either polar orbiting, seeing the same swath of the Earth every 12 hours, or geostationary, hovering over the same spot on Earth by orbiting over the equator while moving at the speed of the Earth's rotation. These meteorological satellites, however, see more than clouds and cloud systems. City lights, fires, effects of pollution, auroras, sand and dust storms, snow cover, ice mapping, boundaries of ocean currents, energy flows, etc., and other types of environmental information are collected using weather satellites. Weather satellite images helped in monitoring the volcanic ash cloud from Mount St. Helens and activity from other volcanoes such as Mount Etna. Smoke from fires in the western United States such as Colorado and Utah have also been monitored.

Other environmental satellites can detect changes in the Earth's vegetation, sea state, ocean color, and ice fields. For example, the 2002 oil spill off the northwest coast of Spain was watched carefully by the European ENVISAT, which, though not a weather satellite, flies an instrument (ASAR) which can see changes in the sea surface.

El Niño and its effects on weather are monitored daily from satellite images. The Antarctic ozone hole is mapped from weather satellite data. Collectively, weather satellites flown by the U.S., Europe, India, China, Russia, and Japan provide nearly continuous observations for a global weather watch.

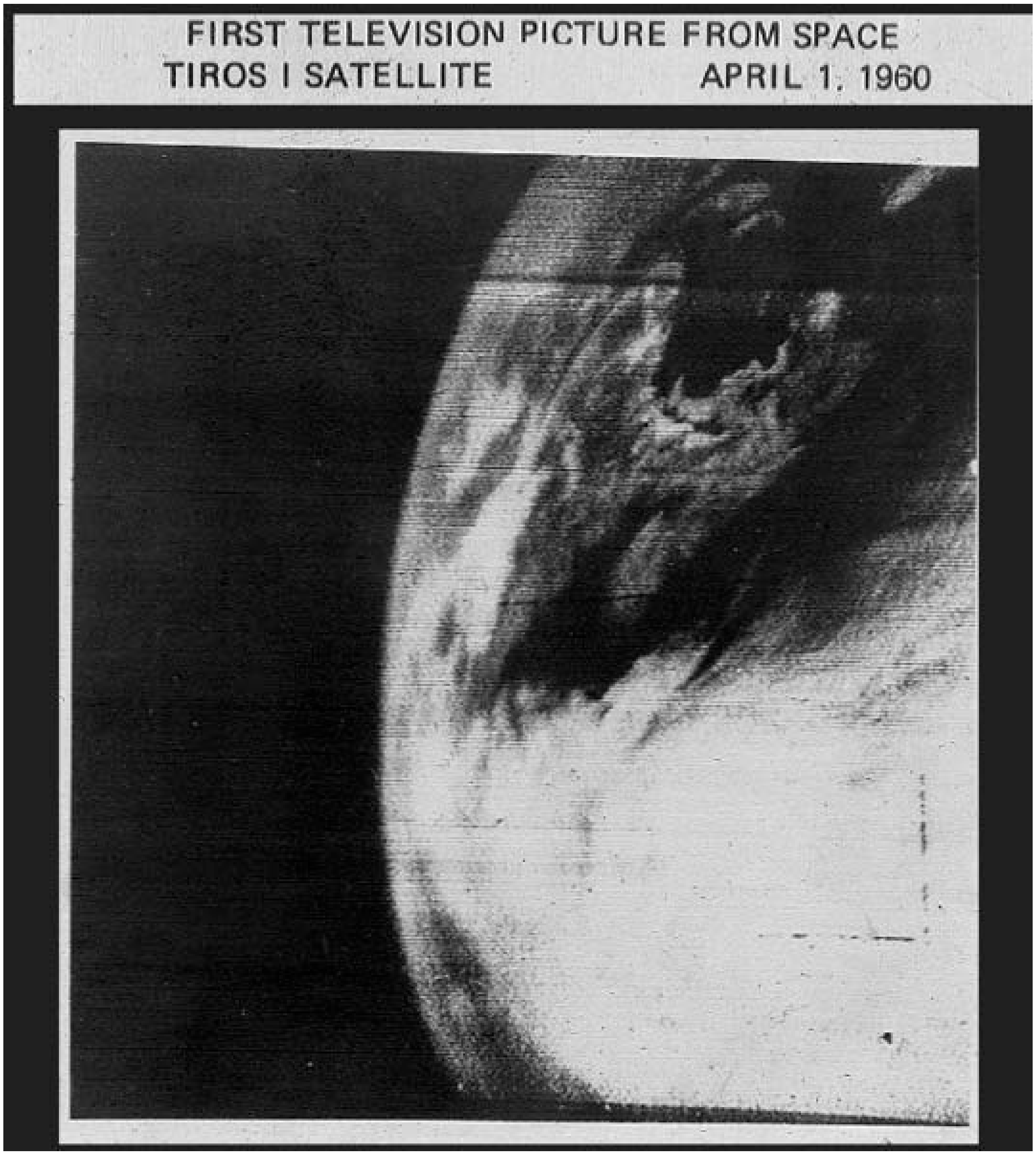
Observation

Observation is typically made via different 'channels' of the Electromagnetic spectrum, in particular, the Visible and Infrared portions.

Some of these channels include:

- *Visible and Near Infrared:* 0.6 µm - 1.6 µm - For recording cloud cover during the day
- *Infrared:* 3.9 µm - 7.3 µm (Water Vapour), 8.7 µm, - 13.4 µm (Thermal imaging)

History



The first television image of Earth from space from the TIROS-1 weather satellite.

The first weather satellite, Vanguard 2, was launched on February 17, 1959. It was designed to measure cloud cover and resistance, but a poor axis of rotation kept it from collecting a notable amount of useful data.

The first weather satellite to be considered a success was TIROS-1, launched by NASA on 1 April 1960. TIROS operated for 78 days and proved to be much more successful than Vanguard 2. TIROS paved the way for the Nimbus program, whose technology and findings are the heritage of most of the Earth-observing satellites NASA and NOAA have launched since then.

Visible spectrum

Visible-light images from weather satellites during local daylight hours are easy to interpret even by the average person; clouds, cloud systems such as fronts and tropical storms, lakes, forests, mountains, snow ice, fires, and pollution such as smoke, smog, dust and haze are readily apparent. Even wind can be determined by cloud patterns, alignments and movement from successive photos.

Infrared spectrum

The thermal or infrared images recorded by sensors called scanning radiometers enable a trained analyst to determine cloud heights and types, to calculate land and surface water temperatures, and to locate ocean surface features. Infrared satellite imagery can be used effectively for tropical cyclones with a visible eye pattern, using the Dvorak technique, where the difference between the temperature of the warm eye and the surrounding cold cloud tops can be used to determine its intensity (colder cloud tops generally indicate a more intense storm). Infrared pictures depict ocean eddies or vortices and map currents such as the Gulf Stream which are valuable to the shipping industry. Fishermen and farmers are interested in knowing land and water temperatures to protect their crops against frost or increase their catch from the sea. Even El Niño phenomena can be spotted. Using color-digitized techniques, the gray shaded thermal images can be converted to color for easier identification of desired information.

Types

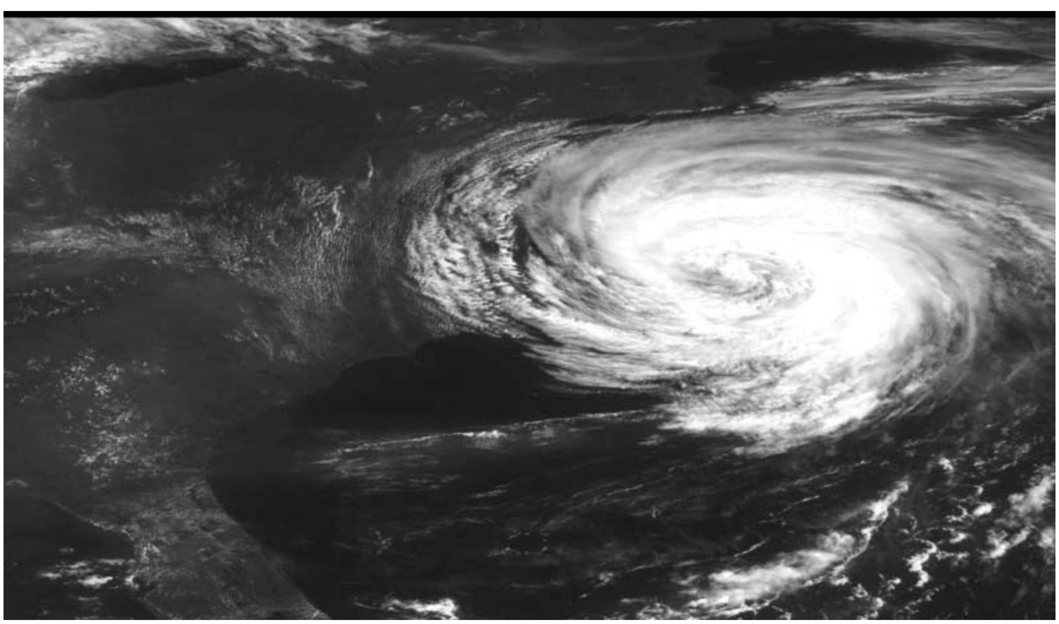


Image from the GOES-9 weather satellite of Hurricane Felix.

There are two basic types of meteorological satellites: geostationary and polar orbiting.

Geostationary

Geostationary weather satellites orbit the Earth above the equator at altitudes of 35,880 km (22,300 miles). Because of this orbit, they remain stationary with respect to the rotating Earth and thus can record or transmit images of the entire hemisphere below continuously with their visible-light and infrared sensors. The news media use the geostationary photos in their daily weather presentation as single images or made into movie loops. These are also available on the city forecast pages of noaa.gov (example Dallas, TX).

Several geostationary meteorological spacecraft are in operation. The United States has two in operation; GOES-11 and GOES-12. GOES-12, designated GOES-East, is located over the Amazon River and provides most of the U.S. weather information. GOES-11 is GOES-West over the eastern Pacific Ocean. Russia's new-generation weather satellite Elektro-L 1 operates at 76°E over the Indian Ocean. The Japanese have one in operation; MTSAT-1R over the mid Pacific at 140°E. The Europeans have Meteosat-8 (3.5°W) and Meteosat-9 (0°) over the Atlantic Ocean and have Meteosat-6 (63°E) and Meteosat-7 (57.5°E) over the Indian Ocean. India also operates geostationary satellites called INSAT which carry instruments for meteorological purposes. China operated the Feng-Yun（風雲) geostationary satellites FY-2D at 86.5°E and FY-2E at 123.5°E, which are no longer in use anymore.

Polar orbiting

Computer controlled motorized parabolic dish antenna for tracking LEO weather satellites.

Polar orbiting weather satellites circle the Earth at a typical altitude of 850 km (530 miles) in a north to south (or vice versa) path, passing over the poles in their continuous flight. Polar satellites are in sun-synchronous orbits, which means they are able to observe any place on Earth and will view every location twice each day with the same general lighting conditions due to the near-constant local solar time. Polar orbiting weather satellites offer a much better resolution than their geostationary counterparts due their closeness to the Earth.

The United States has the NOAA series of polar orbiting meteorological satellites, presently NOAA 17 and NOAA 18 as primary spacecraft, NOAA 15 and NOAA 16 as secondary spacecraft, NOAA 14 in standby, and NOAA 12. Europe has the Metop-A satellite. Russia has the Meteor and RESURS series of satellites. China has FY-1D and FY-3A. India has polar orbiting satellites as well.

DMSP

Turnstile antenna for reception of 137 MHz LEO weather satellite transmissions

The United States Department of Defense's Meteorological Satellite (DMSP) can "see" the best of all weather vehicles with its ability to detect objects almost as 'small' as a huge oil tanker. In addition, of all the weather satellites in orbit, only DMSP can "see" at night in the visual. Some of the most spectacular photos have been recorded by the night visual sensor; city lights, volcanoes, fires, lightning, meteors, oil field burn-offs, as well as the Aurora Borealis and Aurora Australis have been captured by this 450-mile-high space vehicle's low moonlight sensor.

At the same time, energy monitoring as well as city growth can be accomplished since both major and even minor cities, as well as highway lights, are conspicuous. This informs astronomers of light pollution. The New York City Blackout of 1977 was captured by one of the night orbiter DMSP space vehicles.

In addition to monitoring city lights, these photos are a life saving asset in the detection and monitoring of fires. Not only do the satellites see the fires visually day and night, but the thermal and infrared scanners on board these weather satellites detect potential fire sources below the surface of the Earth where smoldering occurs. Once the fire is detected, the same weather satellites provide vital information about wind that could fan or spread the fires. These same cloud photos from space tell the firefighter when it will rain.

Dramatic photos are provided by all the weather satellites, but even more definitive were the DMSP night visible-light pictures of the 700 oil well fires that Iraq started on 23 February 1991 as they fled Kuwait. These fires were vividly illustrated as huge flashes in the night photos, far outstripping the glow of large populated areas. The fires consumed millions of gallons of oil; the last was doused on November 6.

Uses

Snowfield monitoring, especially in the Sierra Nevada, can be helpful to the hydrologist keeping track of how much snow is available for runoff vital to the water sheds of the western United States. This information is gleaned from existing satellites of all agencies of the U.S. government (in addition to local, on-the-ground measurements). Ice floes, packs and bergs can also be located and tracked from weather space craft.

Even pollution whether it's nature-made or man-made can be pinpointed. The visual and infrared photos show effects of pollution from their respective areas over the entire earth. Aircraft and rocket pollution, as well as condensation trails, can also be spotted. The ocean current and low level wind information gleaned from the space photos can help predict oceanic oil spill coverage and movement. Almost every summer, sand and dust from the Sahara Desert in Africa drifts across the equatorial regions of the Atlantic Ocean. GOES-EAST photos enable meteorologists to observe, track and forecast this sand cloud. In addition to reducing visibilities and causing respiratory problems, sand clouds suppress hurricane formation by modifying the solar radiation balance of the tropics. Other dust storms in Asia and mainland China are common and easy to spot and monitor, with recent examples of dust moving across the Pacific ocean and reaching North America.

In remote areas of the world with few local observers, fires could rage out of control for days or even weeks and consume millions of acres before authorities are alerted. Weather satellites can be a tremendous asset in such situations. Nighttime photos also clearly show the burn-off in the gas and oil fields of the Middle East and African countries. This burn-off throws large amounts of carbon dioxide into the atmosphere.

Chapter 3

Photometer

In its widest sense, a **photometer** is an instrument for measuring light intensity or optical properties of solutions or surfaces. Photometers are used to measure:

- Illuminance
- Irradiance
- Light absorption
- Scattering of light
- Reflection of light
- Fluorescence
- Phosphorescence
- Luminescence

History

Before electronic light sensitive elements were developed, photometry was done by estimation by the eye. The relative luminous flux of a source was compared with a standard source. The photometer is placed such that the illuminance from the source being investigated is equal to that of the standard source as equal illuminance can be judged by the eye. The relative luminous fluxes can then be calculated as the illuminance decreases proportionally to the inverse square of distance. A standard example of such a photometer consists of a piece of paper with an oil spot on it that makes the paper there slightly more transparent. When the spot is not visible from either side, the illuminance from the two sides is equal.

Principle of photometers

Most photometers detect the light with photoresistors, photodiodes or photomultipliers. To analyze the light, the photometer may measure the light after it has passed through a filter or through a monochromator for determination at defined wavelengths or for analysis of the spectral distribution of the light.

Photon counting

Some photometers measure light by counting individual photons rather than incoming flux. The operating principles are the same but the results are given in units such as photons/cm^2 or photons·cm^{-2}·sr^{-1} rather than W/cm^2 or W·cm^{-2}·sr^{-1}.

Due to their individual photon counting nature, these instruments are limited to observations where the irradiance is low. The irradiance is limited by the time resolution of its associated detector readout electronics. With current technology this is in the megahertz range. The maximum irradiance is also limited by the throughput and gain parameters of the detector itself.

The light sensing element in photon counting devices in NIR, visible and ultrviolet wavelengths is a photomultiplier to achieve sufficient sensitivity.

In airborne and space-based remote sensing such photon counters are used at the upper reaches of the electromagnetic spectrum such as the X-ray to far ultraviolet. This is usually due to the lower radiant intensity of the objects being measured as well as the difficulty of measuring light at higher energies using its particle-like nature as compared to the wavelike nature of light at lower frequencies. Conversely, radiometers are typically used for remote sensing from the visible, infrared though radio frequency range.

Photography

Photometers are used to determine the correct exposure in photography. In modern cameras, the photometer is usually built in. As the illumination of different parts of the picture varies, advanced photometers measure the light intensity in different parts of the potential picture and use an algorithm to determine the most suitable exposure for the final picture, adapting the algorithm to the type of picture intended. Historically, a photometer was separate from the camera. The advanced photometers then could be used either to measure the light from the potential picture as a whole, to measure from elements of the picture to ascertain that the most important parts of the picture are optimally exposed, or to measure the incident light to the scene with an integrating adapter.

Visible light reflectance photometry

A reflectance photometer measures the reflectance of a surface as a function of wavelength. The surface is illuminated with white light, and the reflected light is measured after passing through a monochromator. This type of measurement has mainly practical applications, for instance in the paint industry to characterize the colour of a surface objectively.

UV and visible light transmission photometry

These are optical instruments for measurement of the absorption of light of a given wavelength (or a given range of wavelengths) of coloured substances in solution. From the light absorption, Beer's law makes it possible to calculate the concentration of the coloured substance in the solution. Due to its wide range of application and its reliability and robustness, the photometer has become one of the principal instruments in biochemistry and analytical chemistry. Absorption photometers for work in aqueous solution work in the ultraviolet and visible ranges, from wavelength around 240 nm up to 750 nm.

The principle of spectrophotometers and filter photometers is that (as far as possible) monochromatic light is allowed to pass through a container (cell) with optically flat windows containing the solution. It then reaches a light detector, that measures the intensity of the light compared to the intensity after passing through an identical cell with the same solvent but without the coloured substance. From the ratio between the light intensities, knowing the capacity of the coloured substance to absorb light (the absorbancy of the coloured substance, or the photon cross section area of the molecules of the coloured substance at a given wavelength), it is possible to calculate the concentration of the substance using Beer's law.

Two types of photometers are used: spectrophotometer and filter photometer. In spectrophotometers a monochromator (with prism or with grating) is used to obtain monochromatic light of one defined wavelength. In filter photometers, optical filters are used to give the monochromatic light. Spectrophotometers can thus easily be set to measure the absorbance at different wavelengths, and they can also be used to scan the spectrum of the absorbing substance. They are in this way more flexible than filter photometers, also give a higher optical purity of the analyzing light, and therefore they are preferably used for research purposes. Filter photometers are cheaper, robuster and easier to use and therefore they are used for routine analysis. Photometers for microtiter plates are filter photometers.

Infrared light transmission photometry

Spectrophotometry in infrared light is mainly used to study structure of substances, as given groups give absorption at defined wavelengths. Measurement in aqueous solution is generally not possible, as water absorbs infrared light strongly in some wavelength ranges. Therefore, infrared spectroscopy is either performed in the gaseous phase (for volatile substances) or with the substances pressed into tablets together with salts that are transparent in the infrared range. Potassium bromide (KBr) is commonly used for this purpose. The substance to be tested is thoroughly mixed with specially purified KBr and pressed into a transparent tablet, that is placed in the beam of light. The analysis of the wavelength dependence is generally not done using a monochromator as it is in UV-Vis, but with the use of an interferometer. The interference pattern can be analyzed using a Fourier transform algorithm. In this way, the whole wavelength range can be analyzed simultaneously, saving time, and an interferometer is also less expensive than a monochromator. The light absorbed in the infrared region does not correspond to electronic excitation of the substance studied, but rather to different kinds of vibrational excitation. The vibrational excitations are characteristic of different groups in a molecule, that can in this way be identified. The infrared spectrum typically has very narrow absorption lines, which makes them unsuited for quantitative analysis but gives very detailed information about the molecules. The frequencies of the different modes of vibration varies with isotope, and therefore different isotopes give different peaks. This makes it possible also to study the isotopic composition of a sample with infrared spectrophotometry.

Atomic absorption photometry

Atomic absorption photometers are photometers that measure the light from a very hot flame. The solution to be analyzed is injected into the flame at a constant, known rate. Metals in the solution are present in atomic form in the flame. The monochromatic light in this type of photometer is generated by a discharge lamp where the discharge takes place in a gas with the metal to be determined. The discharge then emits light with wavelengths corresponding to the spectral lines of the metal. A filter may be used to isolate one of the main spectral lines of the metal to be analyzed. The light is absorbed by the metal in the flame, and the absorption is used to determine the concentration of the metal in the original solution.

Chapter 4

LIDAR

A FASOR used at the Starfire Optical Range for LIDAR and laser guide star experiments is tuned to the sodium D2a line and used to excite sodium atoms in the upper atmosphere.

This lidar (laser range finder) may be used to scan buildings, rock formations, etc., to produce a 3D model. The LIDAR can aim its laser beam in a wide range: its head rotates horizontally, a mirror flips vertically. The laser beam is used to measure the distance to the first object on its path.

LIDAR (**Light Detection And Ranging**, also **LADAR**) is an optical remote sensing technology that can measure the distance to, or other properties of a target by illuminating the target with light, often using pulses from a laser. LIDAR technology has application in Geomatics, archaeology, geography, geology, geomorphology, seismology, forestry, remote sensing and atmospheric physics. Also for 'airborne laser swath mapping' (ALSM), 'laser altimetry' and LIDAR Contour Mapping.

The acronym **LADAR** (*Laser Detection and Ranging*) is often used in military contexts. The term "**laser radar**" is sometimes used even though LIDAR does not employ microwaves or radio waves and is not therefore in reality related to radar.

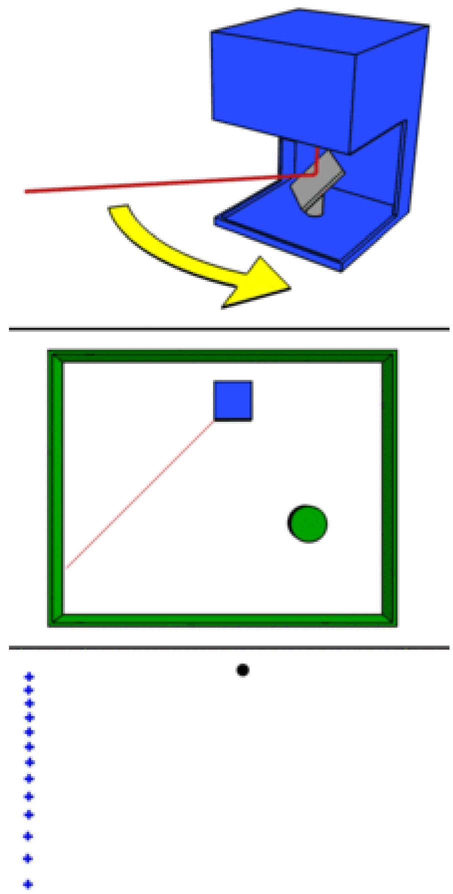
General description

LIDAR uses ultraviolet, visible, or near infrared light to image objects and can be used with a wide range of targets, including non-metallic objects, rocks, rain, chemical compounds, aerosols, clouds and even single molecules. A narrow laser beam can be used to map physical features with very high resolution.

LIDAR has been used extensively for atmospheric research and meteorology. Downward-looking LIDAR instruments fitted to aircraft and satellites are used for surveying and mapping. A recent example being the NASA Experimental Advanced Research Lidar.

Wavelengths in a range from about 10 micrometers to the UV (ca. 250 nm) are used to suit the target. Typically light is reflected via backscattering. Different types of scattering are used for different LIDAR applications, most common are Rayleigh scattering, Mie scattering and Raman scattering as well as fluorescence. Based on different kinds of backscattering, the LIDAR can be accordingly called Rayleigh LiDAR, Mie LiDAR, Raman LiDAR and Na/Fe/K Fluorescence LIDAR and so on. Suitable combinations of wavelengths can allow for remote mapping of atmospheric contents by looking for wavelength-dependent changes in the intensity of the returned signal.

Design



A basic LIDAR system involves a laser range finder reflected by a rotating mirror (top). The laser is scanned around the scene being digitised, in one or two dimensions (middle), gathering distance measurements at specified angle intervals (bottom).

In general there are two kinds of lidar detection schema: "incoherent" or direct energy detection (which is principally an amplitude measurement) and Coherent detection (which is best for doppler, or phase sensitive measurements). Coherent systems generally use Optical heterodyne detection which being more sensitive than direct detection allows them to operate a much lower power but at the expense of more complex transceiver requirements.

In both coherent and incoherent LIDAR, there are two types of pulse models: *micropulse lidar* systems and *high energy* systems. Micropulse systems have developed as a result of the ever increasing amount of computer power available combined with advances in laser technology. They use considerably less energy in the laser, typically on the order of one microjoule, and are often "eye-safe," meaning they can be used without safety precautions. High-power systems are common in atmospheric research, where they are widely used for measuring many atmospheric parameters: the height, layering and densities of clouds, cloud particle properties (extinction coefficient, backscatter coefficient, depolarization), temperature, pressure, wind, humidity, trace gas concentration (ozone, methane, nitrous oxide, etc.).

There are several major components to a LIDAR system:

1. **Laser** — 600–1000 nm lasers are most common for non-scientific applications. They are inexpensive but since they can be focused and easily absorbed by the eye the maximum power is limited by the need to make them eye-safe. Eye-safety is often a requirement for most applications. A common alternative 1550 nm lasers are eye-safe at much higher power levels since this wavelength is not focused by the eye, but the detector technology is less advanced and so these wavelengths are generally used at longer ranges and lower accuracies. They are also used for military applications as 1550 nm is not visible in night vision goggles unlike the shorter 1000 nm infrared laser. Airborne topographic mapping lidars generally use 1064 nm diode pumped YAG lasers, while bathymetric systems generally use 532 nm frequency doubled diode pumped YAG lasers because 532 nm penetrates water with much less attenuation than does 1064 nm. Laser settings include the laser repetition rate (which controls the data collection speed). Pulse length is generally an attribute of the laser cavity length, the number of passes required through the gain material (YAG, YLF, etc.), and Q-switch speed. Better target resolution is achieved with shorter pulses, provided the LIDAR receiver detectors and electronics have sufficient bandwidth.
2. **Scanner and optics** — How fast images can be developed is also affected by the speed at which it can be scanned into the system. There are several options to scan the azimuth and elevation, including dual oscillating plane mirrors, a combination with a polygon mirror, a dual axis scanner. Optic choices affect the angular resolution and range that can be detected. A hole mirror or a beam splitter are options to collect a return signal.
3. **Photodetector and receiver electronics** — Two main photodetector technologies are used in lidars: solid state photodetectors, such as silicon avalanche photodiodes, or photomultipliers. The sensitivity of the receiver is another parameter that has to be balanced in a LIDAR design.
4. **Position and navigation systems** — LIDAR sensors that are mounted on mobile platforms such as airplanes or satellites require instrumentation to determine the absolute position and orientation of the sensor. Such devices generally include a Global Positioning System receiver and an Inertial Measurement Unit (IMU).

3D imaging can be achieved using both scanning and non-scanning systems. "3D gated viewing laser radar" is a non-scanning laser ranging system that applies a pulsed laser and a fast gated camera.

Imaging LIDAR can also be performed using arrays of high speed detectors and modulation sensitive detectors arrays typically built on single chips using CMOS and hybrid CMOS/CCD fabrication techniques. In these devices each pixel performs some local processing such as demodulation or gating at high speed down converting the signals to video rate so that the array may be read like a camera. Using this technique many thousands of pixels / channels may be acquired simultaneously. In practical systems the limitation is light budget rather than parallel acquisition. High resolution 3D LIDAR cameras use homodyne detection with an electronic CCD or CMOS shutter.

A coherent Imaging LIDAR uses Synthetic array heterodyne detection to enables a staring single element receiver to act as though it were an imaging array avoiding the need for a gated camera and all ranges from all pixels are simultaneously available in the image.

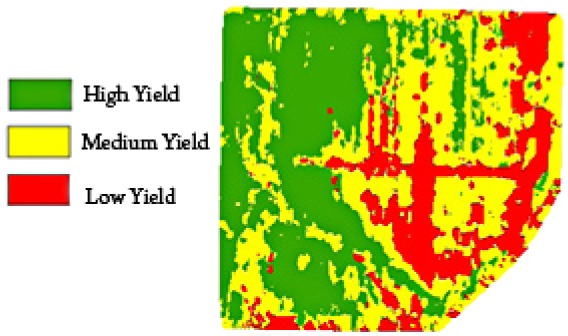
There are ongoing military research programmes in Sweden, Denmark, the USA and the UK with 3-D gated viewing imaging at several kilometers range with a range resolution and accuracy better than ten centimeters.

Applications

This LIDAR-equipped mobile robot uses its LIDAR to construct a map and avoid obstacles.

Other than those applications listed above, there are a wide variety of applications of LIDAR, as often mentioned in National LIDAR Dataset programs.

Agriculture



Agricultural Research Service scientists have developed a way to incorporate LIDAR with yield rates on agricultural fields. This technology will help farmers direct their resources toward the high-yield sections of their land.

LIDAR also can be used to help farmers determine which areas of their fields to apply costly fertilizer. LIDAR can create a topological map of the fields and reveals the slopes and sun exposure of the farm land. Researchers at the Agricultural Research Service blended this topological information with the farm land's yield results from previous years. From this information, researchers categorized the farm land into high-, medium-, or low-yield zones. This technology is valuable to farmers because it indicates which areas to apply the expensive fertilizers to achieve the highest crop yield.

Archaeology

LIDAR has many applications in the field of archaeology including aiding in the planning of field campaigns, mapping features beneath forest canopy, and providing an overview of broad, continuous features that may be indistinguishable on the ground. LIDAR can also provide archaeologists with the ability to create high-resolution digital elevation models (DEMs) of archaeological sites that can reveal micro-topography that are otherwise hidden by vegetation. LiDAR-derived products can be easily integrated into a Geographic Information System (GIS) for analysis and interpretation. For example at Fort Beausejour - Fort Cumberland National Historic Site, Canada, previously undiscovered archaeological features have been mapped that are related to the siege of the Fort in 1755. Features that could not be distinguished on the ground or through aerial photography were identified by overlaying hillshades of the DEM created with artificial illumination from various angles. With LiDAR the ability to produce high-resolution datasets quickly and relatively cheaply can be an advantage. Beyond efficiency, its ability to penetrate forest canopy has led to the discovery of features that were not distinguishable through traditional geo-spatial methods and are difficult to reach through field surveys.

Biology and conservation

LIDAR has also found many applications in forestry. Canopy heights, biomass measurements, and leaf area can all be studied using airborne LIDAR systems. Similarly, LIDAR is also used by many industries, including Energy and Railroad, and the Department of Transportation as a faster way of surveying. Topographic maps can also be generated readily from LIDAR, including for recreational use such as in the production of orienteering maps.

In oceanography, LiDAR is used for estimation of phytoplankton fluorescence and generally biomass in the surface layers of the ocean. Another application is airborne lidar bathymetry of sea areas too shallow for hydrographic vessels.

In addition, the Save-the-Redwoods League is undertaking a project to map the tall redwoods on California's northern coast. LIDAR allows research scientists to not only measure the height of previously unmapped trees but to determine the biodiversity of the redwood forest. Stephen Sillett who is working with the League on the North Coast LIDAR project claims this technology will be useful in directing future efforts to preserve and protect ancient redwood trees.

Geology and soil science

High-resolution digital elevation maps generated by airborne and stationary LIDAR have led to significant advances in geomorphology, the branch of geoscience concerned with the origin and evolution of Earth's surface topography. LIDAR's abilities to detect subtle topographic features such as river terraces and river channel banks, measure the land surface elevation beneath the vegetation canopy, better resolve spatial derivatives of elevation, and detect elevation changes between repeat surveys have enabled many novel studies of the physical and chemical processes that shape landscapes. In addition to LIDAR data collected by private companies, academic consortia have been created to support the collection, processing and archiving of research-grade, publicly available LIDAR datasets. The National Center for Airborne Laser Mapping (NCALM), supported by the National Science Foundation, collects and distributes LIDAR data in support of scientific research and education in a variety of fields, particularly geoscience and ecology.

In geophysics and tectonics, a combination of aircraft-based LIDAR and GPS have evolved into an important tool for detecting faults and measuring uplift. The output of the two technologies can produce extremely accurate elevation models for terrain that can even measure ground elevation through trees. This combination was used most famously to find the location of the Seattle Fault in Washington, USA. This combination is also being used to measure uplift at Mt. St. Helens by using data from before and after the 2004 uplift. Airborne LIDAR systems monitor glaciers and have the ability to detect subtle amounts of growth or decline. A satellite based system is NASA's ICESat which includes a LIDAR system for this purpose. NASA's Airborne Topographic Mapper is also used extensively to monitor glaciers and perform coastal change analysis. The combination is also used by soil scientists while creating a soil survey. The detailed terrain modeling allows soil scientists to see slope changes and landform breaks which indicate patterns in soil spatial relationships.

Hydrology

LIDAR offers a lot of information to the aquatic sciences. High-resolution digital elevation maps generated by airborne and stationary LIDAR have led to significant advances in the field. Hydrology

Meteorology and atmospheric environment

The first LIDAR systems were used for studies of atmospheric composition, structure, clouds, and aerosols. Initially based on ruby lasers, LIDAR for meteorological applications was constructed shortly after the invention of the laser and represent one of the first applications of laser technology.

Elastic backscatter LIDAR is the simplest type of lidar and is typically used for studies of aerosols and clouds. The backscattered wavelength is identical to the transmitted wavelength, and the magnitude of the received signal at a given range depends on the backscatter coefficient of scatterers at that range and the extinction coefficients of the scatterers along the path to that range. The extinction coefficient is typically the quantity of interest.

Differential Absorption LIDAR (DIAL) is used for range-resolved measurements of a particular gas in the atmosphere, such as ozone, carbon dioxide, or water vapor. The LIDAR transmits two wavelengths: an "on-line" wavelength that is absorbed by the gas of interest and an off-line wavelength that is not absorbed. The differential absorption between the two wavelengths is a measure of the concentration of the gas as a function of range. DIAL LIDARs are essentially dual-wavelength backscatter LIDARS.

Raman LIDAR is also used for measuring the concentration of atmospheric gases, but can also be used to retrieve aerosol parameters as well. Raman LIDAR exploits inelastic scattering to single out the gas of interest from all other atmospheric constituents. A small portion of the energy of the transmitted light is deposited in the gas during the scattering process, which shifts the scattered light to a longer wavelength by an amount that is unique to the species of interest. The higher the concentration of the gas, the stronger the magnitude of the backscattered signal.

Doppler LIDAR is used to measure wind speed along the beam by measuring the frequency shift of the backscattered light. Scanning LIDARs, such as NASA's HARLIE LIDAR, have been used to measure atmospheric wind velocity in a large three dimensional cone. ESA's wind mission ADM-Aeolus will be equipped with a Doppler LIDAR system in order to provide global measurements of vertical wind profiles. A doppler LIDAR system was used in the 2008 Summer Olympics to measure wind fields during the yacht competition. Doppler LIDAR systems are also now beginning to be successfully applied in the renewable energy sector to acquire wind speed, turbulence, wind veer and wind shear data. Both pulsed and continuous wave systems are being used. Pulsed systems using signal timing to obtain vertical distance resolution, whereas continuous wave systems rely on detector focusing.

Synthetic Array LIDAR allows imaging LIDAR without the need for an array detector. It can be used for imaging Doppler velocimetry, ultra-fast frame rate (MHz) imaging, as well as for speckle reduction in coherent LIDAR.

Law enforcement

LIDAR speed guns are used by the police to measure the speed of vehicles for speed limit enforcement purposes and offer a number of advantages over radar speed guns.

Military

Few military applications are known to be in place and are classified, but a considerable amount of research is underway in their use for imaging. Higher resolution systems collect enough detail to identify targets, such as tanks. Here the name LADAR is more common. Examples of military applications of LIDAR include the Airborne Laser Mine Detection System (ALMDS) for counter-mine warfare by Arete Associates.

Utilizing LIDAR and THz interferometry wide area raman spectroscopy, it is possible to detect chemical, nuclear, or biological threats at a great distance. Further investigations regarding long distance and wide area spectroscopy are currently conducted by Sandia National Laboratories.

A NATO report (RTO-TR-SET-098) evaluate the potential technologies to do stand-off detection for the discrimination of biological warfare agents. The potenial technologies evaluated were Long-Wave Infrared (LWIR), Differential Scatterring (DISC), and Ultraviolet Laser Induced Fluorescence (UV-LIF). The report conclude that: *Based upon the results of the LIDAR systems tested and discussed above, the Task Group recommends that the best option for the near-term (2008–2010) application of stand-off detection systems is UV LIF*.

The Long-Range Biological Standoff Detection System (LR-BSDS) was developed for the US Army to provide the earliest possible standoff warning of a biological attack. It is an airborne system carried by a helicopter to detect man-made aerosol clouds containing biological and chemical agents at long range. The LR-BSDS, with a detection range of 30 km or more, was fielded in June 1997.

Five LIDAR units produced by the German company Sick AG were used for short range detection on Stanley, the autonomous car that won the 2005 DARPA Grand Challenge.

A robotic Boeing AH-6 performed a fully autonomous flight in June 2010, including avoiding obstacles using LIDAR.

Physics and astronomy

A worldwide network of observatories uses lidars to measure the distance to reflectors placed on the moon, allowing the moon's position to be measured with mm precision and tests of general relativity to be done. MOLA, the Mars Orbiting Laser Altimeter, used a LIDAR instrument in a

Mars-orbiting satellite (the NASA Mars Global Surveyor) to produce a spectacularly precise global topographic survey of the red planet.

In September, 2008, NASA's Phoenix Lander used LIDAR to detect snow in the atmosphere of Mars.

In atmospheric physics, LIDAR is used as a remote detection instrument to measure densities of certain constituents of the middle and upper atmosphere, such as potassium, sodium, or molecular nitrogen and oxygen. These measurements can be used to calculate temperatures. LIDAR can also be used to measure wind speed and to provide information about vertical distribution of the aerosol particles.

At the JET nuclear fusion research facility, in the UK near Abingdon, Oxfordshire, LIDAR Thomson Scattering is used to determine Electron Density and Temperature profiles of the plasma.

Robotics

LIDAR technology is being used in Robotics for the perception of the environment as well as object classification. Refer to the Military section above for further examples.

Surveying

Paraplane surveying

Aerial LiDAR surveying from a paraplane operated by Scandinavian Laser Surveying

Airborne LIDAR sensors are used by companies in the Remote Sensing field to create point clouds of the earth ground for further processing (e.g. used in forestry).

Transportation

LIDAR has been used in Adaptive Cruise Control (ACC) systems for automobiles. Systems such as those by Siemens and Hella use a lidar device mounted on the front of the vehicle, such as the bumper, to monitor the distance between the vehicle and any vehicle in front of it. In the event the vehicle in front slows down or is too close, the ACC applies the brakes to slow the vehicle. When the road ahead is clear, the ACC allows the vehicle to accelerate to a speed preset by the driver. Refer to the Military section above for further examples.

Wind farm optimization

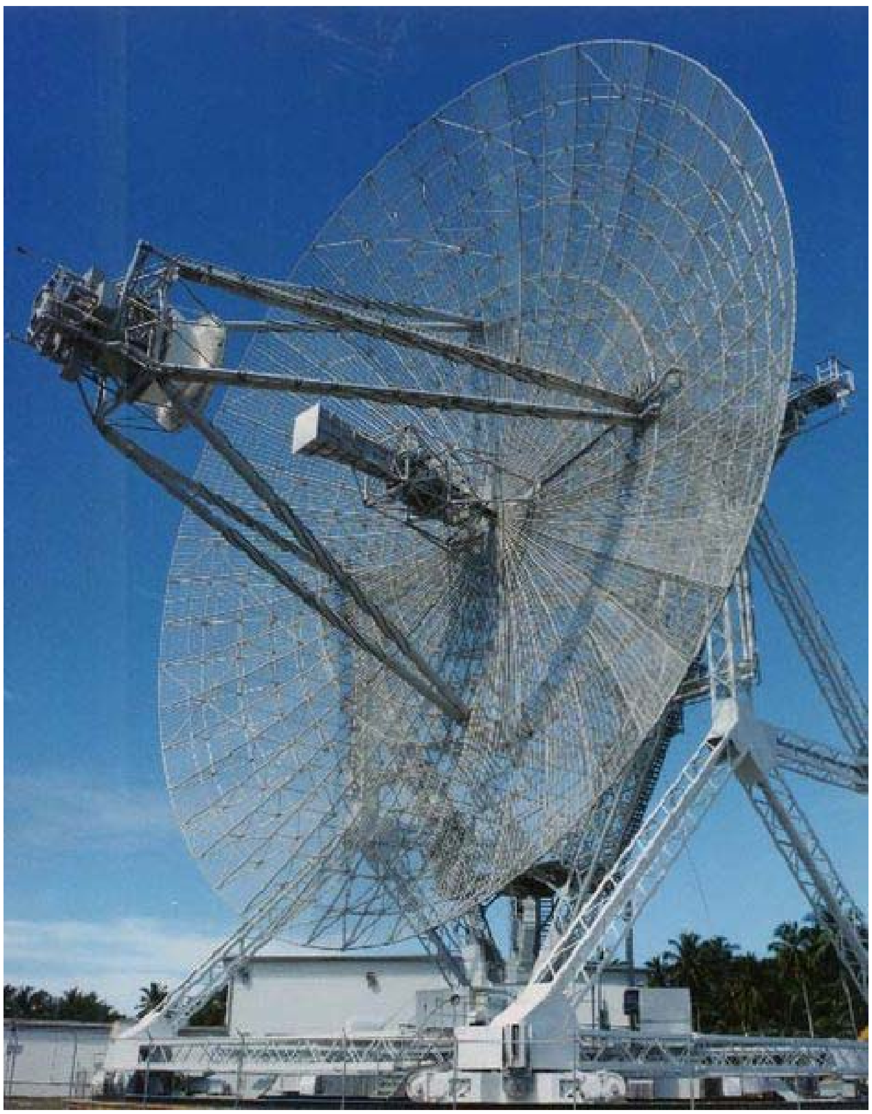
Lidar can be used to increase the energy output from wind farms by accurately measuring wind speeds and wind turbulence., and an experimental lidar is mounted on a wind turbine rotor to measure oncoming horizontal winds, and proactively adjust blades to protect components and increase power.

Other uses

The video for the song "House of Cards" by Radiohead was believed to be the first use of real-time 3D laser scanning to record a music video. The range data in the video is not completely from a LIDAR, as structured light scanning is also used.

Chapter 5

Radar



A long-range radar antenna, known as *ALTAIR*, used to detect and track space objects in conjunction with ABM testing at the Ronald Reagan Test Site on Kwajalein Atoll.

Israeli military radar is typical of the type of radar used for air traffic control. The antenna rotates at a steady rate, sweeping the local airspace with a narrow vertical fan-shaped beam, to detect aircraft at all altitudes.

Radar is an object-detection system which uses electromagnetic waves—specifically radio waves—to determine the range, altitude, direction, or speed of both moving and fixed objects such as aircraft, ships, spacecraft, guided missiles, motor vehicles, weather formations, and terrain. The radar dish, or antenna, transmits pulses of radio waves or microwaves which bounce off any object in their path. The object returns a tiny part of the wave's energy to a dish or antenna which is usually located at the same site as the transmitter.

Practical radar was developed in secrecy during World War II by Britain and other nations. The term *RADAR* was coined in 1940 by the U.S. Navy as an acronym for ***ra****dio* ***d****etection* ***a****nd* ***r****anging*. The term *radar* has since entered the English and other languages as the common noun *radar*, losing all capitalization. In the United Kingdom, the technology was initially called RDF (*range and direction finding*), using the same initials used for radio direction finding to conceal its ranging capability.

The modern uses of radar are highly diverse, including air traffic control, radar astronomy, air-defense systems, antimissile systems; nautical radars to locate landmarks and other ships; aircraft anticollision systems; ocean-surveillance systems, outer-space surveillance and rendezvous systems; meteorological precipitation monitoring; altimetry and flight-control systems; guided-missile target-locating systems; and ground-penetrating radar geological observations.

Other systems similar to radar have been used in other parts of the electromagnetic spectrum. One example is "lidar", which uses visible light from lasers rather than radio waves.

History

Several inventors, scientists, and engineers contributed to the development of radar.

As early as 1886, Heinrich Hertz showed that radio waves could be reflected from solid objects. In 1895 Alexander Popov, a physics instructor at the Imperial Russian Navy school in Kronstadt, developed an apparatus using a coherer tube for detecting distant lightning strikes. The next year, he added a spark-gap transmitter. During 1897, while testing this in communicating between two ships in the Baltic Sea, he took note of an interference beat caused by the passage of a third vessel. In his report, Popov wrote that this phenomenon might be used for detecting objects, but he did nothing more with this observation.

The German Christian Huelsmeyer was the first to use radio waves to detect "the presence of distant metallic objects". In 1904 he demonstrated the feasibility of detecting a ship in dense fog, but not its distance. He received Reichspatent Nr. 165546 for his detection device in April 1904, and later patent 169154 for a related amendment for also determining the distance to the ship. He also received a British patent on September 23, 1904 for the first full Radar application, which he called *telemobiloscope*.

A Chain Home tower in Great Baddow, United Kingdom.

In August 1917 Nikola Tesla outlined a concept for primitive radar units. He stated, "[...] *by their* [standing electromagnetic waves] *use we may produce at will, from a sending station, an electrical effect in any particular region of the globe;* [with which] *we may determine the relative position or course of a moving object, such as a vessel at sea, the distance traversed by the same, or its speed*."

In 1922 A. Hoyt Taylor and Leo C. Young, researchers working with the U.S. Navy, discovered that when radio waves were broadcast at 60 MHz it was possible to determine the range and bearing of nearby ships in the Potomac River. Despite Taylor's suggestion that this method could be used in darkness and low visibility, the Navy did not immediately continue the work. Serious investigation began eight years later after the discovery that radar could be used to track airplanes.

Before the Second World War, researchers in France, Germany, Italy, Japan, the Netherlands, the Soviet Union, the United Kingdom, and the United States, independently and in great secrecy, developed technologies that led to the modern version of radar. Australia, Canada, New Zealand, and South Africa followed prewar Great Britain, and Hungary had similar developments during the war.

In 1934 the Frenchman Émile Girardeau stated he was building an obstacle-locating radio apparatus "conceived according to the principles stated by Tesla" and obtained a patent (French Patent n° 788795 in 1934) for a working system, a part of which was installed on the Normandie liner in 1935. During the same year, the Soviet military engineer P.K.Oschepkov, in collaboration with Leningrad Electrophysical Institute, produced an experimental apparatus, RAPID, capable of detecting an aircraft within 3 km of a receiver. The French and Soviet systems, however, had continuous-wave operation and could not give the full performance that was ultimately at the center of modern radar.

Full radar evolved as a pulsed system, and the first such elementary apparatus was demonstrated in December 1934 by the American Robert M. Page, working at the Naval Research Laboratory. The year after the US Army successfully tested a primitive surface to surface radar to aim coastal battery search lights at night. This was followed by a pulsed system demonstrated in May 1935 by Rudolf Kühnhold and the firm GEMA in Germany and then one in June 1935 by an Air Ministry team led by Robert A. Watson Watt in Great Britain. Later, in 1943, Page greatly improved radar with the monopulse technique that was then used for many years in most radar applications.

The British were the first to fully exploit radar as a defence against aircraft attack. This was spurred on by fears that the Germans were developing death rays. The Air Ministry asked British scientists in 1934 to investigate the possibility of propagating electromagnetic energy and the likely effect. Following a study, they concluded that a death ray was impractical but that detection of aircraft appeared feasible. Robert Watson Watt's team demonstrated to his superiors the capabilities of a working prototype and then patented the device (British Patent GB593017). It served as the basis for the Chain Home network of radars to defend Great Britain. In April 1940, *Popular Science* showed an example of a radar unit using the Watson-Watt patent in an article on air defence, but not knowing that the U.S. Army and U.S. Navy were working on radars with the same principle, stated under the illustration, "This is not U.S. Army equipment."

The war precipitated research to find better resolution, more portability, and more features for radar, including complementary navigation systems like Oboe used by the RAF's Pathfinder. The postwar years have seen the use of radar in fields as diverse as air traffic control, weather monitoring, astrometry, and road speed control.

Applications of radar

Commercial marine radar antenna. The rotating antenna radiates a vertical fan-shaped beam.

The information provided by radar includes the bearing and range (and therefore position) of the object from the radar scanner. It is thus used in many different fields where the need for such positioning is crucial. The first use of radar was for military purposes: to locate air, ground and sea targets. This evolved in the civilian field into applications for aircraft, ships, and roads.

In aviation, aircraft are equipped with radar devices that warn of obstacles in or approaching their path and give accurate altitude readings. They can land in fog at airports equipped with radar-assisted ground-controlled approach (GCA) systems, in which the plane's flight is observed on radar screens while operators radio landing directions to the pilot.

Marine radars are used to measure the bearing and distance of ships to prevent collision with other ships, to navigate and to fix their position at sea when within range of shore or other fixed references such as islands, buoys, and lightships. In port or in harbour, vessel traffic service radar systems are used to monitor and regulate ship movements in busy waters. Police forces use radar guns to monitor vehicle speeds on the roads.

Meteorologists use radar to monitor precipitation. It has become the primary tool for short-term weather forecasting and to watch for severe weather such as thunderstorms, tornadoes, winter storms, precipitation types, etc. Geologists use specialised ground-penetrating radars to map the composition of the Earth's crust.

Principles

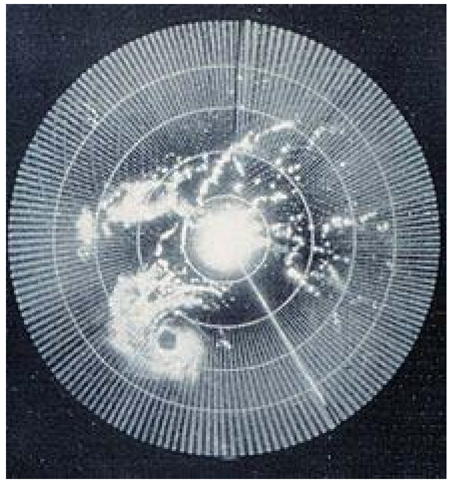
A radar system has a transmitter that emits radio waves called *radar signals* in predetermined directions. When these come into contact with an object they are usually reflected and/or scattered in many directions. Radar signals are reflected especially well by materials of considerable electrical conductivity—especially by most metals, by seawater, by wet land, and by wetlands. Some of these make the use of radar altimeters possible. The radar signals that are reflected back towards the transmitter are the desirable ones that make radar work. If the object is *moving* either closer or farther away, there is a slight change in the frequency of the radio waves, due to the Doppler effect.

Radar receivers are usually, but not always, in the same location as the transmitter. Although the reflected radar signals captured by the receiving antenna are usually very weak, these signals can be strengthened by the electronic amplifiers that all radar sets contain. More sophisticated methods of signal processing are also nearly always used in order to recover useful radar signals.

The weak absorption of radio waves by the medium through which it passes is what enables radar sets to detect objects at relatively-long ranges—ranges at which other electromagnetic wavelengths, such as visible light, infrared light, and ultraviolet light, are too strongly attenuated. In particular, there are weather conditions under which radar works well regardless of the weather. Such things as fog, clouds, rain, falling snow, and sleet that block visible light are usually transparent to radio waves. Certain, specific radio frequencies that are absorbed or scattered by water vapor, raindrops, or atmospheric gases (especially oxygen) are avoided in designing radars except when detection of these is intended.

Finally, radar relies on its own transmissions, rather than light from the Sun or the Moon, or from electromagnetic waves emitted by the objects themselves, such as infrared wavelengths (heat). This process of directing artificial radio waves towards objects is called *illumination*, regardless of the fact that radio waves are completely invisible to the human eye or cameras.

Reflection



Brightness can indicate reflectivity as in this 1960 weather radar image (of Hurricane Abby). The radar's frequency, pulse form, polarization, signal processing, and antenna determine what it can observe.

Electromagnetic waves reflect (scatter) from any large change in the dielectric constant or diamagnetic constants. This means that a solid object in air or a vacuum, or other significant change in atomic density between the object and what is surrounding it, will usually scatter radar (radio) waves. This is particularly true for electrically conductive materials, such as metal and carbon fiber, making radar particularly well suited to the detection of aircraft and ships. Radar absorbing material, containing resistive and sometimes magnetic substances, is used on military vehicles to reduce radar reflection. This is the radio equivalent of painting something a dark color so that it cannot be seen through normal means.

Radar waves scatter in a variety of ways depending on the size (wavelength) of the radio wave and the shape of the target. If the wavelength is much shorter than the target's size, the wave will bounce off in a way similar to the way light is reflected by a mirror. If the wavelength is much longer than the size of the target, the target may not be visible due to poor reflection. Low Frequency radar technology is dependent on resonances for detection, but not identification, of targets. This is described by Rayleigh scattering, an effect that creates the Earth's blue sky and red sunsets. When the two length scales are comparable, there may be resonances. Early radars used very long wavelengths that were larger than the targets and received a vague signal, whereas some modern systems use shorter wavelengths (a few centimeters or shorter) that can image objects as small as a loaf of bread.

Short radio waves reflect from curves and corners, in a way similar to glint from a rounded piece of glass. The most reflective targets for short wavelengths have 90° angles between the reflective surfaces. A structure consisting of three flat surfaces meeting at a single corner, like the corner on a box, will always reflect waves entering its opening directly back at the source. These so-called corner reflectors are commonly used as radar reflectors to make otherwise difficult-to-detect objects easier to detect, and are often found on boats in order to improve their detection in a rescue situation and to reduce collisions.

For similar reasons, objects attempting to avoid detection will angle their surfaces in a way to eliminate inside corners and avoid surfaces and edges perpendicular to likely detection directions, which leads to "odd" looking stealth aircraft. These precautions do not completely eliminate reflection because of diffraction, especially at longer wavelengths. Half wavelength long wires or strips of conducting material, such as chaff, are very reflective but do not direct the scattered energy back toward the source. The extent to which an object reflects or scatters radio waves is called its radar cross section.

Radar equation

The power P_r returning to the receiving antenna is given by the radar equation:

$$P_r = \frac{P_t G_t A_r \sigma F^4}{(4\pi)^2 R_t^2 R_r^2}$$

where

- P_t = transmitter power
- G_t = gain of the transmitting antenna
- A_r = effective aperture (area) of the receiving antenna
- σ = radar cross section, or scattering coefficient, of the target
- F = pattern propagation factor
- R_t = distance from the transmitter to the target
- R_r = distance from the target to the receiver.

In the common case where the transmitter and the receiver are at the same location, $R_t = R_r$ and the term $R_t^2\ R_r^2$ can be replaced by R^4, where R is the range. This yields:

$$P_r = \frac{P_t G_t A_r \sigma F^4}{(4\pi)^2 R^4}.$$

This shows that the received power declines as the fourth power of the range, which means that the reflected power from distant targets is very, very small.

The equation above with $F = 1$ is a simplification for vacuum without interference. The propagation factor accounts for the effects of multipath and shadowing and depends on the details of the environment. In a real-world situation, pathloss effects should also be considered.

Doppler effect

Ground-based radar systems used for detecting speeds rely on the Doppler effect. The apparent frequency (f) of the wave changes with the relative position of the target. The doppler equation is stated as follows for v_{obs} (the radial speed of the observer) and v_s (the radial speed of the target) and f_0 frequency of wave:

$$f = \frac{v + v_{obs}}{v - v_s} f_0$$

However, the change in phase of the return signal is often used instead of the change in frequency. It is to be noted that only the radial component of the speed is available. Hence when a target is moving at right angle to the radar beam, it has no velocity while one parallel to it has maximum recorded speed even if both might have the same real absolute motion.

Polarization

In the transmitted radar signal, the electric field is perpendicular to the direction of propagation, and this direction of the electric field is the polarization of the wave. Radars use horizontal, vertical, linear and circular polarization to detect different types of reflections. For example, circular polarization is used to minimize the interference caused by rain. Linear polarization returns usually indicate metal surfaces. Random polarization returns usually indicate a fractal surface, such as rocks or soil, and are used by navigation radars.

Limiting factors

Beam path and range

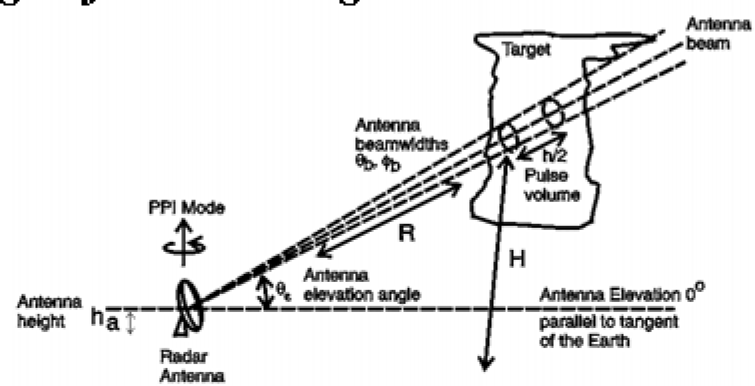
BEAM HEIGHT WITH DISTANCE (AGL)

$$H = \left(\sqrt{r^2 + (k_e a_e)^2 + 2 r k_e a_e \sin(\theta_e)} \right) - k_e a_e + h_a$$

r : distance $\quad$ *k_e : 4/3 (Standard refraction coefficient)*

a_e : Earth radius $\quad$ *θ_e : Elevation angle*

h_a : Height of radar above ground



Echo heights above ground

The radar beam would follow a linear path in vacuum but it really follows a somewhat curved path in the atmosphere due to the variation of the refractive index of air. Even when the beam is emitted parallel to the ground, it will raise above it as the Earth curvature sink below the horizon. Furthermore, the signal is attenuated by the medium it crosses and the beam disperse as its not a perfect pencil shape.

The maximum range of a conventional radar can either be limited by a number of factors:

1. Line of sight, which depends on height above ground.

2. The maximum non-ambiguous range (MUR) which is determined by the Pulse repetition frequency (PRF). Simply put, MUR is the distance the pulse could travel and return before the next pulse is emitted.
3. Radar sensitivity and power of the return signal as computed in the radar equation. This includes factors such as environmentals and the size (or radar cross section) of the target.

Noise

Signal noise is an internal source of random variations in the signal, which is generated by all electronic components. Noise typically appears as random variations superimposed on the desired echo signal received in the radar receiver. The lower the power of the desired signal, the more difficult it is to discern it from the noise (similar to trying to hear a whisper while standing near a busy road). Noise figure is a measure of the noise produced by a receiver compared to an ideal receiver, and this needs to be minimized.

Noise is also generated by external sources, most importantly the natural thermal radiation of the background scene surrounding the target of interest. In modern radar systems, due to the high performance of their receivers, the internal noise is typically about equal to or lower than the external scene noise. An exception is if the radar is aimed upwards at clear sky, where the scene is so "cold" that it generates very little thermal noise.

There will be also flicker noise due to electrons transit, but depending on 1/f, will be much lower than thermal noise when the frequency is high. Hence, in pulse radar, the system will be always heterodyne.

Interference

Radar systems must overcome unwanted signals in order to focus only on the actual targets of interest. These unwanted signals may originate from internal and external sources, both passive and active. The ability of the radar system to overcome these unwanted signals defines its signal-to-noise ratio (SNR). SNR is defined as the ratio of a signal power to the noise power within the desired signal.

In less technical terms, SNR compares the level of a desired signal (such as targets) to the level of background noise. The higher a system's SNR, the better it is in isolating actual targets from the surrounding noise signals.

Clutter

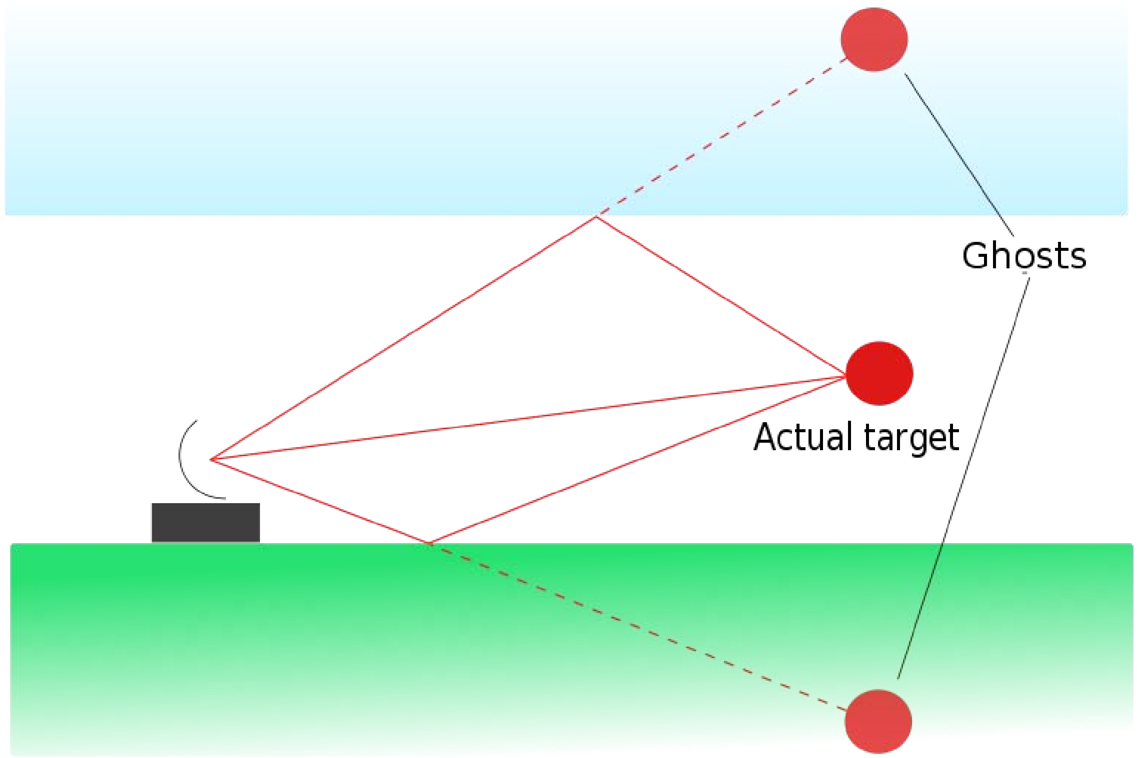
Clutter refers to radio frequency (RF) echoes returned from targets which are uninteresting to the radar operators. Such targets include natural objects such as ground, sea, precipitation (such as rain, snow or hail), sand storms, animals (especially birds), atmospheric turbulence, and other atmospheric effects, such as ionosphere reflections, meteor trails, and three body scatter spike. Clutter may also be returned from man-made objects such as buildings and, intentionally, by radar countermeasures such as chaff.

Some clutter may also be caused by a long radar waveguide between the radar transceiver and the antenna. In a typical plan position indicator (PPI) radar with a rotating antenna, this will usually be seen as a "sun" or "sunburst" in the centre of the display as the receiver responds to echoes from dust particles and misguided RF in the waveguide. Adjusting the timing between when the transmitter sends a pulse and when the receiver stage is enabled will generally reduce the sunburst without affecting the accuracy of the range, since most sunburst is caused by a diffused transmit pulse reflected before it leaves the antenna.

While some clutter sources may be undesirable for some radar applications (such as storm clouds for air-defence radars), they may be desirable for others (meteorological radars in this example). Clutter is considered a passive interference source, since it only appears in response to radar signals sent by the radar.

There are several methods of detecting and neutralizing clutter. Many of these methods rely on the fact that clutter tends to appear static between radar scans. Therefore, when comparing subsequent scans echoes, desirable targets will appear to move and all stationary echoes can be eliminated. Sea clutter can be reduced by using horizontal polarization, while rain is reduced with circular polarization (note that meteorological radars wish for the opposite effect, therefore using linear polarization the better to detect precipitation). Other methods attempt to increase the signal-to-clutter ratio.

Constant False Alarm Rate (CFAR, a form of Automatic Gain Control, or AGC) is a method relying on the fact that clutter returns far outnumber echoes from targets of interest. The receiver's gain is automatically adjusted to maintain a constant level of overall visible clutter. While this does not help detect targets masked by stronger surrounding clutter, it does help to distinguish strong target sources. In the past, radar AGC was electronically controlled and affected the gain of the entire radar receiver. As radars evolved, AGC became computer-software controlled, and affected the gain with greater granularity, in specific detection cells.



Radar multipath echoes from a target cause ghosts to appear.

Clutter may also originate from multipath echoes from valid targets due to ground reflection, atmospheric ducting or ionospheric reflection/refraction (e.g. Anomalous propagation). This clutter type is especially bothersome, since it appears to move and behave like other normal (point) targets of interest, thereby creating a ghost. In a typical scenario, an aircraft echo is multipath-reflected from the ground below, appearing to the receiver as an identical target below the correct one. The radar may try to unify the targets, reporting the target at an incorrect height, or—worse—eliminating it on the basis of jitter or a physical impossibility. These problems can be overcome by incorporating a ground map of the radar's surroundings and eliminating all echoes which appear to originate below ground or above a certain height. In newer Air Traffic Control (ATC) radar equipment, algorithms are used to identify the false targets by comparing the current pulse returns, to those adjacent, as well as calculating return improbabilities due to calculated height, distance, and radar timing.

Jamming

Radar jamming refers to radio frequency signals originating from sources outside the radar, transmitting in the radar's frequency and thereby masking targets of interest. Jamming may be intentional, as with an electronic warfare (EW) tactic, or unintentional, as with friendly forces operating equipment that transmits using the same frequency range. Jamming is considered an active interference source, since it is initiated by elements outside the radar and in general unrelated to the radar signals.

Jamming is problematic to radar since the jamming signal only needs to travel one-way (from the jammer to the radar receiver) whereas the radar echoes travel two-ways (radar-target-radar) and are therefore significantly reduced in power by the time they return to the radar receiver. Jammers therefore can be much less powerful than their jammed radars and still effectively mask targets along the line of sight from the jammer to the radar (*Mainlobe Jamming*). Jammers have an added effect of affecting radars along other lines of sight, due to the radar receiver's sidelobes (*Sidelobe Jamming*).

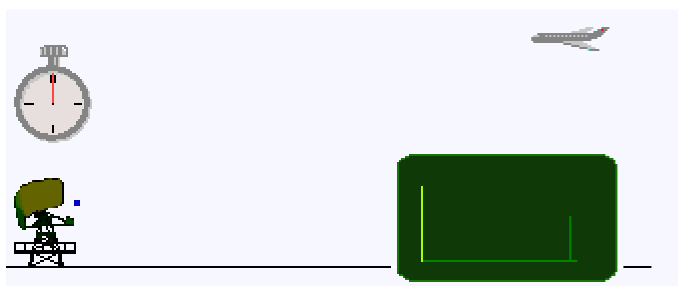
Mainlobe jamming can generally only be reduced by narrowing the mainlobe solid angle, and can never fully be eliminated when directly facing a jammer which uses the same frequency and polarization as the radar. Sidelobe jamming can be overcome by reducing receiving sidelobes in the radar antenna design and by using an omnidirectional antenna to detect and disregard non-mainlobe signals. Other anti-jamming techniques are frequency hopping and polarization.

Interference has recently become a problem for C-band (5.66 GHz) meteorological radars with the proliferation of 5.4 GHz band WiFi equipment.

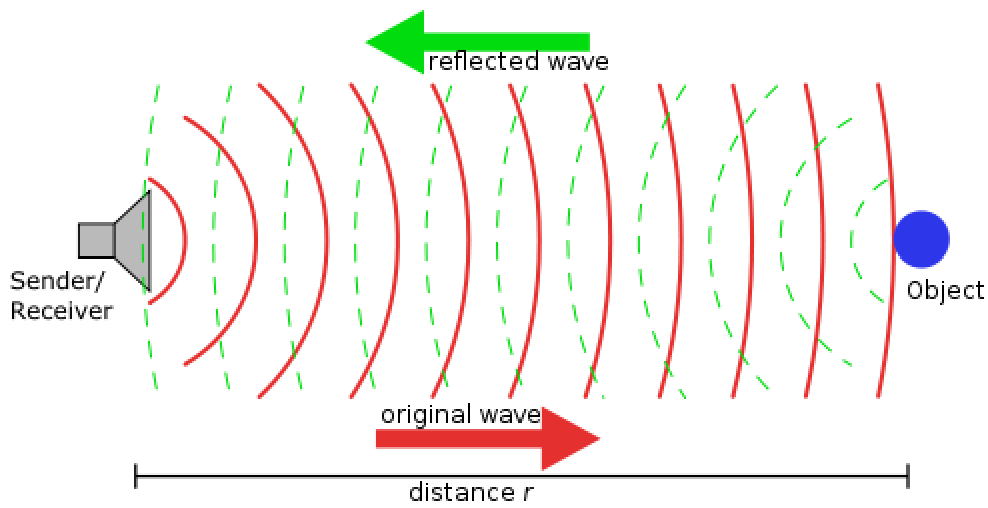
Radar signal processing

Distance measurement

Transit time



Pulse radar: The round-trip time for the radar pulse to get to the target and return is measured. The distance is proportional to this time.



Continuous wave (CW) radar

One way to measure the distance to an object is to transmit a short pulse of radio signal (electromagnetic radiation), and measure the time it takes for the reflection to return. The distance is one-half the product of the round trip time (because the signal has to travel to the target and then back to the receiver) and the speed of the signal. Since radio waves travel at the speed of light (186,000 miles per second or 300,000,000 meters per second), accurate distance measurement requires high-performance electronics.

In most cases, the receiver does not detect the return while the signal is being transmitted. Through the use of a device called a *duplexer*, the radar switches between transmitting and receiving at a predetermined rate. The minimum range is calculated by measuring the length of the pulse multiplied by the speed of light, divided by two. In order to detect closer targets one must use a shorter pulse length.

A similar effect imposes a maximum range as well. If the return from the target comes in when the next pulse is being sent out, once again the receiver cannot tell the difference. In order to maximize range, longer times between pulses should be used, referred to as a pulse repetition time (PRT), or its reciprocal, pulse repetition frequency (PRF).

These two effects tend to be at odds with each other, and it is not easy to combine both good short range and good long range in a single radar. This is because the short pulses needed for a good minimum range broadcast have less total energy, making the returns much smaller and the target harder to detect. This could be offset by using more pulses, but this would shorten the maximum range again. So each radar uses a particular type of signal. Long-range radars tend to use long pulses with long delays between them, and short range radars use smaller pulses with less time between them. This pattern of pulses and pauses is known as the pulse repetition frequency (or PRF), and is one of the main ways to characterize a radar. As electronics have improved many radars now can change their PRF thereby changing their range. The newest radars fire 2 pulses during one cell, one for short range 10 km / 6 miles and a separate signal for longer ranges 100 km /60 miles.

The distance resolution and the characteristics of the received signal as compared to noise depends heavily on the shape of the pulse. The pulse is often modulated to achieve better performance using a technique known as pulse compression.

Distance may also be measured as a function of time. The radar mile is the amount of time it takes for a radar pulse to travel one nautical mile, reflect off a target, and return to the radar antenna. Since a nautical mile is defined as *exactly* 1,852 meters, then dividing this distance by the speed of light (*exactly* 299,792,458 meters per second), and then multiplying the result by 2 (round trip = twice the distance), yields a result of approximately 12.36 microseconds in duration.

Frequency modulation

Another form of distance measuring radar is based on frequency modulation. Frequency comparison between two signals is considerably more accurate, even with older electronics, than timing the signal. By measuring the frequency of the returned signal and comparing that with the original, the difference can be easily measured.

This technique can be used in continuous wave radar, and is often found in aircraft radar altimeters. In these systems a "carrier" radar signal is frequency modulated in a predictable way, typically varying up and down with a sine wave or sawtooth pattern at audio frequencies. The signal is then sent out from one antenna and received on another, typically located on the bottom of the aircraft, and the signal can be continuously compared using a simple *beat frequency* modulator that produces an audio frequency tone from the returned signal and a portion of the transmitted signal.

Since the signal frequency is changing, by the time the signal returns to the aircraft the broadcast has shifted to some other frequency. The amount of that shift is greater over longer times, so greater frequency differences mean a longer distance, the exact amount being the "ramp speed" selected by the electronics. The amount of shift is therefore directly related to the distance traveled, and can be displayed on an instrument. This signal processing is similar to that used in speed detecting Doppler radar. Example systems using this approach are AZUSA, MISTRAM, and UDOP.

A further advantage is that the radar can operate effectively at relatively low frequencies, comparable to that used by UHF television. This was important in the early development of this type when high frequency signal generation was difficult or expensive.

A new terrestrial radar uses low-power FM signals that cover a larger frequency range. The multiple reflections are analyzed mathematically for pattern changes with multiple passes creating a computerized synthetic image. Doppler effects are not used which allows slow moving objects to be detected as well as largely eliminating "noise" from the surfaces of bodies of water.

Used primarily for detection of intruders approaching in small boats or intruders crawling on the ground toward an objective.

Speed measurement

Speed is the change in distance to an object with respect to time. Thus the existing system for measuring distance, combined with a memory capacity to see where the target last was, is enough to measure speed. At one time the memory consisted of a user making grease-pencil marks on the radar screen, and then calculating the speed using a slide rule. Modern radar systems perform the equivalent operation faster and more accurately using computers.

However, if the transmitter's output is coherent (phase synchronized), there is another effect that can be used to make almost instant speed measurements (no memory is required), known as the Doppler effect. Most modern radar systems use this principle in the pulse-doppler radar system. Return signals from targets are shifted away from this base frequency via the Doppler effect enabling the calculation of the speed of the object relative to the radar. The Doppler effect is only able to determine the relative speed of the target along the line of sight from the radar to the target. Any component of target velocity perpendicular to the line of sight cannot be determined by using the Doppler effect alone, but it can be determined by tracking the target's azimuth over time. Additional information of the nature of the Doppler returns may be found in the radar signal characteristics article.

It is also possible to make a radar without any pulsing, known as a continuous-wave radar (CW radar), by sending out a very pure signal of a known frequency. CW radar is ideal for determining the radial component of a target's velocity, but it cannot determine the target's range. CW radar is typically used by traffic enforcement to measure vehicle speed quickly and accurately where range is not important.

Other mathematical developments in radar signal processing include time-frequency analysis (Weyl Heisenberg or wavelet), as well as the chirplet transform which makes use of the fact that radar returns from moving targets typically "chirp" (change their frequency as a function of time, as does the sound of a bird or bat).

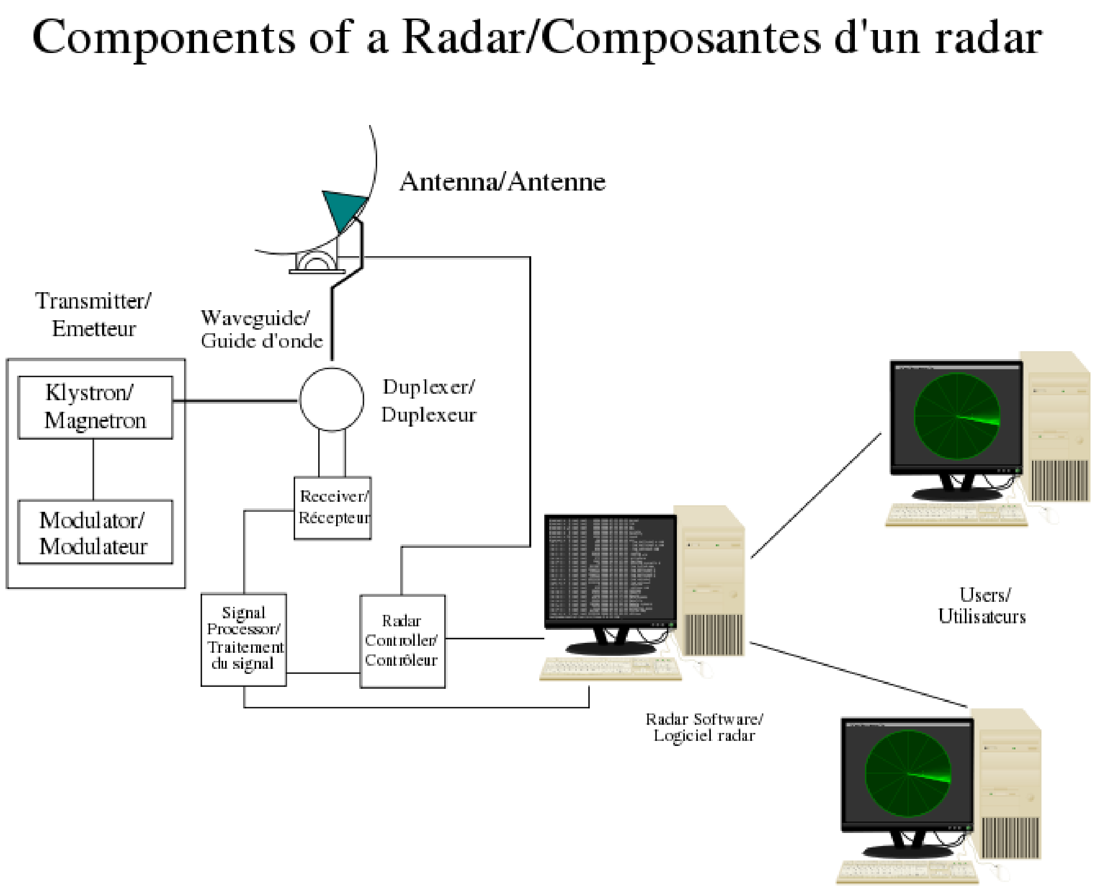
Reduction of interference effects

Signal processing is employed in radar systems to reduce the radar interference effects. Signal processing techniques include moving target indication (MTI), pulse doppler, moving target detection (MTD) processors, correlation with secondary surveillance radar (SSR) targets, space-time adaptive processing (STAP), and track-before-detect (TBD). Constant false alarm rate (CFAR) and digital terrain model (DTM) processing are also used in clutter environments.

Plot and track extraction

Radar video returns on aircraft can be subjected to a plot extraction process whereby spurious and interfering signals are discarded. A sequence of target returns can be monitored through a device known as a plot extractor. The non relevant real time returns can be removed from the displayed information and a single plot displayed. In some radar systems, or alternatively in the command and control system to which the radar is connected, a radar tracker is used to associate the sequence of plots belonging to individual targets and estimate the targets' headings and speeds.

Radar engineering



Radar components

A radars components are:

- A transmitter that generates the radio signal with an oscillator such as a klystron or a magnetron and controls its duration by a modulator.
- A waveguide that links the transmitter and the antenna.
- A duplexer that serves as a switch between the antenna and the transmitter or the receiver for the signal when the antenna is used in both situations.

- A receiver. Knowing the shape of the desired received signal (a pulse), an optimal receiver can be designed using a matched filter.
- An electronic section that controls all those devices and the antenna to perform the radar scan ordered by a software.
- A link to end users.

Antenna design

Radio signals broadcast from a single antenna will spread out in all directions, and likewise a single antenna will receive signals equally from all directions. This leaves the radar with the problem of deciding where the target object is located.

Early systems tended to use omni-directional broadcast antennas, with directional receiver antennas which were pointed in various directions. For instance the first system to be deployed, Chain Home, used two straight antennas at right angles for reception, each on a different display. The maximum return would be detected with an antenna at right angles to the target, and a minimum with the antenna pointed directly at it (end on). The operator could determine the direction to a target by rotating the antenna so one display showed a maximum while the other shows a minimum.

One serious limitation with this type of solution is that the broadcast is sent out in all directions, so the amount of energy in the direction being examined is a small part of that transmitted. To get a reasonable amount of power on the "target", the transmitting aerial should also be directional.

Parabolic reflector

More modern systems use a steerable parabolic "dish" to create a tight broadcast beam, typically using the same dish as the receiver. Such systems often combine two radar frequencies in the same antenna in order to allow automatic steering, or **radar lock**.

Parabolic reflectors can be either symmetric parabolas or spoiled parabolas:

- Symmetric parabolic antennas produce a narrow "pencil" beam in both the X and Y dimensions and consequently have a higher gain. The NEXRAD Pulse-Doppler weather radar uses a symmetric antenna to perform detailed volumetric scans of the atmosphere.

Surveillance radar antenna

- Spoiled parabolic antennas produce a narrow beam in one dimension and a relatively wide beam in the other. This feature is useful if target detection over a wide range of angles is more important than target location in three dimensions. Most 2D surveillance radars use a spoiled parabolic antenna with a narrow azimuthal beamwidth and wide vertical beamwidth. This beam configuration allows the radar operator to detect an aircraft at a specific azimuth but at an indeterminate height. Conversely, so-called "nodder" height finding radars use a dish with a narrow vertical beamwidth and wide azimuthal beamwidth to detect an aircraft at a specific height but with low azimuthal precision.

Types of scan

- Primary Scan: A scanning technique where the main antenna aerial is moved to produce a scanning beam, examples include circular scan, sector scan etc.
- Secondary Scan: A scanning technique where the antenna feed is moved to produce a scanning beam, examples include conical scan, unidirectional sector scan, lobe switching etc.
- Palmer Scan: A scanning technique that produces a scanning beam by moving the main antenna and its feed. A Palmer Scan is a combination of a Primary Scan and a Secondary Scan.

Slotted waveguide

Slotted waveguide antenna

Applied similarly to the parabolic reflector, the slotted waveguide is moved mechanically to scan and is particularly suitable for non-tracking surface scan systems, where the vertical pattern may remain constant. Owing to its lower cost and less wind exposure, shipboard, airport surface, and harbour surveillance radars now use this in preference to the parabolic antenna.

Phased array

Phased array: Not all radar antennas must rotate to scan the sky.

Another method of steering is used in a phased array radar. This uses an array of similar aerials suitably spaced, the phase of the signal to each individual aerial being controlled so that the signal is reinforced in the desired direction and cancels in other directions. If the individual aerials are in one plane and the signal is fed to each aerial in phase with all others then the signal will reinforce in a direction perpendicular to that plane. By altering the relative phase of the signal fed to each aerial the direction of the beam can be moved because the direction of constructive interference will move. Because phased array radars require no physical movement the beam can scan at thousands of degrees per second, fast enough to irradiate and track many individual targets, and still run a wide-ranging search periodically. By simply turning some of the antennas on or off, the beam can be spread for searching, narrowed for tracking, or even split into two or more virtual radars. However, the beam cannot be effectively steered at small angles to the plane of the array, so for full coverage multiple arrays are required, typically disposed on the faces of a triangular pyramid (see picture).

Phased array radars have been in use since the earliest years of radar use in World War II, but limitations of the electronics led to fairly poor accuracy. Phased array radars were originally used for missile defense. They are the heart of the ship-borne Aegis combat system, and the Patriot Missile System, and are increasingly used in other areas because the lack of moving parts makes them more reliable, and sometimes permits a much larger effective antenna, useful in fighter aircraft applications that offer only confined space for mechanical scanning.

As the price of electronics has fallen, phased array radars have become more and more common. Almost all modern military radar systems are based on phased arrays, where the small additional cost is far offset by the improved reliability of a system with no moving parts. Traditional moving-antenna designs are still widely used in roles where cost is a significant factor such as air traffic surveillance, weather radars and similar systems.

Phased array radars are also valued for use in aircraft, since they can track multiple targets. The first aircraft to use a phased array radar is the B-1B Lancer. The first aircraft fighter to use phased array radar was the Mikoyan MiG-31. The MiG-31M's SBI-16 Zaslon phased array radar is considered to be the world's most powerful fighter radar. Phased-array interferometry or, aperture synthesis techniques, using an array of separate dishes that are phased into a single effective aperture, are not typically used for radar applications, although they are widely used in radio astronomy. Because of the Thinned array curse, such arrays of multiple apertures, when used in transmitters, result in narrow beams at the expense of reducing the total power transmitted to the target. In principle, such techniques used could increase the spatial resolution, but the lower power means that this is generally not effective. Aperture synthesis by post-processing of motion data from a single moving source, on the other hand, is widely used in space and airborne radar systems.

Frequency bands

The traditional band names originated as code-names during World War II and are still in military and aviation use throughout the world in the 21st century. They have been adopted in the United States by the IEEE, and internationally by the ITU. Most countries have additional regulations to control which parts of each band are available for civilian or military use.

Other users of the radio spectrum, such as the broadcasting and electronic countermeasures (ECM) industries, have replaced the traditional military designations with their own systems.

Radar frequency bands			
Band name	**Frequency range**	**Wavelength range**	**Notes**
HF	3–30 MHz	10–100 m	coastal radar systems, over-the-horizon radar (OTH) radars; 'high frequency'
P	< 300 MHz	1 m+	'P' for 'previous', applied retrospectively to early radar systems
VHF	30–300 MHz	1–10 m	Very long range, ground penetrating; 'very high frequency'
UHF	300–1000 MHz	0.3–1 m	Very long range (e.g. ballistic missile early warning), ground penetrating, foliage penetrating; 'ultra high frequency'
L	1–2 GHz	15–30 cm	Long range air traffic control and surveillance; 'L' for 'long'

S	2–4 GHz	7.5–15 cm	Moderate range surveillance, Terminal air traffic control, long-range weather, marine radar; 'S' for 'short'
C	4–8 GHz	3.75–7.5 cm	Satellite transponders; a compromise (hence 'C') between X and S bands; weather; long range tracking
X	8–12 GHz	2.5–3.75 cm	Missile guidance, marine radar, weather, medium-resolution mapping and ground surveillance; in the USA the narrow range 10.525 GHz ±25 MHz is used for airport radar; short range tracking. Named X band because the frequency was a secret during WW2.
K_u	12–18 GHz	1.67–2.5 cm	high-resolution
K	18–24 GHz	1.11–1.67 cm	from German *kurz*, meaning 'short'; limited use due to absorption by water vapour, so K_u and K_a were used instead for surveillance. K-band is used for detecting clouds by meteorologists, and by police for detecting speeding motorists. K-band radar guns operate at 24.150 ± 0.100 GHz.
K_a	24–40 GHz	0.75–1.11 cm	mapping, short range, airport surveillance; frequency just above K band (hence 'a') Photo radar, used to trigger cameras which take pictures of license plates of cars running red lights, operates at 34.300 ± 0.100 GHz.
mm	40–300 GHz	7.5 mm – 1 mm	millimetre band, subdivided as below. The frequency ranges depend on waveguide size. Multiple letters are assigned to these bands by different groups. These are from Baytron, a now defunct company that made test equipment.
V	40–75 GHz	4.0–7.5 mm	Very strongly absorbed by atmospheric oxygen, which resonates at 60 GHz.
W	75–110 GHz	2.7–4.0 mm	used as a visual sensor for experimental autonomous vehicles, high-resolution meteorological observation, and imaging.
UWB	1.6–10.5 GHz	18.75 cm – 2.8 cm	used for through-the-wall radar and imaging systems.

Radar modulators

Modulators act to provide the waveform of the RF-pulse. There are two different radar modulator designs:

- high voltage switch for non-coherent keyed power-oscillators These modulators consist of a high voltage pulse generator formed from a high voltage supply, a pulse forming network, and a high voltage switch such as a thyratron. They generate short pulses of power to feed the e.g. magnetron, a special type of vacuum tube that converts DC (usually pulsed) into microwaves. This technology is known as Pulsed power. In this way, the transmitted pulse of RF radiation is kept to a defined, and usually, very short duration.

- hybrid mixers, fed by a waveform generator and an exciter for a complex but coherent waveform. This waveform can be generated by low power/low-voltage input signals. In this case the radar transmitter must be a power-amplifier, e.g. a klystron tube or a solid state transmitter. In this way, the transmitted pulse is intrapulsemodulated and the radar receiver must use pulse compression technique mostly.

Radar coolant

Coolanol and PAO (poly-alpha olefin) are the two main coolants used to cool airborne radar equipment today.

Coolanol (silicate ester) was used in several military radars in the 1970s, for example the AN/APG-63 in the F-15. However, it is hygroscopic, leading to formation of highly flammable alcohol. The loss of a U.S. Navy aircraft in 1978 was attributed to a silicate ester fire. Coolanol is also expensive and toxic. The U.S. Navy has instituted a program named Pollution Prevention (P2) to reduce or eliminate the volume and toxicity of waste, air emissions, and effluent discharges. Because of this Coolanol is used less often today.

PAO is a synthetic lubricant blend of a polyol ester admixed with effective amounts of an antioxidant, yellow metal pacifier and rust inhibitors. The polyol ester blend includes a major proportion of poly (neopentyl polyol) ester blend formed by reacting poly(pentaerythritol) partial esters with at least one C7 to C12 carboxylic acid mixed with an ester formed by reacting a polyol having at least two hydroxyl groups and at least one C8-C10 carboxylic acid. Preferably, the acids are linear and avoid those which can cause odours during use. Effective additives include secondary arylamine antioxidants, triazole derivative yellow metal pacifier and an amino acid derivative and substituted primary and secondary amine and/or diamine rust inhibitor.

A synthetic coolant/lubricant composition, comprising an ester mixture of 50 to 80 weight percent of poly (neopentyl polyol) ester formed by reacting a poly (neopentyl polyol) partial ester and at least one linear monocarboxylic acid having from 6 to 12 carbon atoms, and 20 to 50 weight percent of a polyol ester formed by reacting a polyol having 5 to 8 carbon atoms and at least two hydroxyl groups with at least one linear monocarboxylic acid having from 7 to 12 carbon atoms, the weight percents based on the total weight of the composition.

Radar configurations and types

Radars configurations include Monopulse radar, Bistatic radar, Doppler radar, Continuous-wave radar, etc.. depending on the types of hardware and software used. It is used in aviation (Primary and secondary radar), sea vessels, law enforcement, weather surveillance, ground mapping, geophysical surveys, and biological research.

Chapter 6

Hemispherical Photography

Hemispherical photograph used to study microclimate of winter roosting habitat at the Monarch Butterfly Biosphere Reserve, Mexico (photo by S.B. Weiss).

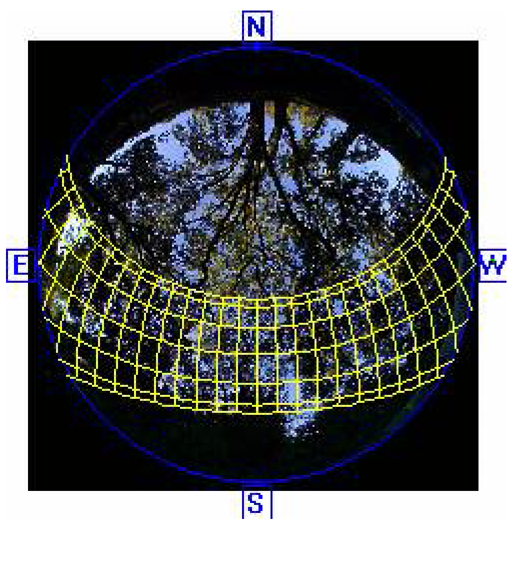
Hemispherical photography, also known as fisheye or canopy photography, is a technique to estimate solar radiation and characterize plant canopy geometry using photographs taken looking upward through an extreme wide-angle lens (Rich 1990). Typically, the viewing angle approaches or equals 180-degrees, such that all sky directions are simultaneously visible. The resulting photographs record the geometry of visible sky, or conversely the geometry of sky obstruction by plant canopies or other near-ground features. This geometry can be measured precisely and used to calculate solar radiation transmitted through (or intercepted by) plant canopies, as well as to estimate aspects of canopy structure such as leaf area index. Detailed treatments of field and analytical methodology have been provided by Paul Rich (1989, 1990) and Robert Pearcy (1989).

History of Hemispherical Photography

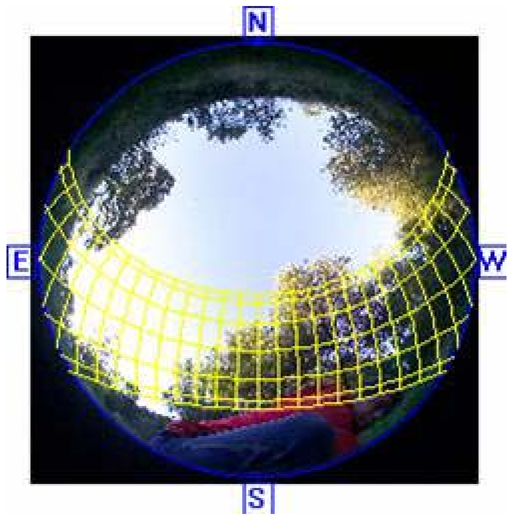
The hemispherical lens (also known as a fisheye or whole-sky lens) was originally designed by Robin Hill (1924) to view the entire sky for meteorological studies of cloud formation. Foresters and ecologists conceived of using photographic techniques to study the light environment in forests by examining the canopy geometry. In particular, Evans and Coombe (1959) estimated sunlight penetration through forest canopy openings by overlaying diagrams of the sun track on hemispherical photographs. Later, Margaret Anderson (1964, 1971) provided a thorough theoretical treatment for calculating the transmission of direct and diffuse components of solar radiation through canopy openings using hemispherical photographs. At that time hemispherical photograph analysis required tedious manual scoring of overlays of sky quadrants and the track of the sun. With the advent of personal computers, researchers developed digital techniques for rapid analysis of hemispherical photographs (Chazdon and Field 1987, Rich 1988, 1989, 1990, Becker et al. 1989). In recent years, researchers have started using digital cameras in favor of film cameras, and algorithms are being developed for automated image classification and analysis. Various commercial software programs have become available for hemispherical photograph analysis, and the technique has been applied for diverse uses in ecology, meteorology, forestry, and agriculture.

Applications of Hemispherical Photography

Hemispherical photography has been used successfully in a broad range of applications involving microsite characterization and estimation of the solar radiation near the ground and beneath plant canopies. For example, hemispherical photography has been used to characterize winter roosting sites for monarch butterflies (Weiss et al. 1991), effects of forest edges (Galo et al. 1991), influence of forest treefall gaps on tree regeneration (Rich et al. 1993), spatial and temporal variability of light in tropical rainforest understory (Clark et al. 1996), impacts of hurricanes on forest ecology (Bellingham et al. 1996), leaf area index for validation of remote sensing (Chen et al. 1997), canopy architecture of boreal forests (Fournier et al. 1997), light environment in old growth temperate rain forests (Weiss 2000), and management of vineyard trellises to make better wine (Weiss et al. 2003).



Hemispherical photograph with sunpath overlay from a closed canopy reach of San Francisquito Creek, San Francisco Peninsula, California, used for studies of steelhead trout habitat (photo by S.B. Weiss).



Hemispherical photograph from an open canopy reach of San Francisquito Creek. Overlay of the sunpath enables calculation of solar exposure as it influences water temperature.

Theory of Hemispherical Photography

Solar Radiation Calculations

Direct and diffuse components of solar radiation are calculated separately. Direct radiation is calculated as the sum of all direct (solar beam) radiation originating from visible (non-obscured) sky directions along the path of the sun. Similarly, diffuse solar radiation is calculated as the sum of all diffuse radiation (scattered from the atmosphere) originating from any visible (non-obscured) sky directions. The sum of direct and diffuse components gives global radiation.

These calculations require theoretical or empirical distributions of direct and diffuse radiation in the open, without canopy or other sky obstruction. Usually calculations are performed for either photosynthetically active radiation (400-700 nanometers) or insolation integrated over all wavelengths, measured in kilowatt-hours per square meter (kW h/m^2).

The fundamental assumption is that most solar radiation originates from visible (unobscured) sky directions, a strong first order effect, and that reflected radiation from the canopy or other near-ground features (non-visible or obscured sky directions) is negligible, a small second order effect. Another assumption is that the geometry of visible (non-obscured) sky does not change over the period for which calculations are performed.

Canopy Calculations

Canopy indices, such as leaf area index, are based on calculation of gap fraction, the proportion of visible (non-obscured) sky as a function of sky direction. Leaf area index is typically calculated as the leaf area per unit ground area that would produce the observed gap fraction distribution, given an assumption of random leaf angle distribution, or a known leaf angle distribution and degree of clumping.

Indices

Direct Site Factor (DSF) is the proportion of direct solar radiation at a given location relative to that in the open, either integrated over time or resolved according to intervals of time of day and/or season.

Indirect Site Factor (ISF) is the proportion of diffuse solar radiation at a given location relative to that in the open, either integrated over time for all sky directions or resolved by sky sector direction.

Global Site Factor (GSF) is the proportion of global solar radiation at a given location relative to that in the open, calculated as the sum of DSF and ISF weighted by the relative contribution of direct versus diffuse components.

Indices may be **uncorrected** or **corrected** for angle of incidence relative to a flat intercepting surface. Uncorrected values weight solar radiation originating from all directions equally. Corrected values weight solar radiation by the cosine of the angle of incidence, accounting for actual interception from directions normal to the intercepting surface.

Leaf Area Index is the total leaf surface area per unit ground area.

Methodology

Hemispherical photography entails five steps: photograph acquisition, digitization, registration, classification, and calculation. Registration, classification, and calculation are accomplished using dedicated hemispherical photography analysis software.

Photograph acquisition

Upward-looking hemispherical photographs are typically acquired under uniform sky lighting, early or late in the day or under overcast conditions. Known orientation (zenith and azimuth) is essential for proper registration with the analysis hemispherical coordinate system. Even lighting is essential for accurate image classification. A self-leveling mount (gimbals) can facilitate acquisition by ensuring that the camera is oriented to point straight up toward the zenith. The camera is typically oriented such that north (absolute or magnetic) is oriented toward the top of the photograph.

The lens used in hemispherical photography is generally a circular fisheye lens, such as the Nikkor 8mm fisheye lens. Full-frame fisheye lenses are *not* suitable for hemispherical photography, as they only capture a full 180° across the diagonal, and do not provide a complete hemispherical view.

In the early years of the technique, most hemispherical photographs were acquired with 35 mm cameras (e.g., Nikon FM2 with a Nikkor 8mm fisheye lens) using high contrast, high ASA black-and-white film. Later, use of color film or slides became common. Recently most photographs are acquired using digital cameras (e.g., Kodak DCS Pro 14nx with a Nikkor 8mm fisheye lens).

When images are acquired from locations with large differences in openness (for example, closed canopy locations and canopy gaps) it is essential to control camera exposure. If the camera is allowed to automatically adjust exposure (which is controlled by aperture and shutter speed), the result is that small openings in closed conditions will be bright, whereas openings of the same size in open conditions will be darker (for example, canopy areas around a gap). This means that during image analysis the same sized holes will be interpreted as "sky" in a closed-canopy image and "canopy" in the open-canopy image. Without controlling exposure, the real differences between closed- and open-canopy conditions will be under-estimated.

Digitization

Photographs are digitized and saved in standard image formats. For film cameras this step requires a negative or slide scanner or a video digitizer. For digital cameras this step occurs as photographs are acquired.

Registration

Photograph registration involves aligning the photographs with the hemispherical coordinate system used for analysis, in terms of translation (centering), size (coincidence of photograph edges and horizon in coordinate system), and rotation (azimuthal alignment with respect to compass directions).

Classification

Photograph classification involves determining which image pixels represent visible (non-obscured) versus non-visible (obscured) sky directions. Typically this has been accomplished using interactive thresholding, whereby an appropriate threshold is selected to best match a binary classification with observed sky visibility, with pixel intensity values above the threshold classified as visible and pixel intensity values below the threshold classified as non-visible. Recently advances have been made in developing automatic threshold algorithms, however more work is still needed before these are fully reliable.

Calculation

Hemispherical photograph calculation uses algorithms that compute gap fraction as function of sky direction, and compute desired canopy geometry and/or solar radiation indices. For solar radiation, rapid calculation is often accomplished using pre-calculated lookup tables of theoretical or empirical solar radiation values resolved by sky sector or position in the sunpath.

Chapter 7

Hyperspectral Imaging

Hyperspectral imaging collects and processes information from across the electromagnetic spectrum. Much as the human eye sees visible light in three bands (red, green, and blue), spectral imaging divides the spectrum into many more bands. This technique of dividing images into bands can be extended beyond the visible.

Humans build sensors and processing systems to provide such capability for application in agriculture, mineralogy, physics, and surveillance. Hyperspectral sensors look at objects using a vast portion of the electromagnetic spectrum. Certain objects leave unique 'fingerprints' across the electromagnetic spectrum. These 'fingerprints' are known as spectral signatures and enable identification of the materials that make up a scanned object. For example, a spectral signature for oil helps mineralogists find new oil fields.

Acquisition and analysis

Two-dimensional projection of a hyperspectral cube

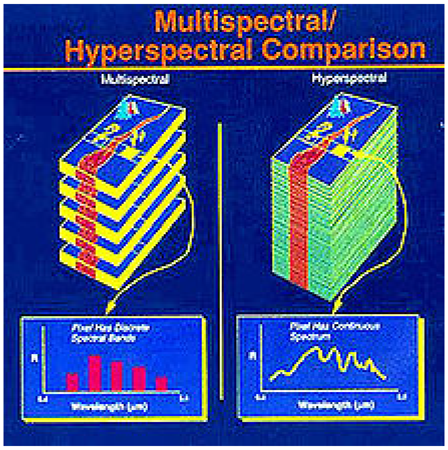
Hyperspectral sensors collect information as a set of 'images'. Each image represents a range of the electromagnetic spectrum and is also known as a spectral band. These 'images' are then combined and form a three-dimensional hyperspectral data cube for processing and analysis.

Hyperspectral cubes are generated from airborne sensors like the NASA's *Airborne Visible/Infrared Imaging Spectrometer* (AVIRIS), or from satellites like NASA's Hyperion. However, for many development and validation studies, handheld sensors are used.

The precision of these sensors is typically measured in spectral resolution, which is the width of each band of the spectrum that is captured. If the scanner detects a large number of fairly narrow frequency bands, it is possible to identify objects even if they are only captured in a handful of pixels. However, spatial resolution is a factor in addition to spectral resolution. If the pixels are too large, then multiple objects are captured in the same pixel and become difficult to identify. If the pixels are too small, then the energy captured by each sensor cell is low, and the decreased signal-to-noise ratio reduces the reliability of measured features.

MicroMSI, Opticks and Envi are three remote sensing applications that support the processing and analysis of hyperspectral data. The acquisition and processing of hyperspectral images is also referred to as imaging spectroscopy.

Differences between hyperspectral and multispectral imaging



Hyperspectral and Multispectral Differences.

Hyperspectral imaging is part of a class of techniques commonly referred to as spectral imaging or spectral analysis. Hyperspectral imaging is related to multispectral imaging. The distinction between hyper- and multi-spectral is sometimes based on an arbitrary "number of bands" or on the type of measurement, depending on what is appropriate to the purpose.

Multispectral deals with several images at discrete and somewhat narrow bands. The "discrete and somewhat narrow" is what distinguishes multispectral in the visible from color photography.

A multispectral sensor may have many bands covering the spectrum from the visible to the longwave infrared. Multispectral images do not produce the "spectrum" of an object. Landsat is an excellent example.

Hyperspectral deals with imaging narrow spectral bands over a contiguous spectral range, and produce the spectra of all pixels in the scene. So a sensor with only 20 bands can also be hyperspectral when it covers the range from 500 to 700 nm with 20 10-nm wide bands. (While a sensor with 20 discrete bands covering the VIS, NIR, SWIR, MWIR, and LWIR would be considered multispectral.)

Ultraspectral could be reserved for interferometer type imaging sensors with a very fine spectral resolution. These sensor often have (but not necessarily) a low spatial resolution of several pixels only, a restriction imposed by the high data rate.

Applications

Hyperspectral remote sensing is used in a wide array of real-life applications. Although originally developed for mining and geology (the ability of hyperspectral imaging to identify various minerals makes it ideal for the mining and oil industries, where it can be used to look for ore and oil) it has now spread into fields as widespread as ecology and surveillance, as well as historical manuscript research such as the imaging of the Archimedes Palimpsest. This technology is continually becoming more available to the public, and has been used in a wide variety of ways. Organizations such as NASA and the USGS have catalogues of various minerals and their spectral signatures, and have posted them online to make them readily available for researchers.

Agriculture

Although the costs of acquiring hyperspectral images is typically high, for specific crops and in specific climates hyperspectral remote sensing is used more and more for monitoring the development and health of crops. In Australia work is under way to use imaging spectrometers to detect grape variety, and develop an early warning system for disease outbreaks. Furthermore work is underway to use hyperspectral data to detect the chemical composition of plants which can be used to detect the nutrient and water status of wheat in irrigated systems.

Another important area in agriculture is the detection of animal proteins in compound feeds in order to avoid the Bovine spongiform encephalopathy (BSE) or mad-cow disease (MCD). For this, different studies have been done in order to propose alternative tools to the reference method (classical microscopy). One of the first alternatives is the use of NIR microscopy (Infrared microscopy), which combines the advantages of microscopy and NIR. In 2004, the first study relating this problematic with Hyperspectral imaging was published. Hyperspectral libraries are constructed, which are representative of the wide diversity of ingredients usually present in the preparation of compound feeds. These libraries can be used together with chemometric tools to investigate the limit of detection, specificity and reproducibility of the NIR hyperspectral imaging method for the detection and quantification of animal ingredient in feed.

Mineralogy

The original field of development for hyperspectral remote sensing, hyperspectral sensing of minerals is now well developed. Many minerals can be identified from images, and their relation to the presence of valuable minerals such as gold and diamonds is well understood. Currently the move is towards understanding the relation between oil and gas leakages from pipelines and natural wells; their effect on the vegetation and the spectral signatures. Recent work includes the PhD dissertations of Werff and Noomen.

Physics

Physicists use an electron microscopy technique that involves microanalysis using either energy-dispersive X-ray spectroscopy (EDS), electron energy loss spectroscopy (EELS), infrared spectroscopy(IR), Raman spectroscopy, or cathodoluminescence (CL) spectroscopy, in which the entire spectrum measured at each point is recorded. EELS hyperspectral imaging is performed in a scanning transmission electron microscope (STEM); EDS and CL mapping can be performed in STEM as well, or in a scanning electron microscope or electron microprobe (also called an electron probe microanalyzer or EPMA). Often, multiple techniques (EDS, EELS, CL) are used simultaneously.

In a "normal" mapping experiment, an image of the sample will be made that is simply the intensity of a particular emission mapped in an XY raster. For example, an EDS map could be made of a steel sample, in which iron X-ray intensity is used for the intensity grayscale of the image. Dark areas in the image would indicate not-iron-bearing impurities. This could potentially give misleading results; if the steel contained tungsten inclusions, for example, the high atomic number of tungsten could result in bremsstrahlung radiation that made the iron-free areas *appear* to be rich in iron.

By hyperspectral mapping, instead, the entire spectrum at each mapping point is acquired, and a quantitative analysis can be performed by computer post-processing of the data, and a quantitative map of iron content produced. This would show which areas contained no iron, despite the anomalous x-ray counts caused by bremsstrahlung. Because EELS core-loss edges are small signals on top of a large background, hyperspectral imaging allows large improvements to the quality of EELS chemical maps.

Similarly, in CL mapping, small shifts in the peak emission energy could be mapped, which would give information regarding slight chemical composition changes or changes in the stress state of a sample.

Surveillance

Hyperspectral surveillance is the implementation of hyperspectral scanning technology for surveillance purposes. Hyperspectral imaging is particularly useful in military surveillance because of measures that military entities now take to avoid airborne surveillance. Airborne surveillance has been in effect since French soldiers used tethered balloons to spy on troop movements during the French Revolutionary Wars, and since that time we have learned not only to hide from the naked eye, but to mask our heat signature to blend in to the surroundings and avoid infrared scanning, as well. The idea that drives hyperspectral surveillance is that hyperspectral scanning draws information from such a large portion of the light spectrum that any given object should have a unique spectral signature in at least a few of the many bands that get scanned. The team of U.S. Navy Seals who killed Osama bin Laden in May of 2011 used this technology while conducting the raid on Osama bin Laden's compound in Abbottabad, Pakistan.

Traditionally, commercially available Thermal Infrared Hyperspectral Imaging Systems have needed liquid nitrogen or helium cooling, which have made them impractical for most surveillance applications. In 2010, Specim introduced a Thermal Infrared Hyperspectral Camera that can efficiently be used for outdoor surveillance and UAV applications without an external light source such as the Sun or the Moon.

Advantages and disadvantages

The primary advantages to hyperspectral imaging is that, because an entire spectrum is acquired at each point, the operator needs no prior knowledge of the sample, and post-processing allows all available information from the dataset to be mined. Hyperspectral imaging can also take advantage of the spatial relationships among the different spectra in a neighbourhood allowing more elaborate spectral-spatial models for a more accurate segmentation and classification of the image.

The primary disadvantages are cost and complexity. Fast computers, sensitive detectors, and large data storage capacities are needed for analyzing hyperspectral data. Significant data storage capacity is necessary since hyperspectral cubes are large multi-dimensional datasets, potentially exceeding hundreds of megabytes. All of these factors greatly increase the cost of acquiring and processing hyperspectral data. Also, one of the hurdles that researchers have had to face is finding ways to program hyperspectral satellites to sort through data on their own and transmit only the most important images, as both transmission and storage of that much data could prove difficult and costly. As a relatively new analytical technique, the full potential of hyperspectral imaging has not yet been realized.

Chapter 8

Collocation (Remote Sensing)

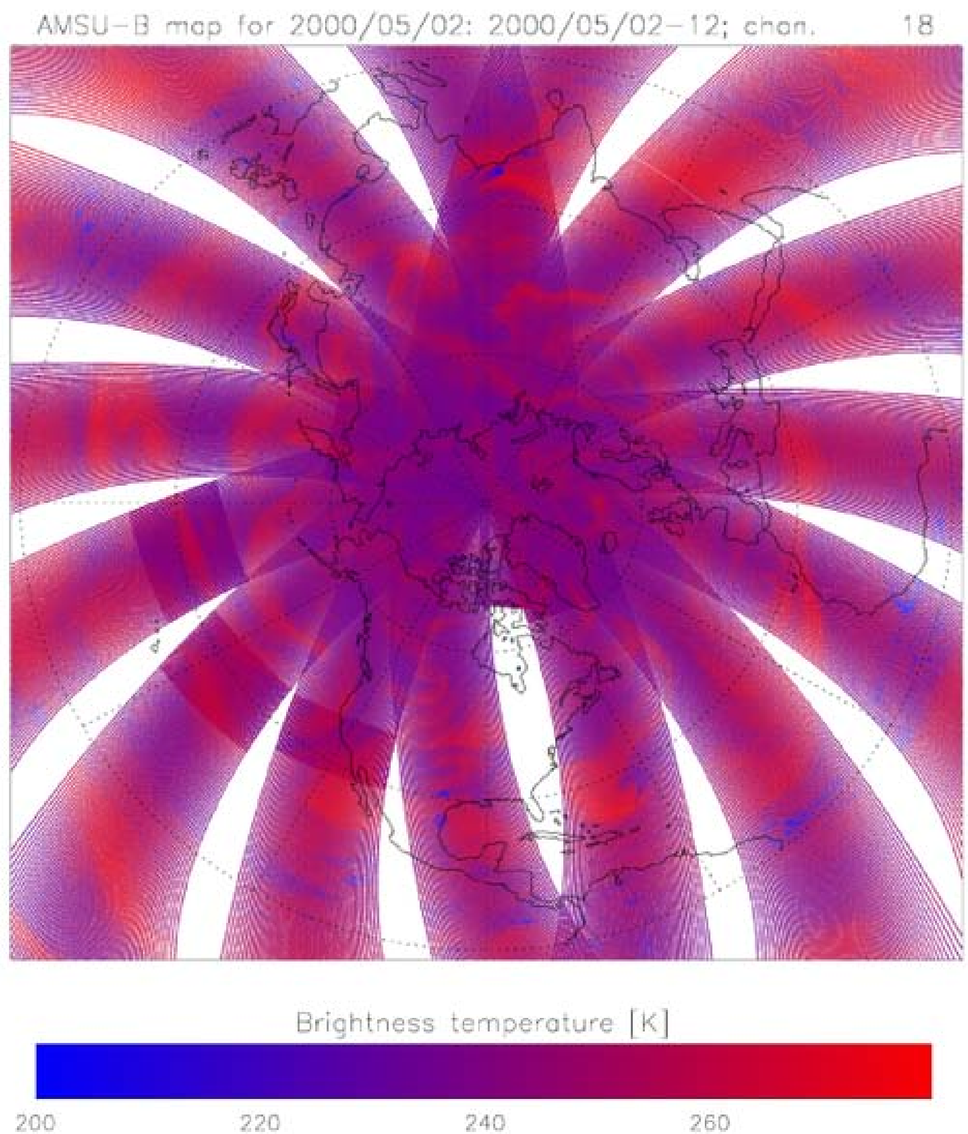
Collocation is a procedure used in remote sensing to match measurements from two or more different instruments. This is done for two main reasons: for validation purposes when comparing measurements of the same variable, and to relate measurements of two different variables either for performing retrievals or for prediction. In the second case the data is later fed into some type of statistical inverse method such as a neural network, statistical classification algorithm, kernel estimator or a linear least squares. In principal, most collocation problems can be solved by a nearest neighbor search, but in practice there are many other considerations involved and the best method is highly specific to the particular matching of instruments. Here we deal with some of the most important considerations along with specific examples.

There are at least two main considerations when performing collocations. The first is the sampling pattern of the instrument. Measurements may be dense and regular, such as those from a cross-track scanning satellite instrument. In this case, some form of interpolation may be appropriate. On the other hand, the measurements may be sparse, such as a one-off field campaign designed for some particular validation exercise. The second consideration is the instrument footprint, which can range from something approaching a point measurement such as that of a radiosonde, or it might be several kilometers in diameter such as that of a satellite-mounted, microwave radiometer. In the latter case, it is appropriate to take into account the instrument antenna pattern when making comparisons with another instrument having both a smaller footprint and a denser sampling, that is, several measurements from the one instrument will fit into the footprint of the other.

Just as the instrument has a spatial footprint, it will also have a temporal footprint, often called the integration time. While the integration time is usually less than a second, which for meteorological applications is essentially instantaneous, there are many instances where some form of time averaging can considerably ease the collocation process.

The collocations will need to be screened based on both the time and length scales of the phenomenon of interest. This will further facilitate the collocation process since remote sensing and other measurement data is almost always binned in some way. Certain atmospheric phenomena such as clouds or convection are quite transient so that we need not consider collocations with a time error of more than an hour or so. Sea ice, on the other hand, moves and evolves quite slowly, so that measurements separated by as much as a day or more might still be useful.

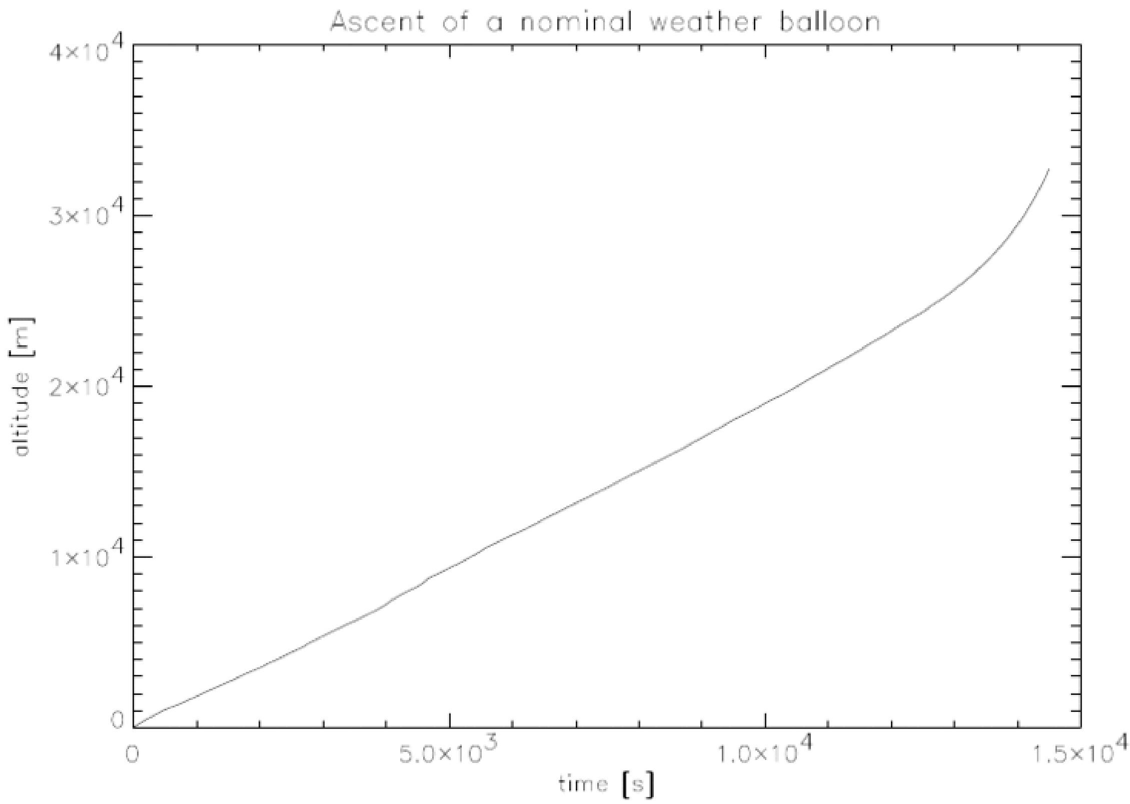
Satellites



Polar-stereographic projection showing 12 hours of measurements from three AMSU-B instruments

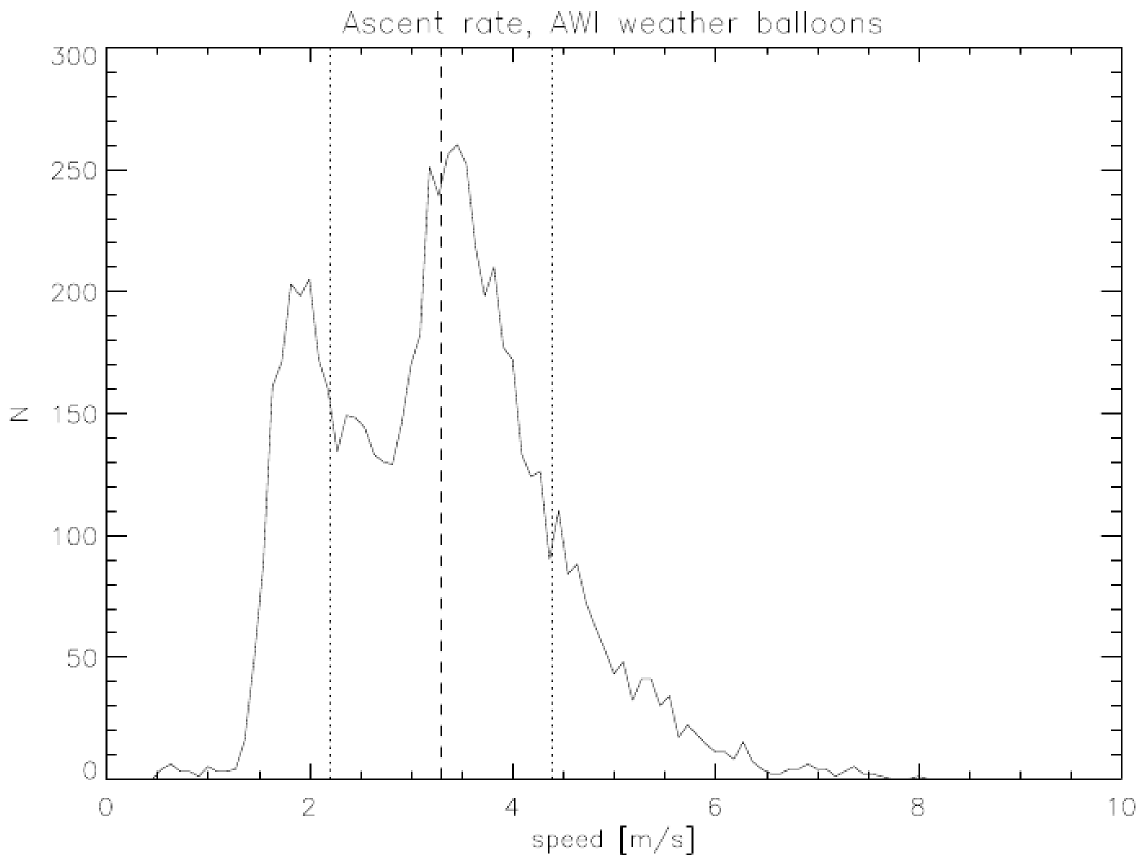
The satellites that most concern us are those with a low-Earth, polar orbit since geostationary satellites view the same point throughout their lifetime. The diagram shows measuremnts from AMSU-B instruments mounted on three satellites over a period of 12 hours. This illustrates both the orbit path and the scan pattern which runs crosswise. Since the orbit of a satellite is deterministic, barring orbit maneuvers, we can predict the location of the satellite at a given time and, by extension, the location of the measurement pixels. In theory, collocations can be performed by inverting the determining equations starting from the desired time period. In practice, partially processed data (usually referred to as level 1b, 1c or level 2) contain the coordinates of each of the measurement pixels and it is common to simply feed these coordinates to a nearest neighbor search. As mentioned previously, the satellite data is always binned in some manner. At minimum, the data will be arranged in swaths extending from pole to pole. The swaths will be labelled by time period and the approximate location known.

Radiosondes



Ascent of a weather balloon launched from the Polarstern research vessel

Radiosondes are particularly important for collocation studies because they measure atmospheric variables more accurately and more directly than satellite or other remote-sensing instruments. In addition, radiosonde samples are effectively instantaneous point measurements. One issue with radiosondes carried aloft by weather balloons is balloon drift. In, this is handled by averaging all the satellite pixels within a 50 km radius of the balloon launch.



Histogram of ascent rates of weather balloons launch from the Polarstern research vessel

If high-resolution sonde data, which normally has a constant sampling rate or includes the measurement time, is used, then the lateral motion can be traced from the wind data. Even with low-resolution data, the motion can still be approximated by assuming a constant ascent rate. Excepting a short bit towards the end, the linear ascent can be clearly seen in the figure above. We can show that the ascent rate of a balloon is given by the following equation:

$$v = \sqrt{\frac{gkh(1 - R_a/R_s)}{c_D}}$$

where *g* is gravitational acceleration, *k* relates the height, *h*, and surface area, *A*, of the balloon to its volume: $V = khA$; R_s is the equivalent "gas constant" of the balloon, R_a is the gas constant of the air and c_D is the drag coefficient of the balloon. Substituting some sensible values for each of the constants, *k*=1. (the balloon is a perfect cylinder), *h*=2. m, c_D = 1. and R_a is the gas constant of helium, returns an ascent rate of 4.1 m/s. Compare this with the values shown in the histogram which compiles all of the radiosonde launches from the Polarstern research vessel over a period of eleven years between 1992 and 2003.

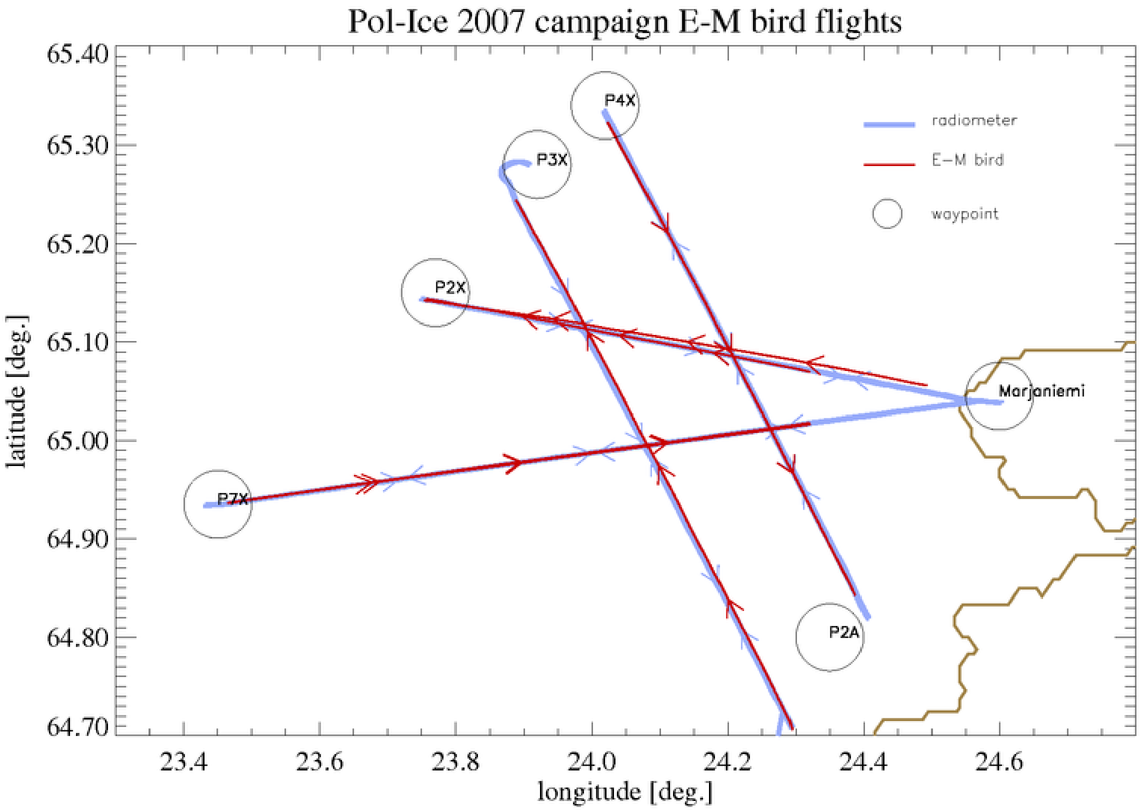
Interpolation

For gridded data such as assimilation or reanalysis data, interpolation is likely the most appropriate method for performing any type of comparison. A specific point in both physical position and time is easy to locate within the grid and interpolation performed between the nearest neighbors. Linear interpolation (bilinear, trilinear etc.) is the most common, though cubic is used as well but is probably not worth the extra computational overhead. If the variable of interest has a relatively smooth rate of change (temperature is a good example of this because it has a diffusion mechanism, radiative transfer, not available to other atmospheric variables), then interpolation can eliminate much of the error associated with collocation.

Interpolation may also be appropriate for many types of satellite instruments, for instance a cross-track scanning instrument like Landsat. In data derived from the Advanced Microwave Sounding Unit (AMSU) are interpolated (although not for the purposes of collocation) using a slight variation of trilinear interpolation. Since measurements within a single scan track are laid out in an approximately rectangular grid, bilinear interpolation can be performed. By searching for the nearest overlapping scan track both forwards and backwards in time, the spatial interpolates can then be interpolated in time. This technique works better with derived quantities rather than raw brightness temperatures since the scan angle will already have been accounted for.

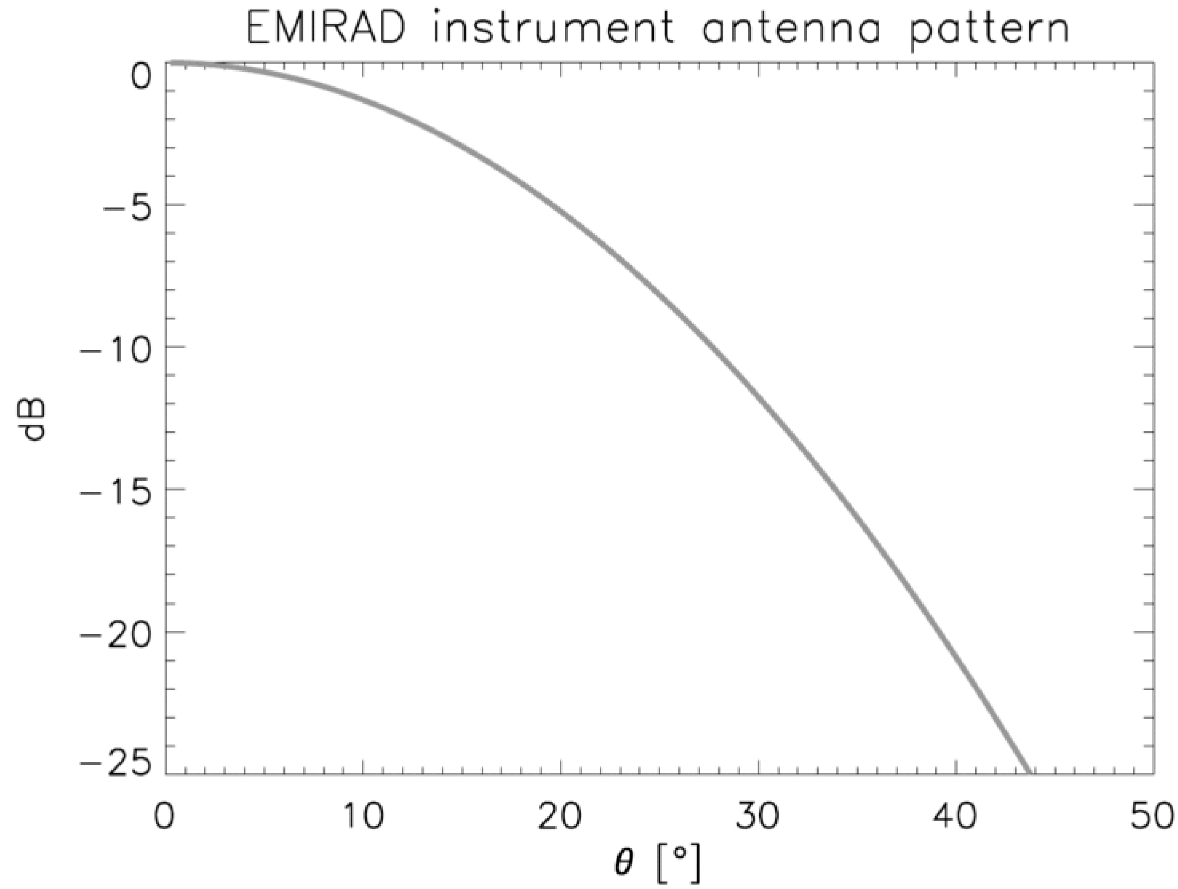
For instruments with a more irregular sampling pattern, such as the Advanced Microwave Scanning Radiometer-EOS (AMSR-E) instrument which has a circular scanning pattern, we need a more general form of interpolation such as kernel estimation. A method commonly used for this particular instrument, as well as SSM/I, is a simple daily average within regularly gridded, spatial bins.

Example: Pol-Ice Campaign



Map of E-M Bird flights from Pol-Ice campaign along with coincident EMIRAD flights

Collocations of sea ice thickness and brightness temperatures taken during the Pol-Ice Campaign are an excellent example since they illustrate many of the most important principles as well as demonstrating the necessity of taking into account the individual case. The Pol-Ice campaign was conducted in the N. Baltic in March 2007 as part of the SMOS-Ice project in preparation for the launch of the Soil Moisture and Ocean Salinity satellite. Because of the low frequency of the SMOS instrument, it is hoped that it will render information on sea ice thickness, therefore the campaign comprised measurements of both sea ice thickness and emitted brightness temperature. Brightness temperatures were measured with the EMIRAD L-band microwave radiometer carried on board an airplane. Ice thickness was measured with the E-M Bird ice thickness meter which was carried by a helicopter. The E-M Bird measures ice thickness with a combination of inductance measurements to determine the location of the ice-water interface and a laser altimeter to measure the height of the ice surface. The map above shows the flight tracks of both instruments which were approximately coincident but obviously subject to pilot error.

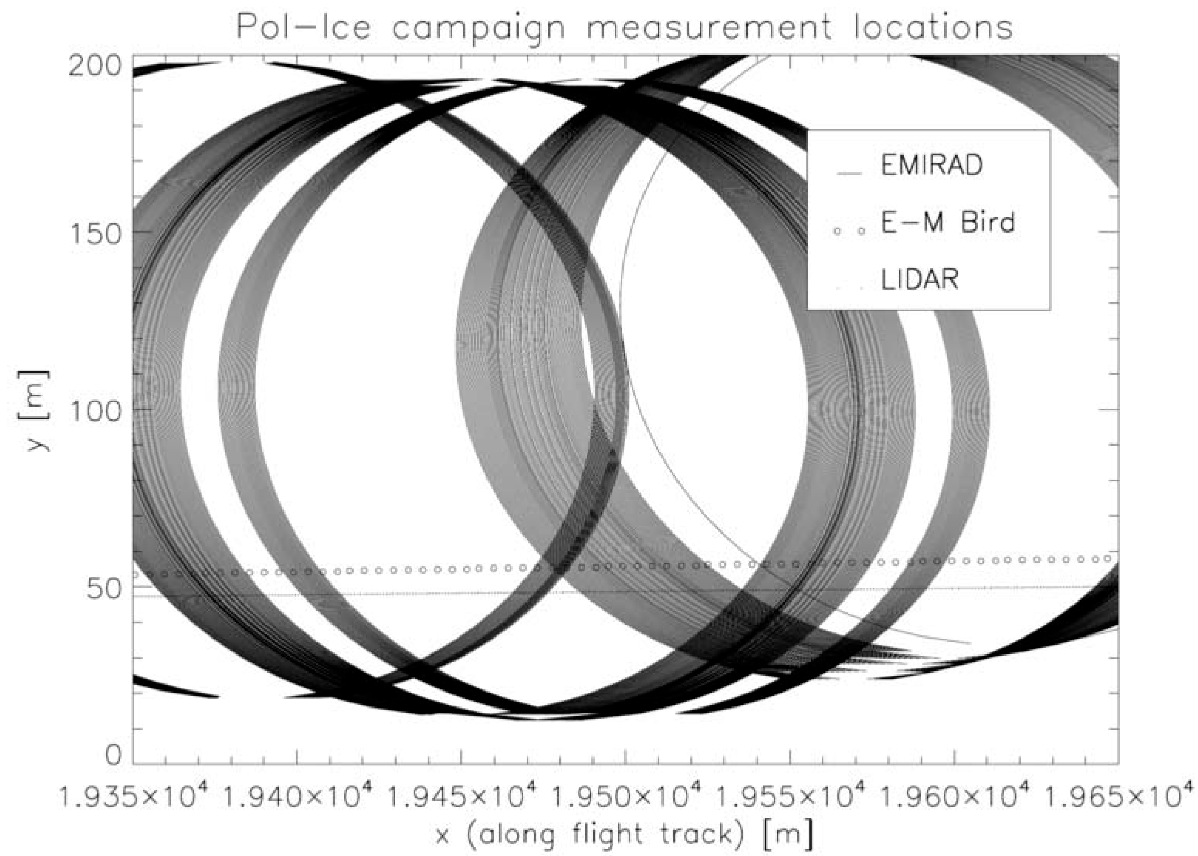


EMIRAD antenna response pattern

Since the flight paths of both aircraft were approximately linear, the first step in the collocation process was to convert all the coincident flights to Cartesian coordinates with the *x*-axis being lateral distance and the *y*-axis transverse distance. In this way, collocations can be performed in two ways: crudely, by matching only the *x* distances, and more precisely by matching both coordinates.

More importantly, the footprint size of the radiometer is many times larger than that of the E-M Bird meter. The figure to the left shows the antenna response function for the radiometer. The full width at half maximum is 31 degrees. Since the aircraft was flying at approximately 500 m, this translates to a footprint size of 200 m or more. Meanwhile, the footprint size of the E-M Bird was roughly 40 m with a sample spacing of only 2 to 4 m. Rather than looking to nearest neighbors, which would have produced poor results, a weighted average of the thickness measurements was performed for each radiometer measurement. Weights were calculated based on the radiometer response function which is almost a perfect Gaussian up to about 45 degrees. Points could be excluded based on distance along the flight path. For validation of sea ice emissivity forward model calculations, this was further refined by performing an emissivity calculation for each thickness measurement and averaging over the radiometer footprint.

The figure below illustrates relative measurement locations from each of the instruments used in the Pol-Ice campaign. Two overpasses are shown: one from the airplane carrying the EMIRAD radiometer and one from the helicopter carrying the E-M Bird instrument. The x-axis is along the line of the flight path. EMIRAD footprints are drawn with lines, E-M Bird inductance measurements are represented by circles and LIDAR measurements with dots.



Relative measurement locations from P4X to P2A flight track: see above map. EMIRAD footprints represent the Gaussian standard-deviation, not FWHM.