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# Fifty Years of Earth Observation Satellites:

## Views from above have lead 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 relationships between natural phenomena and measurements of electromagnetic energy that are 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 processed to form 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 terabits 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 measuring different sections of the visible, infrared and microwave regions of the electromagnetic spectrum. The majority of Earth observation satellites carry "passive" sensors, measuring electromagnetic radiation that has been reflected or emitted 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's surface or atmosphere can be inferred.

The features of the instruments depend on the purpose for which each was designed, varying in several aspects: the minimum size of objects distinguishable on the Earth's surface (spatial resolution), the size of the region of the electromagnetic spectrum sensed (spectral resolution), 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 the sensors they carry. The development of satellites over the last 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 from a camera attached to a V-2 rocket over the New Mexico desert, the era of satellite remote sensing began with the 1957 launch of Sputnik 1, which completed an orbit of the Earth every 96


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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 US 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 technological 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 consequent 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 eventually proved most successful for land and sea 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 infrared and microwave 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 visible and near-infrared, and at spatial resolutions sufficient 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 (ETM), capable of capturing data in up to eight spectral bands, again in the visible to near-infrared, at a spatial resolution of 15 meters. These missions formed a model for similar land observation satellites and sensors over the following decades, such as the French *Systeme Pour l'Observation de la Terre* (SPOT) and more recently NASA's Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER). 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 cameras, infrared and microwave radiometers, spectrometers, ultraviolet backscatter sensors and coastal zone color scanners.

The 1980s saw significant advances in the capabilities of existing technology 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, sounding systems that can sense changes in atmospheric pressure, and spaceborne radar. Active microwave systems have been used for tracking moving objects since the early 20th century, but only in the last 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, and thus establishing 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 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 scatterometers 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, due to the continued declassification of military satellites and improved technologies, we now have the highest spatial-resolution satellite views of the Earth ever seen, with objects of 60 centimeters across distinguishable in images from Quickbird, a privately-owned commercial 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 natural fluoresce at specific wavelengths, allowing for calculation of the amounts of plant life in a certain area, for example such as in an ocean algal bloom. Fluorescence is also useful in studying the atmosphere. NASA's Calipso satellite uses a laser-based radar, or lidar, tool to measure the backscattered reflectance, or fluorescence, of clouds, which not only gives information about the altitudes of clouds but also the properties of aerosols within them. For instance, 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 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 (EOS). The next ones in the works are the National Polar Orbiting Environmental Satellite System (NPOESS), currently scheduled for a 2010 launch. Additionally, March 2002 saw the launch of ESA's Environmental Satellite (ENVISAT), 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 towards 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 and at a cost, in a variety of operational modes.

## Today's Busy Space

Fifty years of Earth observation satellite development has provided a wealth of iconic images and has driven forward our understanding of Earth-system processes. Today satellite observations are our best 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 map creation.

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 proven a consistent and repeatable approach to map making. But satellite imagery has changed the paradigm of mapping, moving it beyond political borders and topological

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landscapes. By sensing beyond the visible spectrum, satellites have also given us the first large-scale maps of weather patterns, vegetation health, atmospheric pollutants, soil moisture and rock types, amongst others. Moreover, satellite-derived maps of the Earth’s climate regions and habitats have, for instance, contributed to the mapping of 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 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, though it has yet to reach the sub-centimeter spatial resolution of aerial photographs.

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, to provide evidence of illegal waste burial and to detect potential fault lines that could cause 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 normalized difference vegetation index (NDVI), which exploits the fact that healthy vegetation absorbs light in the red part of the spectrum, but reflects strongly 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 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 relationships between measured electromagnetic energy reflectance and ecological features, made possible the study of ecology on a global scale. These findings, amongst many others, gave the first quantification of the impacts of El Niño on African crop and livestock production. In addition, the data has shown some unexpected trends in the so-called “greening of the north” phenomenon, where plant productivity in northern high latitudes is thought to be on the rise due to a longer growing season. Greening does continue in tundra regions, but it turns out to actually be on the decline in boreal forest, it turns out due to 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 screening for such activities as illegal logging. The advantages of satellite remote sensing for mapping had similar impact 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 seen a revolution due to satellite-based measurements. Researchers can now rapidly acquire and analyze global data sets on sea surface

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temperature, surface wind speed and direction, height of surface swells, concentrations of phytoplankton and suspended sediments, wave distributions, and changes in sea surface heights associated with tides and currents. Prior to the 1980s such properties could only be determined through expensive and long marine expeditions, but the regular availability of such measurements from spaceborne sensors has now lead to the start of long-term studies of sea level rise and surface-temperature variations, such as the El Niño Southern Oscillation (ENSO). Some of the earliest significant advances came from Nimbus-7's Coastal Zone Color Scanner (CZCS) 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 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

Over 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 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 the length of the waves and also the atmosphere's pressure, 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 Nimbus-7 Total Ozone Mapping Spectrometer (TOMS) 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 also both confirm model results and provide new data that either contradict predictions or indicate where models fall short.

Satellite remote-sensing has proven invaluable in studying the Arctic and Antarctic environments without humans having 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 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 operation and availability of radar data over the last decade has provided perhaps the most significant advance in observing and understanding the cryosphere.

Sea-ice extent and movement are key indicators of climate change, as well as being 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, satellite radar altimeters and infrared radiometers inputs into models have shown promise, especially when on-site data are available for calibration. Satellite altimeter data has even mapped 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 estimations. Radar and laser altimeters, as well as SAR interferometry, have all been shown 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 night-time imagery, satellite imagery is now widely used for societal applications. The 30-year archive of Landsat imagery provides data for land-use and urban-growth modeling, whereas night-time imagery of electrified urban areas is facilitating the construction of global urban and human population spatial databases, which are finding application in disease-burden estimation and epidemic modeling.

Globally consistent satellite data on a range of climatic variables now exist, including temperature, rainfall and vegetation amount. These data are beginning to find significant application 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.

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## The Big Picture

The last 50 years 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 for several reasons. The continued rise in computing power and decrease in costs are making satellite imagery more manageable and affordable. The building of archives of imagery that spans different time periods still requires significant resources, however, and these remain few and far between.

The increasing number of Earth-observation satellites and availability of imagery is driving down data costs. Free online databases and open distribution of ready-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 agencies and operators still charging large amounts for imagery.

Software for handling and processing satellite imagery were previously few and far between, as well as complex and expensive, but are now 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 it becomes a central source of data for numerous disciplines, but cutting-edge computing, imagery and software prices often mean that course-running costs remain prohibitively high for institutions in low-income countries.

Increasingly, limitations in satellite-data applications have shifted from the technology acquiring the data to the techniques and data on the ground required to optimally exploit the information within the remotely sensed data. The conventional trade-offs in spectral, spatial and temporal resolutions, 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 a half a meter, high spatial resolution SAR imagery, laser imaging and detailed night-time data. Improvements in data processing and fusion could help eliminate cloud-obscured and night-time 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 multi-sensor satellites, the design directions in which smaller commercial satellites will head is less clear. The potential for real-time imagery has begun to be explored and there will undoubtedly soon be personalized imagery beamed to handheld devices to show users in real-time their position, traffic conditions or local weather at a destination of choice. Speculating further, the online availability of these imagery and others could facilitate a ”real-time” or “live” Google Earth. Such a resource potentially enables revolutionary studies involving the global tracking of ocean life, animals and human movement, which could facilitate, for instance, real-time disease epidemic models, dynamic traffic control and reactive conservation, but it also raises significant security and privacy concerns.

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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 the US space program risk creating a data gap in the Landsat imagery series and budget overruns have delayed the launch of the NPOESS project. At a time when unprecedented changes are taking place to 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 and stable supply of global data and ensure another 50 years of continuous measurements, stunning images and a deeper understanding of the Earth.