

WHERE I STAND

Daniel Kleppner

To come directly to the point, where I stand is N 42° 24.538', W 71° 10.575', give or take thirty meters. I am reasonably confident about this because Scout tells me so. Scout is a palm-sized package of electronics that slips easily into my coat pocket and is on speaking terms—or more precisely on listening terms—with the Global Positioning System. At the moment I am actually sitting rather than standing, though Scout doesn't notice the difference. Nevertheless it notices whether I am in my office, lab or home. And as I walk north across a field, the last numeral of its latitude indicator dutifully jumps by one digit whenever I advance two paces, marking my progress around the Earth in units of a thousandth of an arcminute. If I were lost trekking in the wilderness or sailing through far-off foggy shoals, Scout would be worth its weight in gold. (This is not much of a claim, since it weighs less than a pound.) But Scout is merely a harbinger of a technology that is just now coming of age.

The story of the Global Positioning System neatly illustrates two key issues of the current science policy debate: the relation of basic research to new technology and the relation of new technology to new industry. My interest in the GPS, however, is fundamentally personal. About a year ago I wandered into a marine supply store. Expecting to see coils of Manila rope, galvanized pumps and caulking irons—images remembered from my youth—I found instead an antiseptic shop where the rope was synthetic, the pumps were plastic, and everything was shrink-wrapped. As I was about to retreat, the letters *G*P*S* flashed from a countertop sign. The incongruity brought me up short, for when last I had heard of

the GPS, it was a military navigation system that required racks of electronics costing roughly a hundred thousand dollars. A bucket of hand grenades would have seemed less out of place in that shop.

The sign rested on a device somewhat smaller than a bread box, designed to withstand salt spray and rain, with a few buttons and a display screen. The device would show a boat's location to an accuracy of 30 meters, essentially anywhere. At the push of a button, the screen displayed the bearing and range to any of the ports in its almanac or wherever you specified. Its price was about fifteen hundred dollars. Not being a sailor, I would have ignored this wizardry, except that once upon a time I occupied a perch on this wizard's sprawling family tree.

This sudden discovery of my distant descendant triggered a memory from two wonderful undergraduate years at Cambridge University. My physics tutor, Kenneth F. Smith, one day explained to me the facts of magnetic resonance and said that it should be possible to make an atomic clock by frequency-locking an oscillator to an atomic hyperfine interval. If the clock were good enough, he added, it could measure the effect of gravity on time—the redshift of the Earth's gravitational field. That gravity alters time seemed incredible to me. It still does.

A little later, I entered Harvard as a graduate student just when Norman Ramsey had hit upon an idea for making a better atomic clock—a clock that might be accurate enough to show the gravitational red shift—by storing atoms in a “bottle.” The result of our research was the hydrogen maser, but we were not destined to observe the Earth's redshift. That honor went to Robert V. Pound and Glen A. Rebka, who used the Mössbauer effect rather than an atomic clock. Some years later, however, the redshift was measured to an accuracy of 0.01% by a group led by Robert F. C. Vessot, who used hydrogen maser clocks that were stable to

better than 1 part in 10^{14} during the two-hour experiment.

As an atomic clock, the hydrogen maser paid off in numerous unexpected ways. For radioastronomers, it played a crucial role in the development of very-long-baseline interferometry. It provided the long-term time base for detecting gravitational radiation from the binary pulsar PSR B1913+16 (see *PHYSICS TODAY*, April 1993, page 9), and it made possible the precise deep-space navigation needed for the spectacular Voyager flyby of Neptune a few years ago. Our international timekeeping system is based on a network of atomic clocks, cesium atomic-beam frequency standards that are often assisted by hydrogen masers.

However, the most spectacular payoff from atomic clocks is the GPS. Maintaining precise and reliable time standards is at the heart of the system. The GPS employs 24 satellites that carry atomic clocks and broadcast timing signals and ephemeris data. Each satellite carries up to four cesium and rubidium clocks. The clocks are periodically updated from a ground-based station in Colorado that keeps the system synchronized.

A GPS receiver decodes the timing signals from several of the satellites. By interpreting the arrival times, the receiver determines latitude, longitude and altitude with an uncertainty that can be as small as 10 meters. By using the GPS in a differential mode, even higher precision is possible for applications such as geodesy or surveying. Differential GPS can provide subcentimeter accuracy over distances of hundreds of kilometers.

Applications for the GPS are proliferating. An acquaintance recently faced the problem of locating land markers in a desert area, a task that a surveyor offered to carry out for \$1700. Instead, he bought a GPS device that allowed him to drive directly to each marker. The cost: \$800. However, the GPS has more serious applications: air avoidance systems, emergency rescue, nationwide truck and freight-car tracking,

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and navigation of vehicles through the labyrinths of cities, to mention some of its more prominent roles. You may recall from an early James Bond film the Aston-Martin in which Bond pursued Goldfinger. Among the car's many gadgets was a pop-up map that showed its location. That little bit of fiction is becoming a reality. GPS receivers on microchips are being integrated with databases of maps and street directories. When these can be installed in autos inexpensively, practically everyone will want one.

As a case study for science policy, the GPS provides a useful lesson in why basic science is a good investment and in what is needed to capitalize on the returns. Without atomic clocks there would be no GPS, though at the time the clocks were conceived nobody dreamt of a satellite-based global navigation system. Possibly this was because the required precision was about a million times higher than the state of the art, but more likely it was simply because there were no satellites. The driving force for developing atomic clocks—at least in my case—was to explore general relativity, a subject that would rank pretty low on any list of useful research. If the nation's goals for science are to include generating the revolutionary advances that create new industries, then a reasonable investment in basic research—research propelled by scientific interest irrespective of possible applications—would seem to be a wise strategy.

Basic research, however, was only a tiny part of the GPS story, hardly more than a drop in the bucket. The cost of the research was trivial compared with the enormous investment required to develop a useful new technology: satellites, microelectronics, time transfer techniques and modern data processing methods. Above all, development of the GPS required sustained support for years. The atomic clock research traces back to the 1950s and '60s. The GPS was initiated by the Navy in the 1970s and taken over by the Air Force in the early 1980s. The Air Force succeeded brilliantly, developing the GPS into an operational system not only for military use but also for civilian applications.

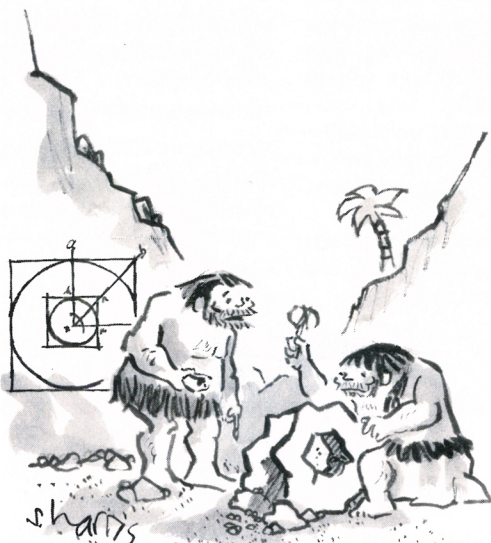
With the launching of the final GPS satellite last June, the Air Force presented the US with a new

industry on a silver platter. The commercial market for GPS devices is in the early stages of exponential growth. One recent study projected total sales of about \$5 billion by 1996. How much of the payoff will be reaped by the US is another matter. The engineering, packaging and marketing that are essential for developing the GPS into an inexpensive mass-market product may come from Japan.

Beyond any economic payoffs, however, the GPS will generate price-less benefits in rescue operations and other emergency services. Nevertheless, every advance in technology carries risk, and the GPS is no exception. The GPS could simplify the lives of smugglers or be employed by fanatics to make guided missiles. There is also a more subtle cost for this new technology. Barring gross carelessness, becoming lost during a mountain trek or while sailing off some strange coast will become a thing of the past. In providing that safety net, the GPS diminishes the romance of the wilderness. Rationally, saving lives is worth some sacrifice of wilderness romance, though nostalgia for nature is not likely to be rational. In any case, it is too late to turn back the clock. But who would want to turn back such a clock?

* * *

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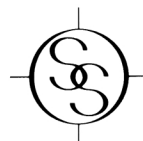
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