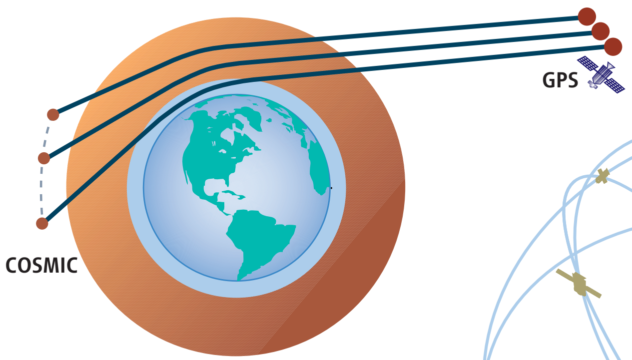
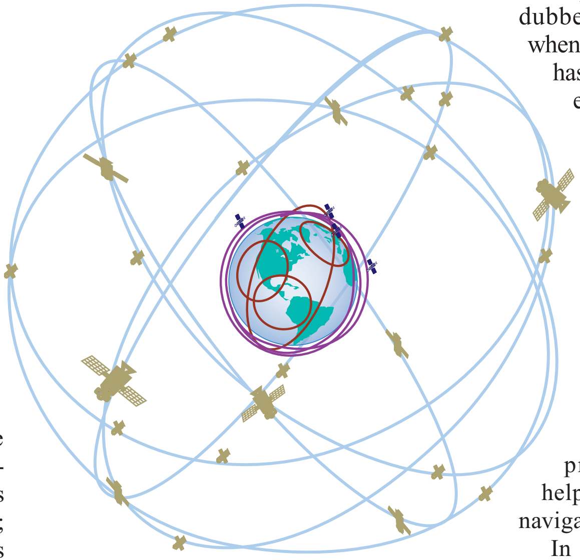
ATMOSPHERIC SCIENCE

Technique From Outer Space Takes On Earth Observation

By keeping a close eye on GPS satellites, a team of researchers hopes to measure atmospheric temperatures on the cheap

Weather forecasting has come a long way since the era of dog-eared almanacs and barn-door barometers. Nowadays, numerical models running on the world's most powerful supercomputers crunch data from a host of sources that include ground-based weather stations, radar, aircraft, and satellites. But one key type of information—vertical profiles of how temperature, pressure, and water vapor vary through the atmosphere—is still gathered the same way it has been since the 1930s: with weather balloons.





Locked on. Cosmic satellites (blue, *right*) track signals from GPS satellites (beige, *right*) and log how the atmosphere bends them (*above*)—data that reveal temperatures.

Every day at noon and midnight, hundreds of them rise from stations around the globe bearing small instrument packages skyward. Each "radiosonde" beams down data as it climbs to an altitude of about 30 kilometers; then the balloon bursts, and the instruments parachute back to Earth. The system isn't perfect. The balloons fly only twice a day and are concentrated over the populated Northern Hemisphere. The oceans and the south are data deserts. It's wasteful, too. The U.S. National Weather Service estimates that of the 75,000 radiosondes it launches every year, 80% disappear without a trace. So far, however, no other data-gathering method can match their accuracy and vertical resolution. "Radiosondes are the gold standard," says atmospheric physicist Sean Healy of the European Centre for Medium-Range Weather Forecasts (ECMWF) in Reading, U.K.

That may be about to change, thanks to six simple satellites collectively known as Cosmic, due for launch in mid-April. Each carries a Global Positioning System (GPS) receiver, a communications link to the ground, and not much else. The receivers will lock onto transmissions from the U.S. Air Force's constellation of 24 GPS satellites and watch how the atmosphere bends the radio waves. From that information, each Cosmic spacecraft can get a vertical profile of the atmosphere's temperature, pressure, and water content above one spot on Earth's surface with surprising accuracy and vertical resolution. All together, the fleet will make 3000 "soundings" a day, evenly distributed across the globe.

Cosmic is an academic research project largely financed by the Taiwanese space agency, but its proponents expect it to have a major impact on day-to-day weather forecasts: Meteorologists at the world's major weather agencies are poised to receive Cosmic's data. "It will be a major breakthrough in the science of climate, … [providing] a whole new scale of accuracy," says atmospheric chemist James Anderson of Harvard University. Anderson likens current efforts to measure the state of the climate to trying to reconstruct a rugby game from five or six fuzzy photographs. Cosmic data will be like having "thousands of high-resolution pictures" of the match, he says.

For atmospheric scientists used to large, expensive Earth-observation satellites operated by the likes of the U.S. National Oceanic and Atmospheric Administration and EUMETSAT, Europe's weather satellite operator, GPS sounding is an unknown quantity. "For most, it is still a strange idea from out in the wilderness," says sounding pioneer Thomas Yunck of NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California. But he predicts Cosmic data will be "far beyond anything we have imagined" and will lead to a "major sea change in atmospheric sensing." Healy agrees: "When people see the data and the quality of it, they will be won over."

From outer space

The methods that Cosmic will use were first forged deep in space. In the early days of planetary exploration, researchers realized that as a spacecraft passed behind a planet during a flyby, the planet's atmosphere would briefly refract radio signals passing through it en route to Earth. In the early 1960s, teams at JPL and Stanford University worked out how to use the radio signals to deduce information about planetary atmospheres. The technique, dubbed radio occultation, made its debut when Mariner 4 visited Mars in 1965, and it has now probed the atmosphere of almost every planet in the solar system and many of their moons.

Closer to home, however, radio occultation had a harder time finding a niche. Researchers weren't sure that the new technique would be more accurate than established methods for studying the atmosphere. What's more, to achieve global coverage, an occultation-based system would need a constellation of satellites transmitting radio signals—an unthinkably expensive proposition until the U.S. Air Force helpfully began lofting GPS satellites for navigation in the 1980s.

In 1988, a team at JPL, including Yunck, won approval for a proposal to put GPS receivers for radio occultation onto all the craft of NASA's Earth Observing System and other satellites, but the plan fell victim to budget cuts. Researchers at the University Corporation for Atmospheric Research (UCAR) in Boulder, Colorado, had better luck with a National Science Foundation–funded project to launch a proof-of-principle receiver. The GPS/MET instrument took to the skies in 1995 aboard NASA's Microlab I satellite; it exceeded everyone's expectations. The experiment produced data for 2 years, and UCAR researchers achieved vertical resolution of 100 meters and temperature accuracy of better than a degree. "GPS/MET was a great success," says Bill Kuo of UCAR, director of the

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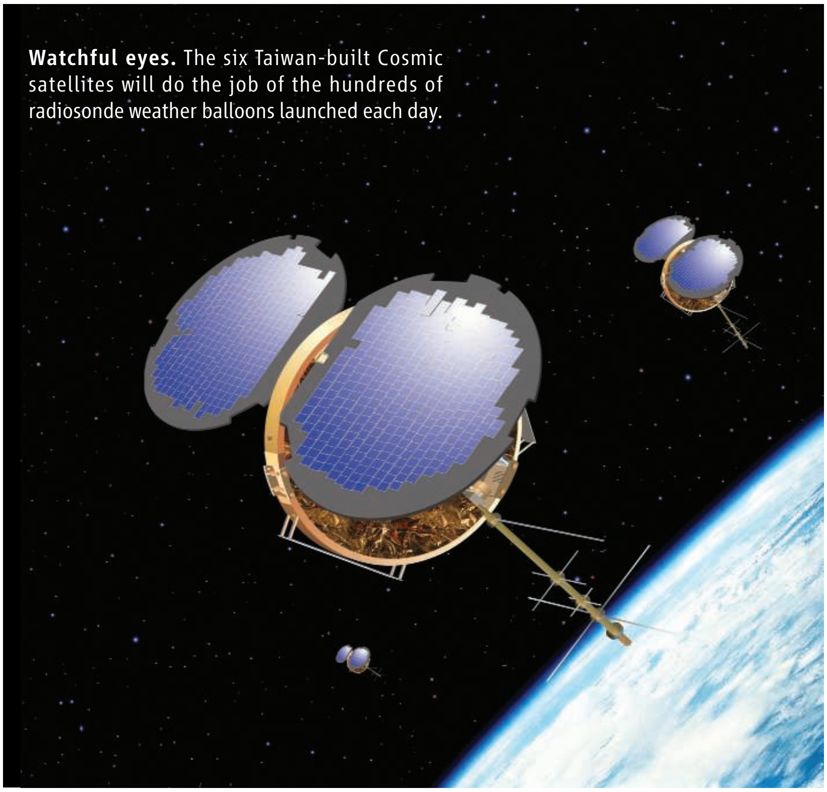

Watchful eyes. The six Taiwan-built Cosmic satellites will do the job of the hundreds of radiosonde weather balloons launched each day.

Cosmic project. NASA then sponsored receivers to fly on the Danish Ørsted mission, South Africa's Sunsat, Argentina's SAC-C, and Germany's CHAMP.

CHAMP, which has operated in low Earth orbit continuously since 2000, gave researchers a chance to hone occultation into a precision instrument. To take a sounding, a GPS receiver on the satellite locks onto the signal from a GPS satellite descending toward the horizon. As it gets lower, the atmosphere bends the path of the signal and delays its progress, until the limb of Earth cuts it off altogether. The whole process takes between 1 and 2 minutes.

CHAMP ignores the navigation information that the signal carries and just looks at the underlying radio wave. "The receiver counts cycles, looking for a Doppler shift in the frequency," says JPL's Ian Harris, who worked on the Cosmic receivers. The shifts give the bending angles; from the angles, researchers can calculate the atmosphere's refractivity at each altitude. A computer model of the atmosphere can then work out a profile of temperature and water vapor from the refractivity. "There is real art and elaborate theory in extracting the data," says Yunck.

Despite the evidence that GPS sounding worked and produced valuable data, researchers found it hard to get backing for a constellation of craft to produce enough regular soundings for weather forecasters. "We tried to talk to U.S. agencies, but they were focused on big, established missions," says Kuo. Many atmospheric scientists work for decades on large missions that cost $400 million apiece. A science-grade GPS receiver hardened for space, by contrast, costs only a few hundreds of thousands of dollars, and the whole of Cosmic costs $100 million. "Cheap sounding missions are potentially a threat, so the community is suspicious," says Kuo.

Kuo, who was born in Taiwan, discovered through his contacts there that Taiwan's fledgling National Space Organization was looking for projects to help build up the country's space industry. In 1997, a deal was signed in which Taiwan would assemble the Cosmic satellites with JPL-designed receivers, and UCAR would provide the ground processing and archiving. Taiwan is footing 80% of the bill.

With funding from various U.S. agencies, UCAR has worked hard to streamline the processing so that the data can reach forecasters as soon as possible. With ground stations in Fairbanks, Alaska, and Kiruna, Sweden, each of the satellites can download data once per 100-minute orbit. Transfer to Boulder takes 5 minutes, and processing takes 10 to 15 minutes, so Kuo predicts that data can be in the hands of weather agencies on average 90 minutes after the sounding was made. The U.S. National Centers for Environmental Prediction, ECMWF, and the U.K. Met Office hope to start receiving the data a couple of months after Cosmic is launched. "Researchers love this stuff and are well prepared for the data," says Yunck.

Climatologists, too, are looking to GPS sounding for a solution to a long-standing problem in their field: getting consistent measures of the atmosphere. Over years and decades, instruments drift away from calibration, and new instruments may be biased differently from the ones they replace. Cosmic data don't have those problems, says Harvard's Anderson, because the frequencies the receivers record are basic measurements. "There are no fudge factors, no conversions," Anderson says. "These very high accuracy global measures produce a climate record of Earth that is permanent and unequivocal."

If GPS sounding enthusiasts are right, soon the weather will hold fewer surprises, and climate researchers will be building up an accurate three-dimensional map of the atmosphere that will keep them busy for decades. Already, some are looking ahead to an expanded "Cosmic 2" constellation or to new efforts as other agencies jump on the bandwagon. "The success of Cosmic could stimulate a multisatellite mission in Europe," says Jens Wickert of the CHAMP team at Germany's GFZ geosciences research center in Potsdam. In a possible sign of what's to come, EUMETSAT is putting a single GPS receiver on its Metop-2 satellite, due for launch in June. This will be the first truly operational radio-occultation receiver.

Before fleets of other sounding spacecraft can take wing, however, Cosmic will have to show what can be done with a few simple satellites and some GPS receivers. JPL physicist James Zumberge, for one, is betting on the underdog. "Radio occultation has a bright future," he says, "and Cosmic is the next step in that future."

–DANIEL CLERY

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