PHYSICS TODAY

DOI:10.1063/PT.5.4026

28 Oct 2016 in Research & Technology

Satellites: Invaluable eyes in the sky

Space-based sensors, which acquire measurements of the atmosphere above even the most remote places on Earth, are used to improve weather and climate models.

Ethan Nelson

On 24 October 1946, a repurposed V-2 rocket fitted with a 35 mm motion picture camera launched from White Sands Missile Range in New Mexico. After reaching an altitude of more than 100 km, the rocket crashed back to Earth—with hundreds of pioneering photographs stored in its film canister. For the first time, humans had observed Earth’s atmosphere from space.

In the ensuing 70 years, numerous satellites have been designed, built, and launched to measure Earth’s atmosphere from above. Instruments collect data on everything from atmospheric temperature and humidity to land cover or surface winds over the ocean. By leveraging satellite-based sensors, scientists have gained unprecedented observational coverage of Earth that is impossible to achieve with sensors on the ground.

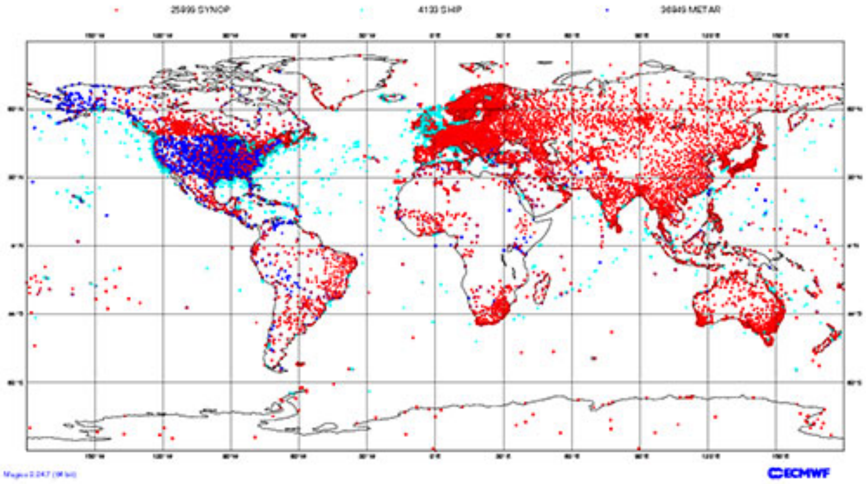
But observations taken thousands of kilometers above Earth's surface do not simply translate into measurements for use in weather forecasting and climate projections. The entire process of obtaining observations from afar and then reliably interpreting them is known as remote sensing.

As the name suggests, remote sensing involves measuring a variable from a distance. When you see a thunderstorm on the horizon and assume it is raining in a nearby city, you are remotely sensing that storm cloud and the associated precipitation. Indeed, geologists, astronomers, and even speed-monitoring police officers rely on remote sensing. In the most basic sense, we remotely sense objects every time we make use of our vision or hearing.

Because it is difficult to observe the entire atmosphere from every point on Earth's surface, remote sensing is essential to understanding our climate. Observations used by the European Centre for Medium-Range Weather Forecasts (ECMWF) in its weather model for a given day are shown in figure 1. Figure 1a shows the available surface observations from weather stations and ships. Most of those observations are concentrated over land and mainly in populated areas; large areas over the ocean, however, are unobserved.

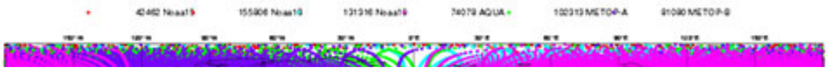
(a)

ECMWF Data Coverage (All obs DA) - Synop-Ship-Metar
07/Apr/2016; 00 UTC
Total number of obs = 66881



(b)

ECMWF Data Coverage (All obs DA) - AMSU-A
07/Apr/2016; 00 UTC
Total number of obs = 587055



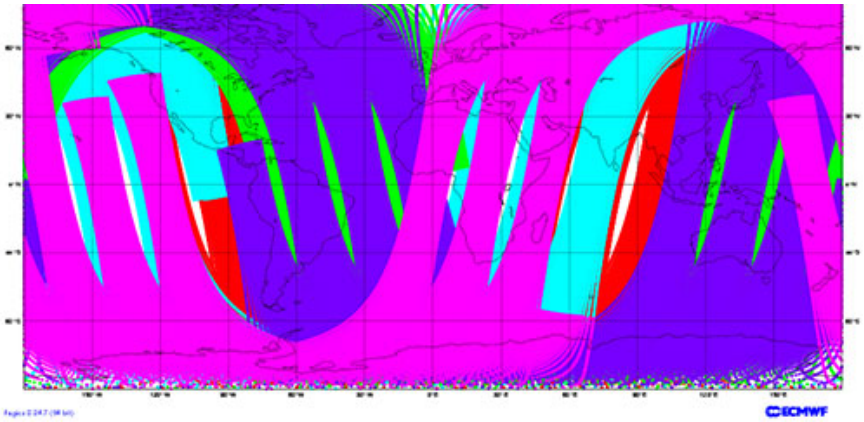


Figure 1. Satellites provide many more data points for forecasters than do surface-based stations. Daily observations from **(a)** the ground and **(b)** the Advanced Microwave Sounding Unit-A satellite are shown for the European Centre for Medium-Range Weather Forecasts model on 7 April 2016. Credit: ECMWF

Figure 1b shows the coverage provided by one type of satellite instrument. Not only are the number of observations a factor of 10 higher than the number of observations in figure 1a, but also the spatial extent of the observations nearly covers the globe. Dozens of satellites provide a similar amount of data that are assimilated into weather prediction models daily. Remote sensing is therefore vital to observing and understanding the atmosphere.

Remote sensing instruments

Atmospheric scientists approach the venture of remote sensing in different ways, and the methodology depends largely on the type of instrument used. Active sensors—as the name implies—send out some sort of signal or pulse and record the response as the signal bounces off the target. Passive sensors only observe or listen for a signal already present. In either case, the sensors exploit electromagnetic radiation to generate observations.

Radars and lidars are two examples of active sensors. Each transmits a pulse of energy and listens for both the timing and intensity of the returning signal. Particles closer to the instrument will be detected sooner than those farther away because the radiation has less distance to travel. Active sensors are good, for example, at measuring water and ice droplets (called hydrometeors) in the atmosphere, and thus provide the familiar radar image that you see regularly on the evening news. What you are less likely to have seen is a corresponding downward-looking vertical perspective of hydrometeors provided by radars in orbit aboard satellites; however, the same principles apply.

Radiometers and imagers are examples of passive sensors. Similar to feeling the radiant energy of a nearby fire, passive sensors measure the amount of electromagnetic radiation naturally emitted from the surface or from air and hydrometeors in the atmosphere. Passive sensors can also measure the amount of sunlight reflected by clouds and the surface.

Along with a myriad of other instruments that are used in remote sensing, radars, lidars, radiometers, and imagers provide atmospheric scientists with substantial, useful data. Passive instruments on satellites are more common, given their relatively cheaper cost and lower power requirements. Just as a camera using flash drains its batteries faster than one with the flash turned off, so too do active instruments require more battery capacity to operate.

Retrievals from active and passive sensors

Information from active and passive sensors can tell us a lot about the atmosphere. But deducing physical characteristics of the atmosphere or surface from those sensors requires some type of algorithm or retrieval methodology.

The early-20th-century meteorologist Lewis Fry Richardson imagined that weather models would be completed by a room of 64 000 people solving equations that govern the atmospheric system. The same concept could apply to calculating variables such as temperature, radiative heating, and water mixing ratios from the massive amount of observations coming from satellites. However, today's meteorologists have the advantage of advanced computers, which can be told or taught how to use remotely sensed variables to determine information about Earth's atmosphere and surface.

To understand the process of “telling” the computer a relationship, consider an electric stove. When the power is turned off and the stove is at room temperature, the heating element is dark brown or black. Turn the temperature on low, and the element will probably shift to a lighter brown. Continue to increase the temperature, and the element transitions from brown to orange to bright red. The increasing color results from more and more electromagnetic radiation being emitted as the element heats up.

From those stovetop observations, you could develop a burner color versus temperature relationship. If you connect a computer with a camera that views the element and then program in the relationship, you’ve created a passive sensor algorithm. In a similar way, scientists build algorithms that can estimate the atmospheric temperature profile based on the vertical distribution of radiation emission.

An alternative to empirically derived relationships is a physically derived retrieval. For example, meteorologists can use the reflectivity Z measured by radar at a given location to calculate the distribution of raindrop size, which in turn can be used to determine the rainfall rate. Using a relationship that defines the distribution of hydrometeors by size $n(D)$, the reflectivity Z measured follows

$$Z = \int_0^\infty n(D) \cdot D^6 dD,$$

with D the diameter of hydrometeors.

Rain rate is a measure of the flux, or flow, of water onto an area of ground over a given time period—a product of the hydrometeor size distribution, the volume of each hydrometeor *V(D)*, and the speed with which the hydrometeors fall *v(D)*. All of those variables depend on the size of the drop (for example, a larger droplet will generally fall faster than a smaller droplet), so the rain rate can be written as

$$R = \int_0^\infty n(D) \cdot V(D) \cdot v(D) dD.$$

By combining the equations, we can physically relate a measurement of reflectivity from a place off in the distance to the rainfall occurring there. An example of the relationship between reflectivity and rain rate, using a sample drop size distribution relationship, is shown in figure 2.

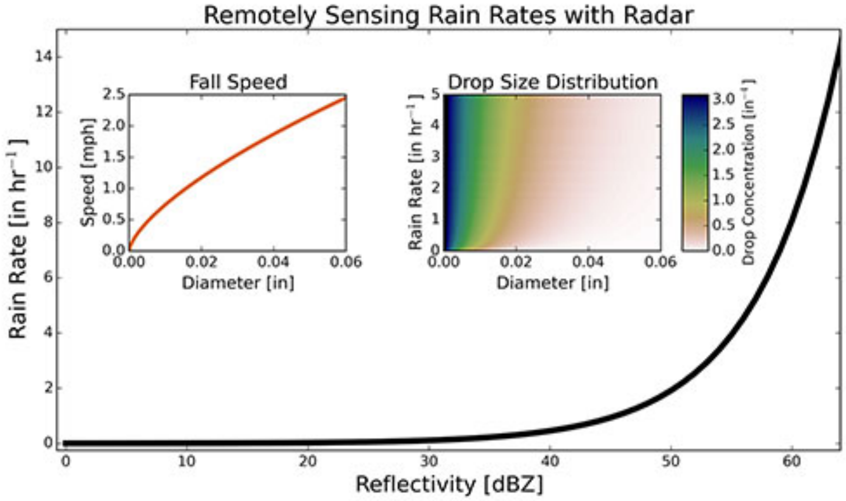


Figure 2. The radar reflectivity–rain rate relationship shown in the main graph is derived using the connections between drop diameter and fall speed (inset left) and drop diameter and rain rate (inset right). The code for the figure is available here.

Beyond physical and empirical algorithms, meteorologists also use Bayesian schemes. Bayesian retrievals are methods that take advantage of the inferences in Bayes’s theorem. Given measurement information and the probability distribution of prior observations, computers are trained to determine the most probable solution. In one instance, by matching passive instrument observations with corresponding active radar measurements of rainfall, a Bayesian algorithm built a database that trains passive instruments to estimate rainfall rates based on those from previously collocated observations.

Accounting for uncertainties

In all methods of retrieval, there is potential for uncertainty, bias, or error in the algorithm system. That is at the root of what is called the inverse problem: Indirect measurement can never be as accurate as direct measurement.

Uncertainties derive from such factors as noise in the measurements and faulty assumptions or methodology. The burners of one kitchen stove may have a reliable color response to changes in temperature, but that relationship may not hold for all stoves or in all conditions. For a remote sensing measurement to be useful, the uncertainties in the product must be qualified and understood properly. To provide a suite of atmospheric observations and to better estimate the uncertainties in associated algorithms, scientists often rely on data taken from intensive but limited field observing campaigns.

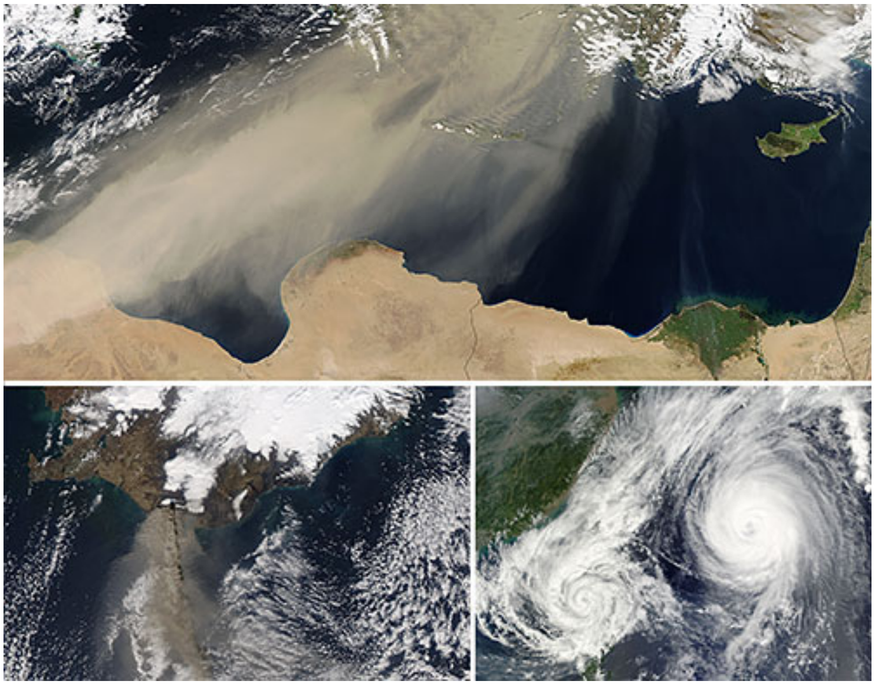


Figure 3. A collage of visible satellite images from the Moderate Resolution Imaging

Spectroradiometer instrument. Clockwise from top: Saharan dust transported over the Mediterranean Sea; a superposition of two tropical cyclones near the East China Sea in 2009; the ash plume erupting from Iceland's Eyjafjallajökull volcano in 2010. Credit: NASA Earth Observatory

Despite the care required to interpret the data, satellite remote sensing has enabled us to observe the Earth more intensively than at any other time in human history. We can gain information about the atmosphere by employing algorithms based on observed and theoretical relationships—or we can simply observe beautiful pictures of our planet like those in figure 3. Nevertheless, the importance of satellites in monitoring the climate relies on a continuous record of observations over a long period of time. And the more data we collect, the better we can understand and predict our environment.

Ethan Nelson, a PhD fellow at the University of Wisconsin–Madison, is studying the effects of warm rain through remote sensing under the direction of Tristan L'Ecuyer.

DOWN-TO-EARTH