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Fifty Years of Earth-observation Satellites

Views from space have led to countless advances on the ground in both scientific knowledge and daily life

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The former Soviet Union's launch of the world's first artificial satellite, Sputnik 1, heralded the era of satellite remote sensing. Since that epic moment on October 4, 1957, hundreds of Earth-observing satellites have followed. Half a century of imagery has provided both iconic views and unprecedented scientific insights.

The science of satellite remote sensing integrates the understanding, interpretation and establishment of relations between natural phenomena and measurements of electromagnetic energy that is either emitted or reflected from the Earth's surface or its atmosphere. These measurements are made for a large number of locations on the Earth's surface by sensors onboard spaceborne satellites and are output as imagery. The 50 years since the first satellite was launched have seen spaceborne remote sensing advance from the small-scale production of low-resolution images

for a select few, motivated primarily by military requirements in the Cold War era, to the daily acquisition of over 10 terabytes of information, increasingly available to all, motivated largely by the needs of Earth-observation science.

More than 150 Earth-observation satellites are currently in orbit, carrying sensors that measure different sections of the visible, infrared and microwave regions of the electromagnetic spectrum. The majority of Earth-observation satellites carry "passive" sensors, measuring either reflected solar radiation or emitted thermal energy from the Earth's surface or atmosphere. Newer satellites also employ "active" sensors that emit energy and record the reflected or backscattered response, from which information about the Earth can be inferred.

The features of the instruments depend on the purpose for which each was designed, varying in several aspects. In simple terms, these are: the minimum size of objects distinguishable on the Earth's surface (spatial resolution), the size of the region of the electromagnetic spectrum sensed (spectral extent), the number of digital levels used to express the data collected (radiometric resolution) and the intervals between imagery acquisition (temporal resolution). Moreover, the number of regions of the spectrum for which data are collected, the time taken to revisit the same area of the Earth, the spatial extent of images produced, and whether the satellite's orbit follows the Sun-illuminated section of the Earth (Sun synchronous) or remains over a fixed point on the Earth (geostationary) all vary between satellites and their sensors. The development of satellites over the past 50 years has also been in step with increasing computing capabilities.

As data storage capacities and processing speeds increase, so has the ability of Earth-observation satellites to capture, process and return information.

Taking Off

Although the first images of Earth from space were actually taken in 1946 over the New Mexico desert from a camera attached to a V-2 rocket, the era of satellite remote sensing began with Sputnik 1, which completed an orbit of the Earth every 96 minutes and transmitted radio signals that could be received on Earth. This success was followed by Sputnik 2 a month later, in November 1957, and by the first U.S. satellites, Explorer 1 in January 1958 and Vanguard 1 in March 1958. Vanguard 1 remains the oldest satellite still orbiting the Earth and produced the first upper-atmospheric density measurements. The first satellite designed specifically for Earth observation was Vanguard 2, but technical problems meant that it collected little of the intended data on cloud cover. It was superseded by TIROS-1 in 1960, which produced the first television footage of weather patterns from space.

The success of TIROS-1 led to a stream of meteorological satellites and also provided the basis for subsequent development of devices designed specifically for land observation. The National Oceanic and Atmospheric Administration (NOAA) series of satellites followed the TIROS satellites and carried an instrument called the Advanced Very High Resolution Radiometer (AVHRR), which measured the reflectance from Earth in five spectral bands, ranging from the visible to the infrared. Although it was designed for meteorological purposes, this sensor proved successful for land and sea

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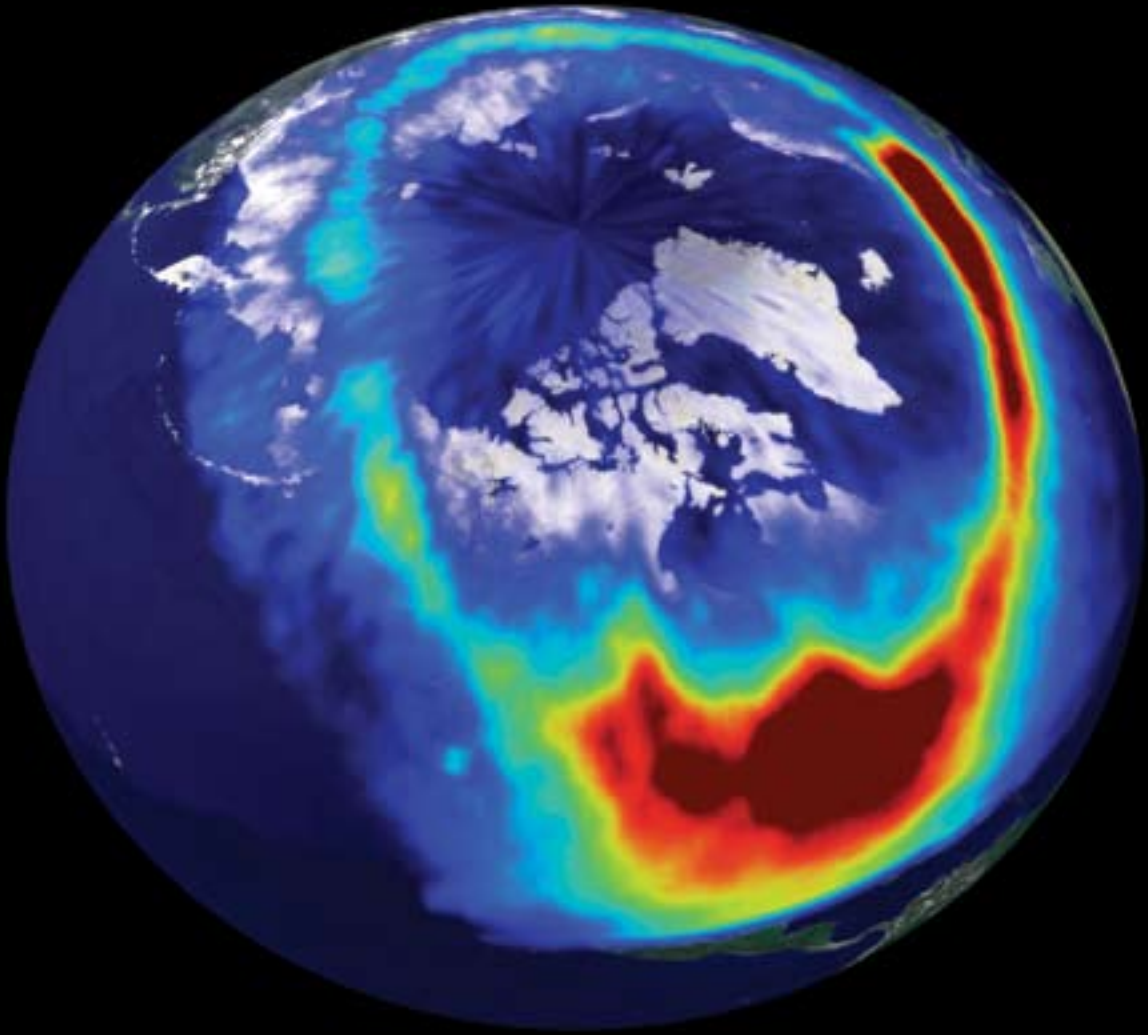


Figure 1. Views such as this one are made possible by satellites orbiting the planet, a feat they have been performing for the past half-century. Although such satellites were initially put in place for military uses, most current ones are used to observe the Earth, and they have provided a wealth of information about the world. This image of an aurora was compiled from data collected in July 2000 by NASA's Polar satellite, which ceased operation earlier in 2008. The data were recorded in ultraviolet light, as the event occurred during daylight hours. False color from blue to red corresponds to increasing magnetic activity. Image is courtesy of NASA/Goddard Space Flight Center and the Scientific Visualization Studio.

observation, providing multitemporal measurements at a global scale.

A key development from 1960 to 1980 was the use of multispectral sensors, stimulated in part by the declassification of military satellites that used both the infrared and microwave bands to observe the Earth's surface. Following pioneering research by the U.S. National Aeronautics and Space Administration (NASA) and the U.S. National Academy of Sciences to assess the utility of Earth observation in forestry and agriculture, NASA launched Landsat 1 in 1972 to monitor Earth's land areas. Landsat images depicted large areas of the Earth's surface in several regions of the electromagnetic spectrum, including both the visible and the near-infrared, and at spatial resolutions useful for many practical applications, such as assessing land cover and use.

Landsat 1 spawned a series of "enhanced" Landsat missions, eventually carrying to orbit the Enhanced Thematic Mapper Plus, capable of capturing data in as many as eight spectral bands, again in the visible to near-infrared, at a spatial resolution of predominantly 30 meters. These missions formed a model for similar land-observation satellites and sensors over the following decades, such as the French *Système Pour l'Observation de la Terre* and more recently NASA's Advanced Spaceborne Thermal Emission and Reflection radiometer. The Nimbus satellites, begun in 1964, were also a landmark series, carrying sensors capable of monitoring oceanic biological processes, atmospheric composition and ice-sheet topography. The Nimbus sensors included visible-light cameras, infrared and microwave radiometers, spectrom-

eters, ultraviolet backscatter sensors and coastal-zone color scanners.

The 1980s saw significant advances in the capabilities of existing technologies as well as the development of new ones, including hyperspectral sensors that combine information from several spectral bands, multi-angle spectrometers that combine the views from several azimuths, and spaceborne radar. Active microwave systems have been used for tracking moving objects since the early 20th century, but only in the past two decades have sensors onboard satellites produced active microwave images, where the instruments send out radar pulses and measure their reflectance. Synthetic aperture radar (SAR) is a variation on this technology that can sense through cloud cover and without daylight, measuring the time delay between emission and return, thus es-

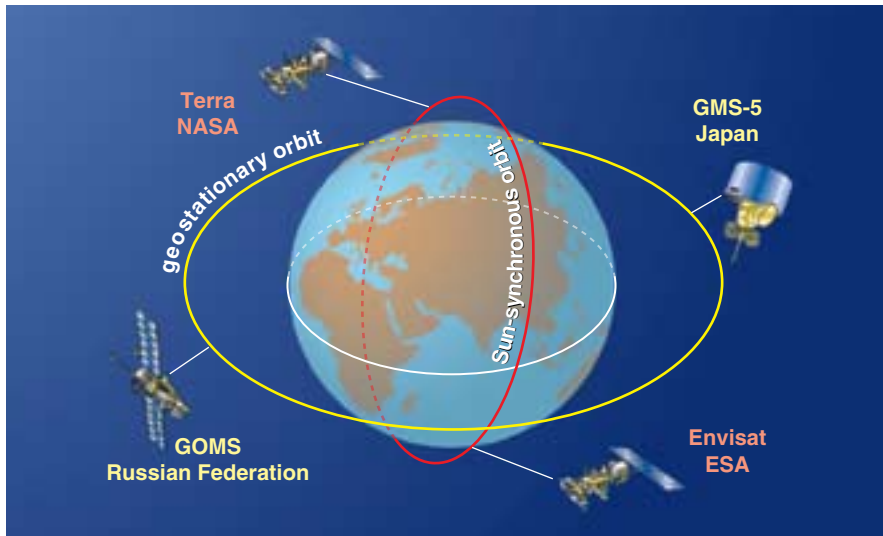


Figure 2. Most of the hundreds of earth-observing satellites occupy one of two types of orbits. A geostationary orbit rotates in sync with the planet, keeping the satellite over a particular location. Examples of satellites in geostationary orbit include Russia's GOMS and Japan's GMS-5, both used for meteorological purposes. A Sun-synchronous orbit passes over the same spot on the Earth at the same time every day; many of these orbits also go over the poles. NASA's Terra satellite and the European Space Agency (ESA) Envisat occupy this orbit. Illustration based on information from the World Meteorological Organization.

tablishing the location, height and scattering properties of the Earth's surface. SAR takes data with its relatively small antenna in multiple positions when it is transmitting and receiving. These signals are combined, accounting for the time delay between them, to give the same information as a much more

costly and cumbersome large antenna would be able to provide.

Satellite radar applications have now diversified considerably, with sensor configurations that include altimeters sensitive enough to measure sea-level height with a precision of several millimeters and scatterom-

eters to measure surface roughness. Polarimetric imagers, which detect the relative intensity of the polarized components of reflected radiation, and interferometric imagers, which sense the superposition of different wavelengths, are used to monitor minute land and ice movements. In addition, improved technologies and the continued declassification of military satellites now provide the highest spatial-resolution satellite views of the Earth ever seen, with objects 60 centimeters across distinguishable in images from Quickbird, a privately owned satellite.

The most recently introduced satellite remote-sensing instrument is the laser, principally used for topographic and ice-sheet mapping, but also to measure atmospheric properties and the Earth's surface by fluorescence. Substances such as chlorophyll naturally fluoresce at specific wavelengths, allowing for calculation of the amount of plant life in a certain area, such as in an oceanic algal bloom. Fluorescence is also useful in studying the atmosphere. NASA's Calipso satellite uses green and infrared lidar, or laser pulses, to measure the backscattered reflectance, or fluorescence, of clouds, which gives information not only about the altitudes of clouds but also the properties of aerosols within them. For instance,

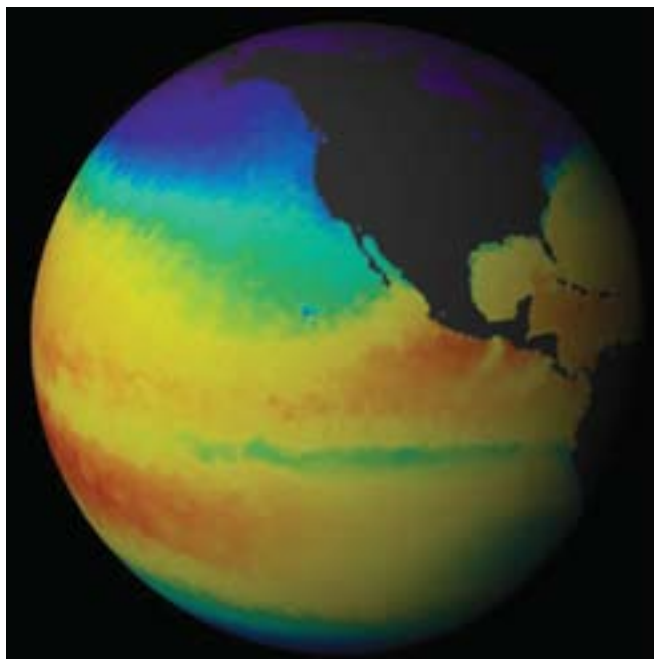


Figure 3. A 1999 image of the El Niño Southern Oscillation (ENSO) event, from the radiometer aboard ESA's ERS-2 satellite, shows rising sea-surface temperature in the Pacific Ocean. This image captures the period when ENSO currents were switching to colder "La Niña" conditions. Image courtesy of ESA.

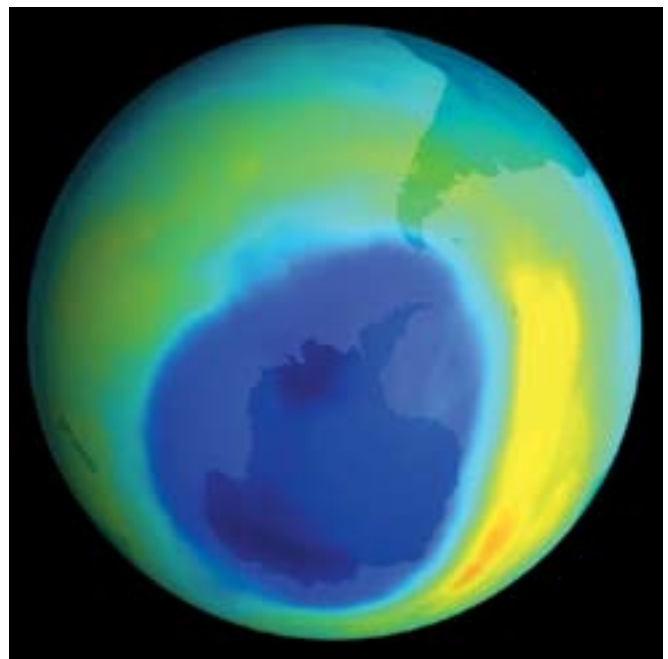


Figure 4. Although it's not really a "hole," there is an "ozone depleted area" over the Earth's southern pole. Taken in September 2000 by NASA's Earth Probe satellite, this image shows the area at 11 million square miles. Image courtesy of the TOMS science team and the Scientific Visualization Studio, NASA/GSFC.

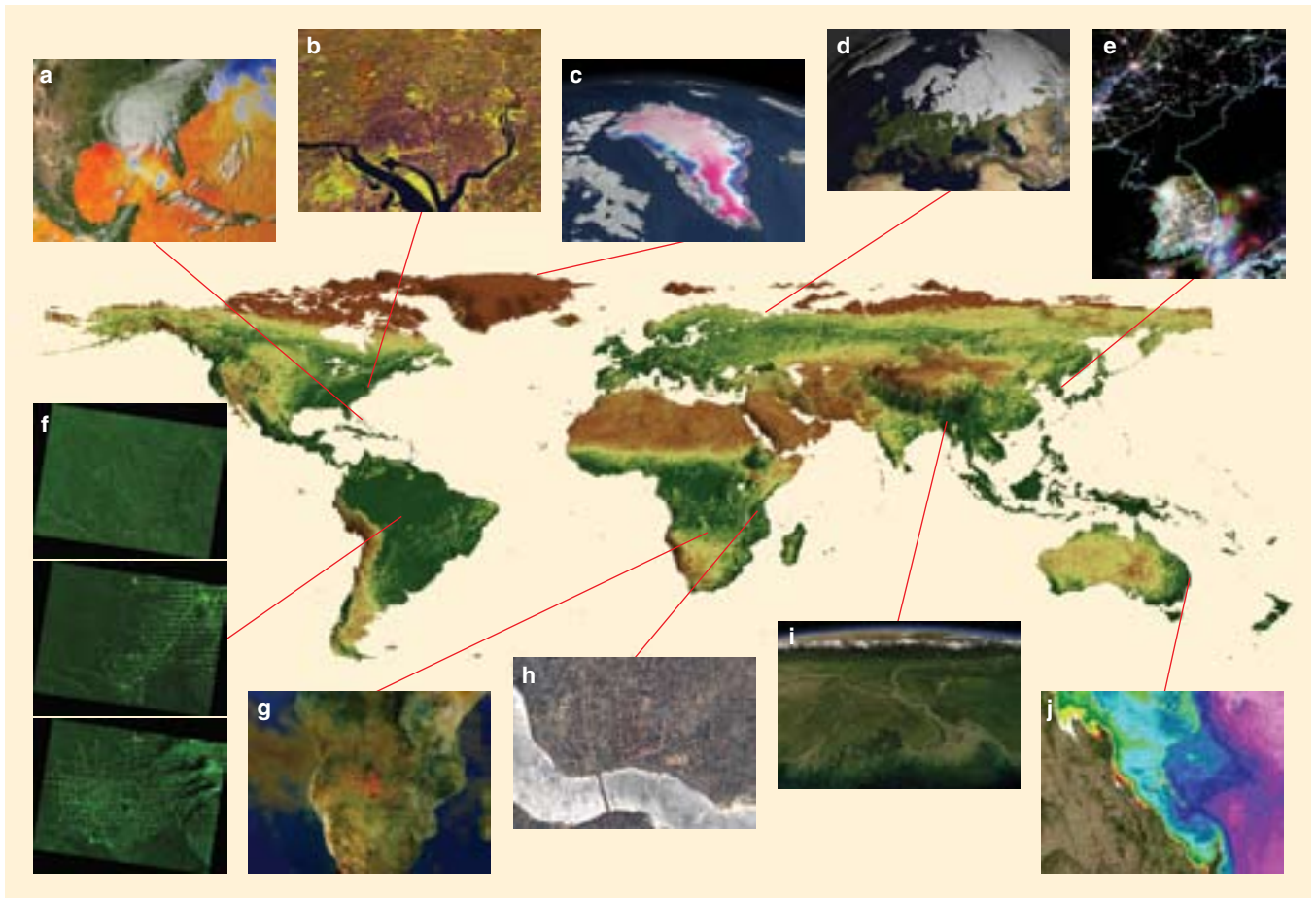


Figure 5. Satellites provide a wealth of information across the globe and in multiple measurement bands. A compilation of satellite images taken in multiple spectral bands gives a whole-Earth picture of land cover, called the normalized difference vegetation index (NDVI) (center). Other images show Hurricane Katrina and sea-surface temperatures as seen by the Terra satellite's Moderate Resolution Imaging Spectrometer (MODIS) (a); a view of Washington, D.C., in false color from Landsat (b); recent Greenland ice sheet elevation changes, red showing an increase and blue a decrease, from SeaSat data (c); European snow coverage from MODIS imagery (d); the stark difference in nighttime lights between North and South Korea, as shown by Defense Meteorological Satellite Programme Operational Linescan System data (e); the progression of Brazilian rainforest loss from Landsat images taken in 1975, 1992 and 2001 (f, from top to bottom); wildfires and smoke in South Africa, as measured by the TIROS and Nimbus satellites (g); the Kenyan coastal resort town of Kilifi, from IKONOS, a commercially owned satellite (h); a Landsat-ETM view of Bangladesh and the Himalayas, with vertical exaggeration applied (i) and chlorophyll concentrations off the northeast coast of Australia, from MODIS data (j). Images are courtesy of the authors and the Scientific Visualization Studio, NASA/GSFC.

Calipso spotted a large sulfur dioxide plume that would not have been visible to many other sensors.

Since the early 1990s, two diverging trends in satellite design and operation have developed. First, the large national space organizations, including both NASA and the European Space Agency (ESA), have focused their Earth-observation resources principally on the design and launch of large multisensor platforms, with each sensor designed to monitor a specific aspect of Earth-system processes, frequently at the global scale. Launched in December 1999 and May 2002 respectively, Terra and Aqua are the first of a series of multi-instrument spacecraft forming NASA's Earth Observing System. The next one in the works is the National Polar Orbiting Environmental Satellite System

(NPOESS) Preparatory Project, designed as a "bridge mission" to provide a link between the current Terra and Aqua platforms and the next-generation NPOESS mission, currently scheduled for launch in 2013. Additionally, March 2002 saw the launch of ESA's Environmental Satellite, which carries 10 different sensors; at the size of a double-decker bus, it is the largest Earth-observation satellite ever built.

A second, contrasting trend in satellite design is toward smaller, cheaper national satellites. More than 20 countries are now either developing or operating remote-sensing satellites. Typically these are modeled after the Landsat design. Since instrument and launch costs have fallen, lower-income countries such as India, Brazil and Nigeria have launched their own Earth-observation satellites.

Many of these new satellites are developed and launched by commercial operators, and are capable of collecting images on demand for a per-item fee, in a variety of operational modes.

Today's Busy Space

Fifty years of Earth-observation satellite development has provided a wealth of memorable images and has driven forward our understanding of Earth-system processes. Today satellite observations are significant data sources for monitoring, measuring and understanding the Earth's terrestrial, aquatic and climatic environments, as well as how they are changing and how each reacts to human influence. Some of the most revolutionary advances brought about by 50 years of remote-sensing progress have been in improving and updating maps.

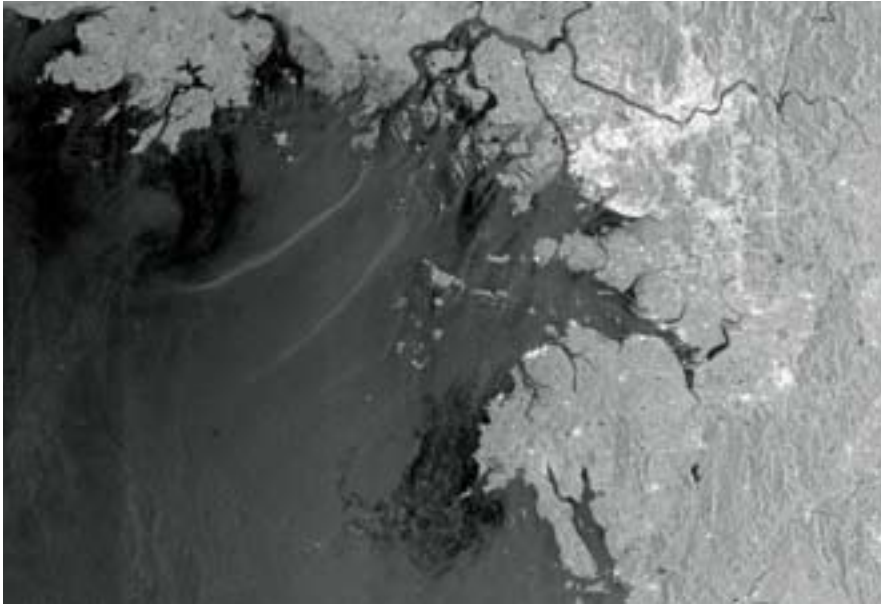
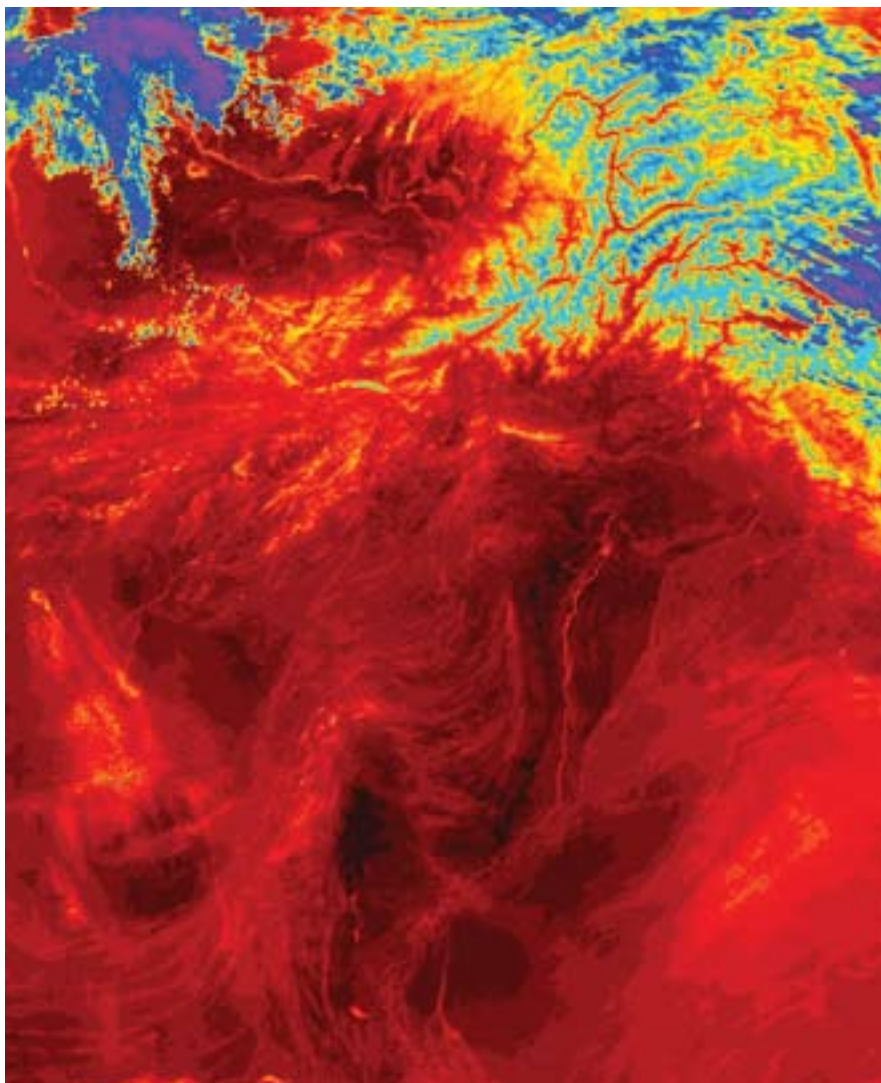


Figure 6. In December 2007 the Hong Kong-based *Heibei Spirit* tanker, at anchor off the coast of South Korea, was punctured by a crane-carrying barge that broke free of its towing tugboat, creating a huge slick of more than 2.5 million gallons of crude oil. The spill (dark area) was captured by the synthetic aperture radar instrument aboard ESA's *Envisat*. Image courtesy of ESA.



From the first basic satellite-derived land-cover maps of the 1960s, to today's stunning online three-dimensional replicas of the Earth, cartography based on satellite imagery has proved to be a consistent and repeatable approach. Such imagery has changed the paradigm of mapping, moving it beyond political borders and topographic landscapes. By sensing outside the visible spectrum, satellites have given us the first large-scale maps of weather patterns, vegetation health, atmospheric pollutants, soil moisture and rock types, among others. Moreover, satellite-derived cartography of the Earth's climate regions and habitats has helped to map species distributions (from tsetse flies to elephants) and disease risks (from Ebola to malaria).

Since the 1940s, the interpretive use of aerial photography for geological and land-cover mapping and evaluation has been widespread, providing an efficient and low-cost approach for resource allocation and for targeting key areas for ground-based surveys. The advent of satellite imagery added further advantages by introducing digital processing, allowing larger areas to be viewed in single scenes, and enabling the combination of visible-light images with a variety of compatible imagery types, such as topography and radar. Satellite imagery is also much easier to update and refine, although it has yet to reach the sub-centimeter spatial resolution of aerial photographs.

Not surprisingly, then, some of the earliest scientific advances based on satellite observations came in the field of geology, where mineral and energy exploration, waste disposal and tectonic modeling all took advantage of the new data sources. For instance, in waste disposal, satellite imagery has been used to locate ideal sites, to detect contaminated land or illegal waste burial and to identify potential fault lines that could allow seepage of waste into groundwater.

Additionally, multispectral measurements significantly improved land-cover assessments as the reflectance from different regions of the spectrum could be combined into indices, such as the

Figure 7. NASA's *Aqua* satellite recorded this image of the area around the Indus River during a heat wave in May 2004. Land temperatures peaked at 153 degrees Fahrenheit. Blue at the top of the image shows frozen peaks in the Himalaya mountains, in sharp contrast to the deep red of the scorching valleys below. Image is courtesy of Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC.

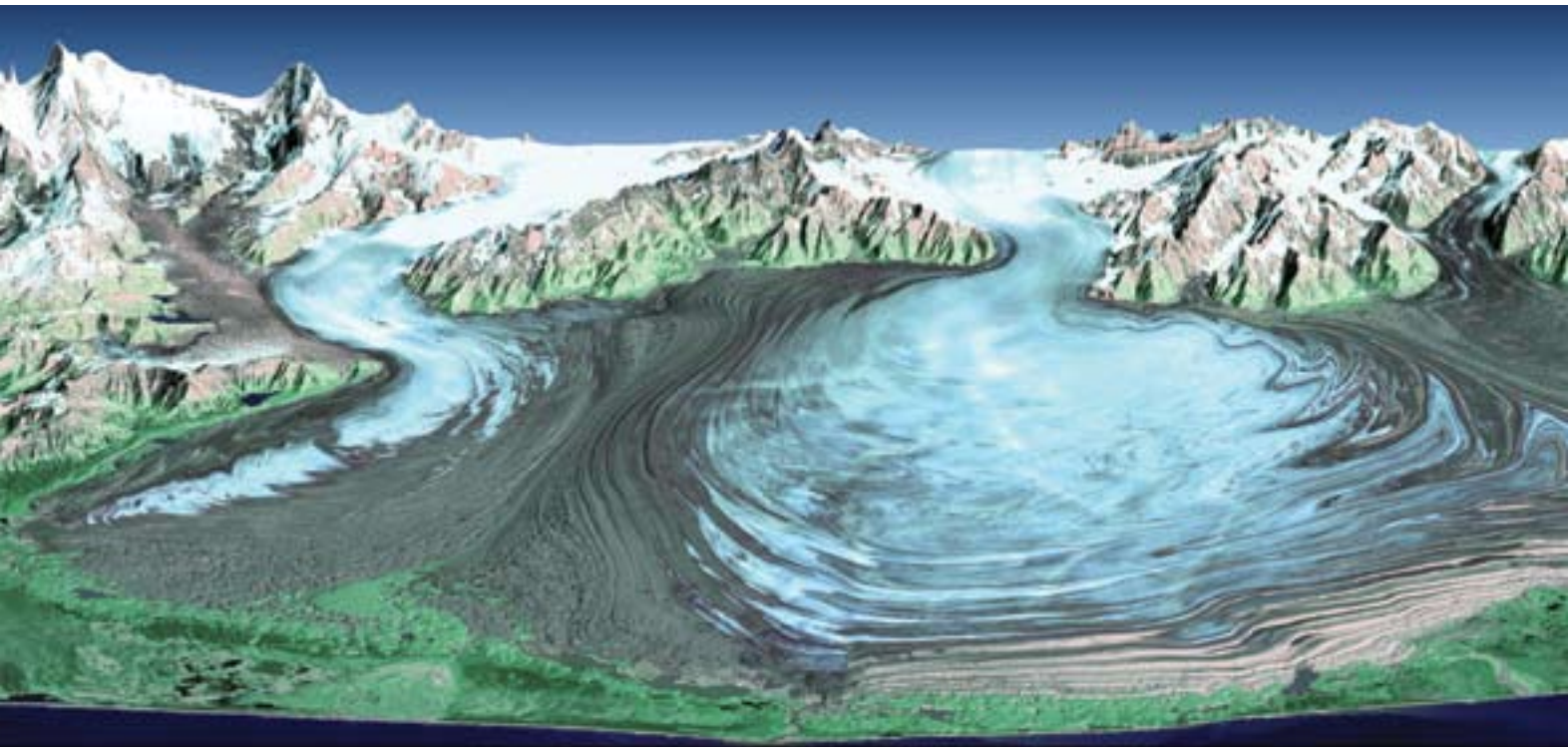


Figure 8. Malaspina Glacier in southeastern Alaska is a classic example of a piedmont glacier, where valley glaciers exit a mountain range onto a broad lowland and spread out. A unique perspective was created by combining a Landsat image, made with both visible and infrared light, with an elevation model from the Shuttle Radar Topography Mission aboard the Space Shuttle Endeavor in 2000. Image courtesy of NASA/JPL/NIMA.

normalized difference vegetation index (NDVI), which exploits the fact that healthy vegetation absorbs light in the red part of the spectrum but strongly reflects near-infrared radiation. The unique multispectral reflectance signatures of each type of surface on the Earth could also be quantified and exploited for accurate and automated mapping.

Although efficient land-cover classification approaches were developed and refined for mapping based on Landsat imagery, it was the AVHRR and its more

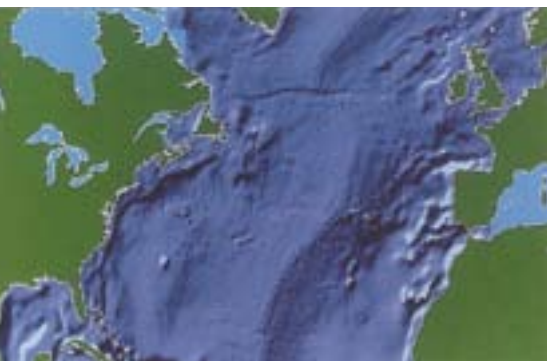


Figure 9. The surface of the ocean is not flat, but contains hills and valleys that echo the shape of the ocean floor over which it flows. ESA's ERS-1 radar altimeter recording over the North Atlantic shows the mid-ocean ridge and continental shelves. Image courtesy of Carel Wakkers, TU Delft, the Netherlands, and ESA.

frequently acquired imagery that provided unprecedented insights about our changing planet. Weekly imagery from the sensor provided the first views of the dynamics of land cover, biomass and primary production across entire continents. Analysis of the long time series of AVHRR imagery, along with an improved understanding of the relations between electromagnetic-energy reflectance and ecological features, made possible the study of ecology on a global scale. These findings, among many others, gave the first quantification of the impacts of the El Niño Southern Oscillation (ENSO) on African crop and livestock production. In addition, the data have shown some unexpected trends in the so-called "greening of the north" phenomenon, where plant productivity in northern high latitudes was thought to be on the rise due to a longer growing season. Greening does continue in tundra regions, but it turns out actually to be on the decline in boreal forest because of hotter, drier air masses over continental interiors.

As archives of Landsat imagery have built up over the years, so have more-detailed insights into land-cover changes, exemplified by large-scale mapping of deforestation, useful not only for land-use planning but also for screening for such activities as illegal logging. The



Figure 10. Storms in the Sahara desert often blow copious amounts of sand and dust out to sea. The Cape Verde islands, about 300 miles off the western coast of Africa, can experience violent dust storms from this distant source, as captured by NASA's Terra satellite in 2000. Image courtesy of Liam Gumley, MODIS Atmosphere Science Team.



Figure 11. Before-and-after images provide an essential resource for understanding the extent of disasters. Images such as this one of New Orleans before Hurricane Katrina (*left*) make it clear just how extensively the city was flooded in a second image 17 days after the storm (*right*). NASA's Terra satellite captured both of these images, covering an area 10 kilometers by 7 kilometers. Image courtesy of NASA/JPL.

advantages of satellite remote sensing for mapping had similar impacts on soil, agricultural and forestry sciences. Some examples include continental-scale mapping of fires and the advent of precision agriculture and forest management, where growth, water stress, disease and pests can be monitored.

Oceanographic research has also been revolutionized by satellite-based measurements. Researchers can now rapidly acquire and analyze global data sets on sea-surface temperature, surface wind speed and direction, height of surface swells, concentrations of phytoplankton and suspended sediments, wave distributions, and changes in sea-surface height associated with tides and currents. Prior to the 1980s such properties could only be determined through expensive and extensive marine expeditions, but the regular availability of such measurements from spaceborne sensors has now led to long-term studies of sea-level rise and surface-temperature variations, such as the ENSO. Some of the earliest significant advances came from Nimbus-7's Coastal Zone Color Scanner and its pioneering large-scale data collection of oceanic biological processes. Later, the Sea-viewing Wide Field-of-View Sensor (SeaWiFS) provided unprecedented measurements of the response of oceanic biological processes to ENSO and agricultural runoff.

Oceanic phytoplankton contributes around half of the biosphere's net primary production of biomass and therefore represents a significant component of the global carbon cycle. Measurements of chlorophyll distribution from satellites provided the basis for the first large-

scale estimates of oceanic net primary production and the discovery of its close coupling to climate. The development of satellite altimeters also enabled global mapping and a new understanding of a range of features through the detection of changes in water height that indicate gravitational concentrations. These include sea-floor topography, tidal-energy dissipation and sea-level rise, as well as detailed characterization of the December 2004 Sumatra tsunami.

Looking from Above

More than 100 satellites have been launched solely for monitoring the Earth's atmosphere. Half have been designed to support weather forecasting, whereas the others have been more research focused. Short-term weather-prediction science has advanced significantly through the use of active microwave instruments, as these operate through cloud cover and without daylight. Microwave and infrared sensors can now be used to map atmospheric temperature profiles, water vapor distribution, surface pressure and precipitation. The Tropical Rainfall Measuring Mission (TRMM) satellite launched in 1997 carries various microwave instruments for precipitation monitoring. TRMM data have contributed to an increased understanding of tropical rainfall processes, including quantification of the inhibiting effects of air pollution on rainfall. As with many satellites initially launched for research purposes, the success of TRMM has meant that its mission has been extended annually well past its expected life.

The interactions of electromagnetic waves with the Earth's atmosphere are

determined by both their wavelength and by the atmosphere's pressure and temperature and the particulates suspended within it. The scattering, emission, refraction and absorption of electromagnetic waves interacting with the atmosphere is a complex science, but Earth-observation satellite data have formed the basis of some significant advances in this realm, including the first global measurements and maps of the Arctic and Antarctic ozone "holes," through use of the Nimbus-7 Total Ozone Mapping Spectrometer to measure backscattered solar ultraviolet radiation. The same sensor was used to quantify global tropospheric ozone levels related to air pollution, whereas improved sensors provided unprecedented maps of global smoke, dust and nitrogen oxide levels.

The study of the mechanisms controlling the global climate system and its changes has become heavily dependent on the use of satellite observations. The data are routinely used to populate models of climate, but they also both confirm model results and provide new data that either contradict predictions or indicate where models fall short.

Satellite remote sensing has proved invaluable in studying the Arctic and Antarctic without the need for humans to disturb or endure these fragile, extreme environments. Remote sensing of the cryosphere is, however, sometimes restricted by the polar environment. The orbital inclination of many satellites means that their sensors do not cover regions with latitudes greater than 80 degrees. Moreover, at any time, at least 50 percent of the polar regions are covered

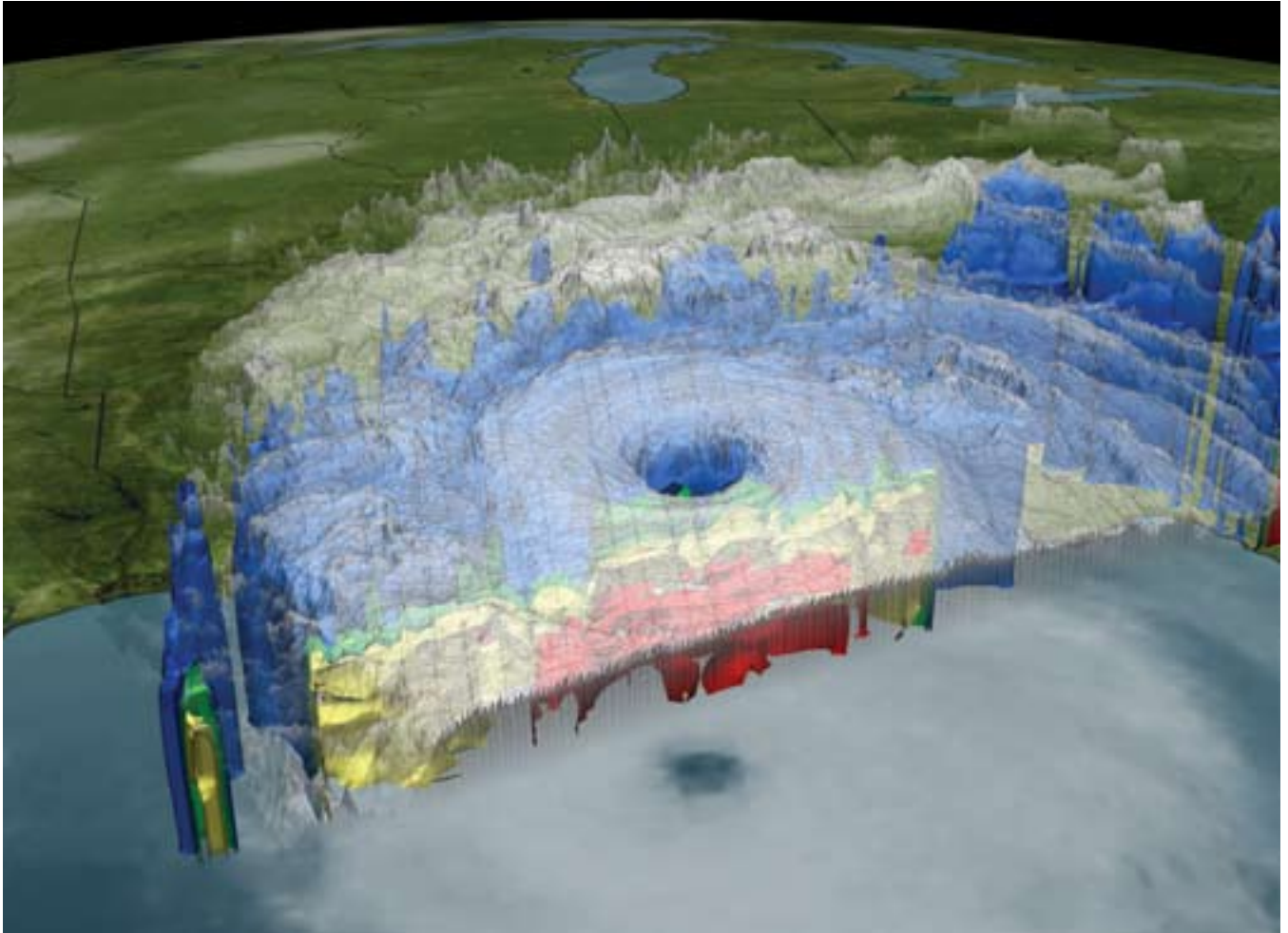


Figure 12. A composite view of Hurricane Katrina on August 28, 2005, shows data from several instruments aboard two satellites. The Tropical Rainfall Measuring Mission satellite, a joint venture of NASA and the Japan Aerospace Exploration Agency, looks underneath a storm's clouds to reveal the underlying rain structure. Blue indicates at least a quarter inch of rain an hour, whereas green represents half an inch, yellow an inch and red two inches. The Geostationary Operational Environmental Satellite, run by NASA and the National Oceanic and Atmospheric Administration, provided visible meteorological data. Image courtesy of NASA/JAXA.

by cloud, and during their respective winters each endures extended periods of darkness, making the consistent use of visible and infrared sensors problematic. These issues have led to the extensive use of microwave instruments. The continuous availability of radar data over the past decade has provided significant advances in understanding the cryosphere.

Sea-ice extent and movement are key indicators of climate change, and are also important for ship routing and weather forecasting. A succession of passive microwave radiometers has led to continuous records since 1972, with spatial resolution improving with each new radiometer. At the same time, SAR data have enabled discrimination between seasonal and persistent ice types, and monitoring of sea-ice reductions consistent with global warming. Significant disintegrations of Antarctic Peninsula ice shelves, also coincident with

climate warming, were observed using optical and SAR imagery, as was accelerated ice discharge on Greenland.

Ice thickness also represents an important climate-change indicator. Although its measurement is problematic, data from satellite radar altimeters and infrared radiometers have shown promise as model inputs, especially when on-site numbers are available for calibration. Satellite altimeter data have even been used to map a vast freshwater lake beneath Antarctica. Topography remains perhaps the most fundamental observation for an ice sheet, with regular, accurate measurements providing information on direction and magnitude of flows, which are vital parameters for glacial mass-balance estimates. Radar and laser altimeters, as well as SAR interferometry, have all proved capable of producing accurate measurements of ice-sheet topography and dynamics.

Recent years have seen the application of data from Earth-observation satellites extend into new research fields. Urban and regional planners require nearly continuous acquisition of data to formulate policies and programs, and new satellites with increased spatial and spectral resolution provide data to meet these requirements. From flood-risk modeling, subsidence detection and traffic management, to archaeological surveying, landmine detection and even crime-risk mapping from nighttime imagery, satellite imagery is now widely used for societal applications. The 35-year archive of Landsat imagery provides data for land-use and urban-growth modeling, whereas nighttime imagery of electrified urban areas is facilitating the construction of global human-population spatial databases, which are finding applications in disease-burden estimation and epidemic modeling.

Globally consistent satellite data on a range of climatic variables now exist, including temperature, rainfall and vegetation area. These data are beginning to find significant applications across the low-income regions of the world in exploring food security, resource accessibility and the construction of early-warning systems in planning for the effects of crop failure and disease outbreaks. The resultant maps are improving decision making and efficient resource allocation. Moreover, with the climatic and environmental preferences and tolerances of numerous species quantified, the same global imagery is helping to infer present and future distributions for improved conservation planning. From the availability of habitats for giant pandas, to the distributions of malarial mosquitoes, satellite imagery has become an important asset for ecologists and epidemiologists alike.

The Big Picture

The last half-century has seen satellite remote sensing come of age as a multidisciplinary research field, with a balance of theory, practice and operational application. It still faces barriers to becoming a fully global and cross-disciplinary data source, particularly in low-income countries, but in many cases these limitations are being reduced. The continued increase in computing power and decrease in costs are making satellite imagery more manageable and affordable. However, the building of image archives spanning different time periods still requires significant resources.

The increasing number of Earth-observation satellites and the availability of imagery are driving down data costs. Free online databases and open distribution of processed imagery are making many types of data available to all. Although this is a welcome trend, it remains exceptional, with even unprocessed data from numerous satellites not readily available and many operators still charging high fees for imagery.

Software for handling and processing satellite imagery was previously rare, as well as complex and expensive, but is becoming widespread and more user-friendly. Basic software is now, in many cases, cheap or even free, but the most powerful and advanced programs still require costly licenses. Training in the use of satellite imagery has also grown as such data become central to numerous disciplines, but cutting-edge computing, imagery and software often mean that

course costs remain prohibitively high for institutions in low-income countries.

Increasingly, limitations in satellite-data applications have shifted from the technology of acquiring the data to the techniques on the ground required to optimally exploit the information within the remotely sensed data. The conventional trade-offs in spectral, spatial and temporal characteristics, which must now be solved by choosing imagery from different satellite sensors, are gradually being made unnecessary by new technology. Forthcoming launches and plans should herald the first images with a spatial resolution under half a meter, high spatial resolution SAR imagery, laser imaging and detailed nighttime data. Improvements in data processing and fusion could help eliminate cloud-obscured and nighttime data loss, and provide multi-image virtual databases for modeling of environmental and social processes. Finally, the declassification of military space technology may well provide valuable new data in the future, just as it has in the past.

There can be no doubt that satellite remote sensing is likely to continue to grow as an operational tool for mapping, monitoring and managing the Earth, as a profit-making entity and as a primary data source for Earth-system science. Existing trends in satellite design are likely to continue, and new ones will emerge, driven by both operational need and profits. Although global issues such as climate change and its effects will continue to provide justification for large multisensor satellites, the design directions in which smaller commercial satellites will head is less clear. The potential for real-time imagery has just begun to be realized, and personalized imagery beamed to handheld devices will soon show users their positions in traffic or current weather at their destinations. To speculate further, the online availability of such imagery could facilitate a real-time or "live" Google Earth. Such a resource potentially enables revolutionary studies involving the global tracking of terrestrial and oceanic life, which could help create, for instance, real-time disease epidemic models, dynamic traffic control and reactive conservation—but it also raises significant security and privacy concerns.

Despite significant proven potential, the future supply of high-quality Earth-observation data for research and other applications remains unclear. For instance, funding cuts in U.S. programs

have generated concern over a possible data gap in the Landsat imagery series, and budget overruns have both modified the scope and delayed the launch of the NPOESS project. At a time when unprecedented changes are taking place in the Earth's atmosphere, oceans and land surface, it is difficult to rationalize any scaling back of demonstrably successful and valuable satellite remote-sensing programs. Such examples emphasize the need for multinational cooperation in Earth observation to maintain a consistent supply of global data and ensure another 50 years of continuous measurements, stunning images and a deeper understanding of the Earth.

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