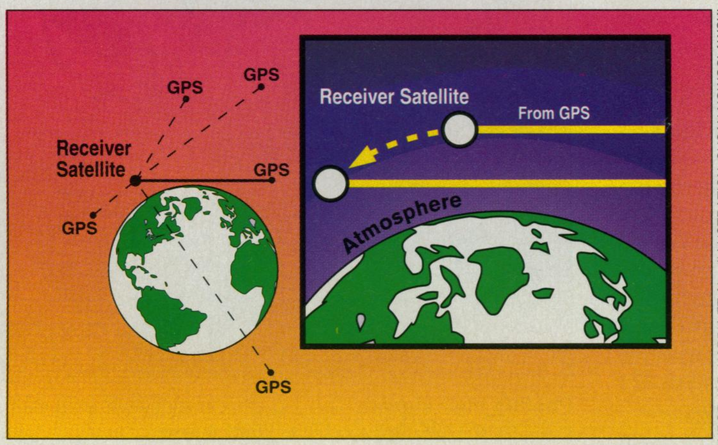
A Military Navigation System Might Probe Lofty "Weather"

How do you keep an eye on a couple of hundred billion cubic kilometers of Earth's atmosphere as it changes from day to day and year to year? For 30 years the answer has been to go into space, but even satellite monitoring has had distinct limitations. Now there is a prospect of large-scale measurements from space on the grandest scale ever using the Department of Defense's (DOD) multisatellite Global Positioning System (GPS). DOD lofted GPS radio beacons to guide troop movements and weapons, not to do science. But even as GPS helps wage war, geodicists have sponged off it in order to track the centimeters-per-year drift of continents (see article on page 333). Now it's researchers looking upward toward the stratosphere and beyond who are trying to twist GPS to their own purposes by using its radio signals as probes of atmospheric properties.

Some researchers hope GPS will track the progress of greenhouse-induced changes in the stratosphere—where they should far exceed those at the surface—with unprecedented accuracy. Other proponents see GPS as the first means of routinely producing "weather" maps of the ionosphere—the ionized upper atmosphere between altitudes of 80 and 600 kilometers, which acts as a vital reflector of radio transmissions and possibly as a link between the sun and climate. Atmospheric scientists stress, however, that extracting data about specific atmospheric layers from the GPS signal won't be easy. "If it works to the extent claimed, it could...be very useful for monitoring," says Francis Bretherton, a global change specialist at the University of Wisconsin. "[But] these things are often more complicated than they look."

Hardware. In outline, GPS atmospheric monitoring couldn't look much simpler. Sixteen of a planned 21 GPS satellites are already in place, at a cost to the DOD of $5 billion dollars, each of them beaming radio signals at two precisely controlled frequencies. Equipped with a shoebox-sized radio receiver, a soldier anywhere on Earth can pinpoint his position to within 10 meters or so based on the signals from three GPS satellites overhead (*Science*, 1 March 1991, p. 1012). Geodicists squeeze out an accuracy of a few millimeters over distances of hundreds of kilometers (*Science*, 26 June 1987, p. 1625).

For atmospheric studies, the GPS receiver would have to go into space, aboard another satellite. Then the timing of radio signals beaming from GPS satellites just as they rise or set behind Earth could provide a precise measure of atmospheric properties. Slicing through the atmosphere on their way from GPS satellite to the orbiting receiver, the signals would slow down by an amount that depends on the density of the atmosphere along the signal's path. In the case of the ionosphere, the signal's speed would depend on the abundance of electrons.



SOURCE: K.R. HARDY *ET AL.* ILLUSTRATION: SUSAN NOWOSLAWSKI

Eye on the sky. Monitoring how the radio signal from a Global Positioning System satellite *(top)* slows as it cuts deeper into Earth's atmosphere could reveal changes due to a strengthening greenhouse.

Determining the signal's slowing to the needed precision—a billionth of a second—would require accurate measurements of the position and velocity of both satellites and the changing frequency of the received signal. But the feat has already been achieved for other planets using signals from space probes like the Voyagers. Those precedents are encouraging to meteorologist Kenneth Hardy of Lockheed Missiles and Space Company in Palo Alto. "There are still some serious problems" in terrestrial applications, he concedes, but "we're reasonably confident we can do it for Earth since it's been done for other planets."

To confirm that the method is practicable, Hardy and Robert Kursinski of the Jet Propulsion Laboratory (JPL) have used computers to simulate GPS monitoring of atmospheric density—a quantity from which the temperature of the stratosphere or, in certain circumstances, the water vapor content of the troposphere could be estimated. Yam-Tsi Chiu of Lockheed, meanwhile, is thinking about ways of using the GPS signal to probe the state of the ionosphere. The three researchers are working toward a proposal for a one-satellite, proof-of-concept mission that could lead to a system of up to 24 tiny satellites called GPS/MET.

A close watch. The atmospheric properties GPS might probe are already being measured one way or another, but proponents expect that it will, in at least some crucial respects, do a better job. Ground-based radars and a few satellites are monitoring the ionosphere, notes Chiu, but the observations are so widely separated in time and space that on a global scale only a picture of long-term ionospheric "climate" emerges. Each GPS receiver, however, would profile the ionosphere 600 times a day at sites ranging from one pole to the other. That would be more like watching the weather than climate, says Chiu, which would help researchers unravel the ionosphere's interaction with sunlight and the overlying magnetosphere, as well as its impact on deeper layers of atmosphere.

Ironically, what might be exciting data to specialists in the ionosphere would be a major nuisance to those studying the stratosphere, which the GPS system would have to view through the ionosphere. The ionosphere affects radio signals far more than the stratosphere, so stratospheric researchers would need a highly accurate correction for ionospheric effects. The ionosphere's differing effect on GPS's two frequencies could in principle be used to make the correction, notes Kursinski, but the details still have to be worked out.

Suitably corrected for the ionosphere, though, GPS temperatures could have an accuracy of 0.2 K, compared with about 1 K for conventional satellites that measure temperature using infrared radiation emanating from below, according to Kursinski. And the GPS technique can yield a specific temperature for every kilometer of altitude, while vertical sounders are limited to a resolution of several kilometers. The accuracy of a GPS system might also be more stable than that of a satellite sounder, because the receiver could be calibrated every time it views a transmitter unobstructed by the atmosphere.

In the troposphere, GPS might seem to be getting in over its head. The troposphere contains so much water vapor that humidity and temperature both have great effects on the signal. Disentangling the two might prove difficult, though feasible, Hardy thinks, in the coldest and the warmest regions of the atmosphere—the tropics and the wintertime arctic, for example. And even when moisture and temperature variations can't be teased apart, the combination might provide a useful long-term measure of the state of the atmosphere that could anchor other less comprehensive measurements, Bretherton thinks.

As appealing as GPS looks for monitoring the lower and middle atmosphere, it isn't the only proposal for fine-scale, global probing. A satellite-borne infrared instrument now in the late stages of design could equal the temperature accuracy of GPS while measuring 10 trace gases, including ozone and water vapor, according to its U.S. principal investigator, John Gille of the National Center for Atmospheric Research in Boulder. Called the High-Resolution Dynamics Limb Sounder, the instrument would surpass the resolution of vertical-sounding satellites by looking toward Earth's edge rather than straight down, and it would have a low-noise design for greater accuracy. Launch is scheduled for 2002, if not sooner, as part of NASA's Earth Observing System.

But Hardy and Kursinski think the long-term stability of a GPS monitoring system might give it an edge. And considering the low cost involved, they think it deserves a try. Only $10 million would be needed for the trial mission they hope to propose, and a full 24-satellite system would probably cost less than $100 million to deploy. If the concept works, atmospheric researchers might share the use of GPS receivers on future commercial satellites for the cost of a bit of additional electronics. A small price to pay, they say, to harness a machine of war for the battle against global change.

–Richard A. Kerr

Cosmologists Search the Universe For a Dubious Panacea

Einstein was wrong once. In 1917, to keep the universe from collapsing under its own gravity, Einstein added to his equations of general relativity a constant that countered the inward pull of gravity with a universal outward push. The result was a universe that was unchanging in all directions, for all time—a universe that just sat there. A few years later, though, theorists and observers found that the universe does change—it expands. And it does this, they concluded, apparently without needing any extra push. To everyone's relief, the master quickly killed off his cosmological constant. But lately cosmologists have suspected that Einstein may have been wrong when he killed the constant, not when he created it. The extra push, they think, might have a role even in an expanding universe. And yet, cosmologists by necessity being among the subtlest of theorists, virtually none of them wants it.

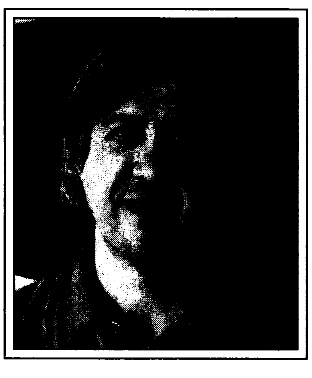
Why not? "It's ugly," says Princeton University theorist James Peebles. "It's an addition. If I were building a universe, I would not put in a cosmological constant." The simplest universe cosmologists can envision doesn't need this extra cog, which would act to infuse "empty space" with extra energy. But theorists may not get their way: The cosmological constant, like one of those late-night movie characters, won't stay dead.

In its latest incarnation, starting about 2 years ago, cosmologists realized that the constant could come in handy in ways that could never have been envisioned in 1917. Specifically, it might solve several of the field's worst embarrassments at once: the seeming shortfall of mass in the universe, the mysterious large-scale clumping of galaxies, and the mounting evidence suggesting that the universe might be younger than its oldest stars. A cosmological adjustment that could solve all those problems at once, though perhaps too good to be true, is surely too good to ignore. And that is spurring several groups to conduct the largest of large-scale measurements, scanning the farthest galaxies and quasars for signs of the constant.

The search is necessary because theorists alone can't set a value for the constant. General relativity, Einstein's theory of gravity, offers no clues about its value, says Michael Turner, a physicist at the University of Chicago and Fermilab, though the theory gives the constant "every right to be there." The so-called standard model of particle physics, which describes forces and particles operating at the smallest scales, does predict a value for the constant—but a patently improbable one. In the late 1980s, physicists using the laws of quantum physics to calculate how much energy would be dumped into empty space by the random quantum fluctuations of matter and energy came up with an astoundingly high value. The cosmological constant was so large, they found, that it would have blown the universe apart before gravity could collect matter into galaxies or planets. The very fact that cosmologists are around to debate the constant means that its value is close to, if not exactly, 0. And that poses a major problem for particle physicists, says William Press, an astrophysicist at the Harvard-Smithsonian Center for Astrophysics. Solving it, he says, will take "either a miracle or an unexplained principle."

"It's unnatural. It would be nice to get rid of it."

—Alex Szalay



JOHNS HOPKINS

A neat fit. While particle physicists wrestle with the question of where their theory went wrong, cosmologists have realized that just the tiniest fraction of the value from particle physics would solve three of their most pressing problems "with one fell swoop," as Michael Turner puts it. Princeton cosmologist Edwin Turner (no relation) agrees: "It could balance all the books at once." Just to keep things complicated, though, the cosmological constant would solve different problems in different ways.

Besides giving a push—adding "an extra springiness to the universe," as Edwin Turner puts it—the extra energy density would also have a gravitational effect. In the language of Einstein's theory of relativity, it would affect the curvature of the universe. That could solve one major problem in cosmology. Since the 1980s, for what Peebles calls "theoretical but nonetheless plausible reasons," theorists have more or less agreed that the universe is flat. But the gravitational effect of observable matter is at most 20% of what is needed for a flat universe. A nonzero cosmological constant could add the other 80%, substituting for the missing mass.

As for the second conundrum, maps drawn up in the last 2 years show galaxies clustered into ropes and sheets on scales of tens of