It was good to see Neil Ashby's article about general relativity and the global positioning system. Let me add a few historical details.

In 1965, I landed a position with Aerospace Corp in El Segundo, California; I had completed a PhD in general relativity some years earlier. Aerospace Corp had become involved in developing what was eventually to become the GPS, and W. Begley of the tracking and radar department asked me to do a study of possible relativistic effects on clocks carried by satellites.

The project was classified, so all I was told was that the military had become very interested in setting up an ultraprecise navigation system. I was happy to help by writing a research report; a brief, unclassified version of it was later submitted for publication.[1]

Many years later, pocket-sized GPS receivers hit the civilian market, and I began to realize the full implications of my research. I could finally tell my wife what I had been up to 30 years before!

It is remarkable that the GPS is presently the only practical application of Einstein's gravitation theory. I urge that the general public be made more aware of this very useful result of a very abstract physical theory.

Reference

1. W. J. Cocke, *Phys. Rev. Lett.* **16**, 662 (1966).

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Ashby replies: Dieter Proetel raises the very interesting question of whether the propagation speed of gravity, c_g, can be observed by accurate position measurements on satellites orbiting Earth. A clear answer cannot be given without also considering retardation effects from all important sources in the system, such as Earth, the Sun, and the Moon. Some terms in the approximate solutions of Einstein's field equations for the Solar System resemble the retarded Liénard–Wiechert potentials of electrodynamics. One can therefore obtain estimates of perturbations that are due to retardation by changing the speed c in such terms to a propagation speed c_g that is different from c. Electromagnetic waves that propagate with speed c are universally used, however, to make meaningful position and timing measurements in Earth's neighborhood. One way to approach the problem is to introduce normal Fermi coordinates, which are simple to interpret in terms of proper distances and proper times.

If the propagation speed for gravity is c_g, one finds, after transforming to normal Fermi coordinates, several small new orbital effects that are proportional to the quantity $Q = [(c/c_g)^2 - 1]$. Such a form for the orbital perturbations results from a combination of many relativistic effects: Lorentz contraction, resynchronization of local clocks, rescaling of lengths due to external potentials, relativistic precession of axes, and so on. The calculation is lengthy.[1]

When $c = c_g$, Q vanishes. There are then no surviving retardation corrections to the relativistic equations of motion of a satellite as it orbits Earth, to the order $1/c^2$ of the calculation. This finding is consistent with the analysis by Steven Carlip,[2] who points out that such cancellations occur as a result of velocity-dependent terms in general relativity. He also says that, for a uniformly moving source, the force is directed toward the instantaneous, rather than the retarded, position of the source. Similar effects occur in electrodynamics.

Even if c and c_g are unequal, the coefficients of Q are discouragingly small. Considering only the Earth-Moon-satellite system as point masses, the coefficients of Q that correspond to corrections to lunar tidal displacements of Earth-orbiting satellites are far smaller than a millimeter. Furthermore, observations of the orbital decay of binary pulsars[3] imply $Q < 0.02$. It thus appears that retardation effects from the Moon's gravity field will be extremely small and difficult to detect. A more attractive possibility would be to look for retardation effects from the gravity field of Earth or the Sun on more rapidly moving satellites such as LAGEOS (Laser Geodynamic Satellite), for which the coefficients of Q are considerably larger—a few centimeters. Some years ago, I discussed this possibility with John Ries of the Texas Center for Space Research. He analyzed some LAGEOS data with retardation effects from Earth's and the Sun's gravity included, but found that such effects were too small to discern.

References

1. N. Ashby, B. Bertotti, *Phys. Rev. D* **34**, 2246 (1986).
2. S. Carlip, *Phys. Lett. A* **267**, 81 (2000).
3. J. H. Taylor, *Rev. Mod. Phys.* **66**, 711 (1994).

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On the Chemical Purity of Marine Microfossils

As a paleontologist, I was pleased to see the 35-million-year-old shell of the planktonic foraminiferan *Cribrohantkenina inflata* grace the cover of Physics Today (December 2001; story on page 16). Calcium carbonate–secreting microfossils are a powerful proxy for estimating sea-surface temperature change through time using stable oxygen isotopes. Another challenge that biogeochemists and geoscientists face is the alteration of in vivo isotopic values by mineral and chemical changes after an organism's death. Implicit in any isotopic analysis using calcite shells, or fossil mammal teeth, or even dinosaur bones, is the assumption that the original stable isotopes survived the passage of millions of years.

A hemisphere away from the late Cretaceous marine localities of Paul Pearson's work,[1] dinosaur bones lie buried in late Cretaceous clays above the Arctic Circle on the North Slope of Alaska.[2] They are so well preserved that an oil geologist in the 1960s originally identified them as the fossil remains of Ice Age mammals. A collection of those bones is cataloged in the University of California Museum of Paleontology. Under high magnification, the Alaska fossils reveal a beautifully preserved system of bone cells that are identical to the micron-scale architecture of a modern vertebrate bone. Similar to the Pearson group's foraminifera, the dinosaur bones are entombed in clay sediments and do not appear altered by secondary remineralization or recrystallization. Microbeam particle-induced x-ray emission analysis revealed, however, that the bones showed significant postmortem enrichment by metals, primarily iron and manganese, more than 10^4 times greater than in the bones of modern crocodilians and birds (a dinosaur's closest living relatives).[3] Clay surrounding the Alaska dinosaurs was also markedly enriched in these metals from the burial environment.

Understandably, such factors are