A snag in space-time

"To approach Einstein's general theory of relativity, you have to change the way you think. It touches the imagination."

Ignazio Ciufolini
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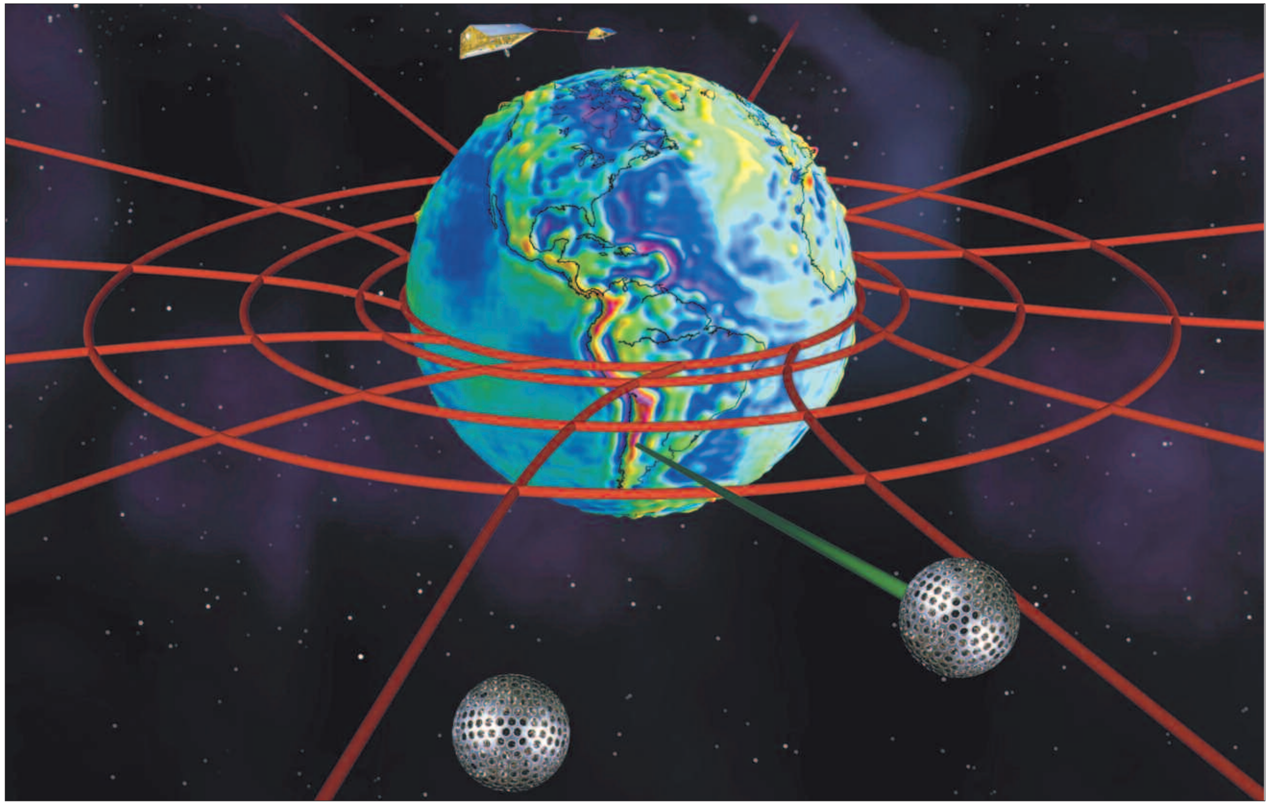
by Stephanie Renfrow

Einstein's general theory of relativity is a bit like a handle attached to a very large and mysterious object; when you grab on to the handle and tug, a whole bunch of unexpected possibilities come along with it. Ignazio Ciufolini, an astrophysicist who specializes in general relativity, said, "To approach Einstein's general theory of relativity, you have to change the way you think. It touches the imagination."

Einstein's theory helps provide a framework for physicists who have dedicated their careers to exploring questions that capture the human imagination: Can time flow backwards? Is the

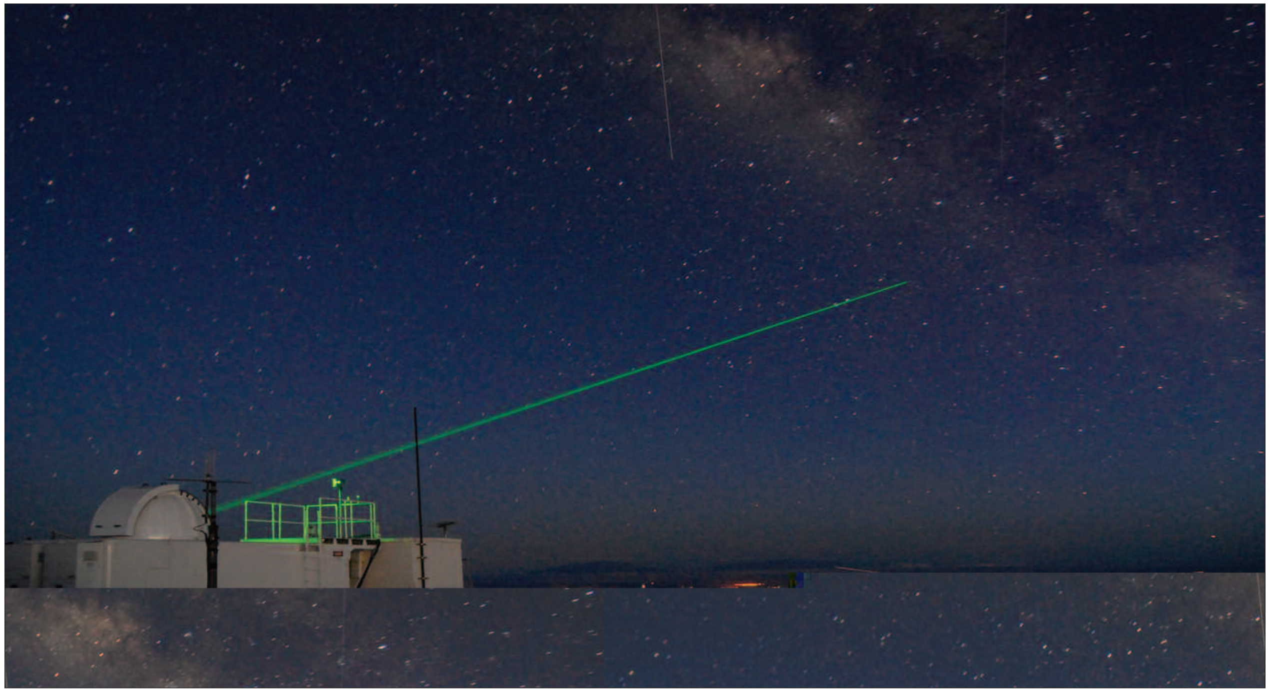


An artistic rendering shows that Earth's rotation has dragged space-time with it. A particle dropping from infinity towards the center of the planet would not fall in a straight line; it would be dragged along a curved path. In the foreground, the Laser Geodynamics Satellites (LAGEOS) spin in an orbit high above Earth. In the background, the Gravity Recovery and Climate Experiment (GRACE) satellites pass over Earth; their data have revealed the detail in Earth's gravitational field, shown as color relief on the surface. Warmer colors indicate stronger gravity, and cooler colors indicate weaker gravity. (Courtesy F. Ricci and I. Ciufolini, globe by GFZ Potsdam) universe infinite? What happens if you get sucked into a black hole? The theory also has implications for slightly more mundane questions, such as how to determine accurate satellite orbits around Earth or the most efficient way for a probe to travel through outer space to visit other planets.

But do we even know that the general theory of relativity is real? "One couldn't believe it to be true if it were not for the math and experiments that have been done. Reality is much more complex than our everyday experience makes us think," Ciufolini said. "Scientists have seen an incredible number of tests showing relativity to be true." Ciufolini would know; he and fellow scientist Erricos Pavlis have focused their research on measuring a particular effect predicted by Einstein's theory. The effect, called frame-dragging, occurs when a massive rotating object drags particles along with it, causing them to skip through space and time in an unexpected way. But how on Earth can scientists measure that?

Frame-dragging and time

One way to observe frame-dragging would be to put two clocks high up in space near Earth, then send them in opposite directions on the same path around Earth. Ciufolini said, "When the two clocks complete a full circle and come back to where they started, they'll arrive at the same time, but the one that was going with the direction of Earth's rotation will show a later time than the one that went against the Earth's rotation." In other words, time goes faster with the planet's rotation and slower against the planet's rotation. "This is not a speed-dependent effect," Ciufolini said. "The clocks would have moved through space at the same very low speed. The change in the passing of time is simply because they were moving near a current of mass—generated by the rotating Earth—and that current of mass has dragged space-time around it."



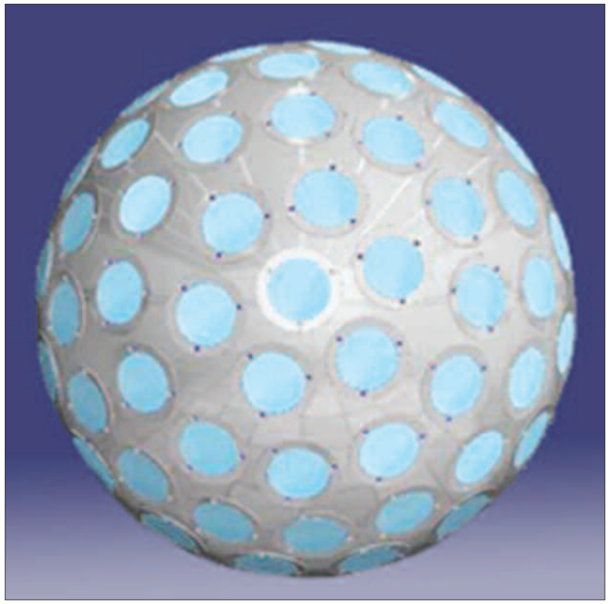
This laser-ranging station, at the Haleakala Observatory on the island of Maui, Hawaii, makes extremely precise measurements of laser-ranging satellite positions by bouncing pulses of laser light off the satellites as they orbit Earth. (Courtesy R. Ratkowski, University of Hawaii)

The effect of frame-dragging on the passage of time is strange, but it is real. Although the effect is quite minute around Earth, which has a relatively weak gravitational pull, frame-dragging affects time around dense objects much more. "For example," Ciufolini said, "if you exaggerated the clock analogy and placed twins who were born at exactly the same time in spacecraft going around a black hole in opposite directions in the same orbit—and if they circled many many times—there would be a real effect on their age," Ciufolini said. "The twin going against the rotation of the black hole would be younger than the twin going with the rotation because the black hole's current of mass caused time to skip."

However, performing either the clock or twin experiment offers logistical challenges that relegate them to the realm of the purely hypothetical. "So instead of clocks or people," Ciufolini said, "we used satellites."

Real observations of relativity

Ciufolini and Pavlis teamed up to devise a way to observe and even measure frame-dragging, using tools already available to them. Their work has spanned many decades, and the accuracy of their measurement has improved as their tools have improved. Their most recent effort corresponds with the effects predicted by



The planned Laser Relativity Satellite (LARES) will increase the precision of laser-ranging data, aiding studies of general relativity. LARES will be an extremely dense sphere of tungsten, covered by 92 corner cube reflectors. (Courtesy Italian Space Agency)

Einstein's theory to approximately 99 percent, with only 10 percent error. How did they do it?

To measure the effect of frame-dragging, the scientists used data from two satellite missions: the NASA Laser Geodynamics Satellites (LAGEOS) mission, and the Gravity Recovery and Climate Experiment (GRACE) mission, which was a joint effort between NASA, the Center for Space Research at the University of Texas at Austin, and the German Research Center for Geosciences (GeoForschungsZentrum Potsdam). Ciufolini and Pavlis retrieved the LAGEOS laser-ranging data from the NASA Crustal Dynamics Data Information System (CDDIS), and the GRACE data from the NASA Physical Oceanography Distributed Active Archive Center.

The LAGEOS mission was primarily designed to gather data to explore topics such as plate tectonics and the measurements of Earth's shape. The two LAGEOS satellites currently orbiting Earth are physically identical, and orbit at about 6,000 kilometers (4,000 miles) above Earth so that they experience as little of Earth's gravitational pull as possible. Pavlis said, "They are basically like cannonballs put up in space; they have no power or sensors and they don't transmit anything." So what do they do? Put simply, they reflect light back to Earth. Each LAGEOS satellite is a perfect sphere covered with 426 glass prisms. Light entering these prisms bounces back in exactly the same direction, in this case back down to international laser ranging stations polka-dotting Earth. The laser-ranging data (accurate to a few millimeters) gave Ciufolini and Pavlis a reliable measurement of the satellites' location in their orbit around Earth, accurate to a fraction of a centimeter. The scientists needed extremely precise measurements in order to observe the minute effects of frame-dragging on the orbits.

Accounting for gravity

However, before Ciufolini and Pavlis could measure the effects of frame-dragging on the LAGEOS satellites, they first needed to account for and remove other effects, like the pull of Earth's gravity on the two satellites. To account for gravity and other effects in their equations, the scientists used a model of Earth's gravitational field, based on data from the GRACE satellite mission. The GRACE mission, like LAGEOS, happens to rely on two identical satellites. However, the similarities between the missions end there. Pavlis said, "The GRACE satellites fly in a low 450-kilometer [280-mile] orbit so that the effects of Earth's gravitational pull will be as strong as possible to capture more detail." The twin satellites work as a team to maintain continuous data on the distance between them, sending radio frequency signals back and forth to each other and receiving Global Positioning System (GPS) signals; laser stations on Earth also track the satellites. As the satellites pass over the planet, features like mountains and bodies of water tug at them because of their varying densities, allowing the satellites to map the details of Earth's gravitational field. Pavlis said, "Using GRACE data improved the models of Earth's gravitational field by several orders of magnitude almost overnight, and that meant we improved the accuracy of our measurements of the tiny effects of frame-dragging on the LAGEOS satellites."

The scientists put the data from the LAGEOS and GRACE satellite missions together to measure the effect of frame-dragging on the LAGEOS satellites' orbit. "Removing the effects of tides, atmosphere, gravity, and so on from the data, we could determine where the satellites were in their orbital arcs," said Pavlis. "We could see the orbital plane change because of the effects of relativity." The effects of frame-dragging on the LAGEOS satellite orbits are small, but measurable. Ciufolini said, "We're observing differences of just small fractions of a second of arc, about 10 to the minus 5 degrees, between the two satellites. But it's still proof that frame-dragging is real, and it's another important test validating the general theory of relativity."

The future of frame-dragging

Ciufolini and Pavlis have long pushed for an addition to the LAGEOS mission; with a third satellite in orbit, the accuracy of their measurements could be improved even further. Talk of launching a hypothetical LAGEOS-III has long subsided. However, the Italian Space Agency, ASI, has designed a new satellite for launch in the next year. Laser-ranging data from the new Laser Relativity Satellite (LARES) would likely be archived at NASA CDDIS. Ciufolini said, "Unless there's an unknown denser asteroid in our solar system, LARES will be the densest single object: about 387 kilograms [853 pounds] of tungsten in a sphere 36 centimeters [14 inches] in diameter." Pavlis looks forward to studying the data from LARES, after its planned launch in early 2010.

In addition to a third laser-ranging satellite, the two scientists also hope to see additional laser-ranging stations placed on Earth, improving the coverage of the LAGEOS satellite orbit and, in turn, their frame-dragging measurements. Pavlis said, "Right now, we only have snapshots of the orbit over land; if we don't have real estate, we can't put up a station." Another challenge is the cost of the stations, which require high levels of onsite infrastructure and support; not all countries have stations where they are needed. Automated stations, and new locations in the near future, would help fill in the gaps.

Why do Ciufolini, Pavlis, and so many other scientists spend vast amounts of their time trying to improve our understanding of Einstein's theory? Ciufolini said, "Space research is incredibly important. We can discover new things, new ways of thinking about our universe and our own lives. And the discoveries that will be made in the future, building on what we're doing now . . . like Einstein's theories, they will break our way of thinking about the universe."

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About the remote sensing data used

Satellites	Laser Geodynamics Satellites 1 and 2 (LAGEOS-1 and -2)	Gravity Recovery and Climate Experiment (GRACE)
Data sets	ILRS Normal Points for 1993 to 2003	GRACE Level 2 Gravity Products
Resolution	Global coverage	Not applicable
Parameters	Laser ranging data	Global gravity fields
Data centers	NASA Crustal Dynamics Data Information System (CDDIS)	NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC)

About the scientists

Ignazio Ciufolini is a researcher in general relativity and gravitation. He teaches physics at the University of Salento in Italy and won the 2001 International Tomassoni-Chisesi Award for Physics. He co-authored *Gravitation and Inertia* with John Archibald Wheeler; the Association of American Publishers named it the best 1995 physics book. He is the principal investigator of the Laser Relativity Satellite (LARES). The Italian Space Agency (ASI) funded his research. (Photograph courtesy I. Ciufolini)

Erricos Pavlis is a geodesist and research professor at the University of Maryland Joint Center for Earth Systems Technology with NASA Goddard Space Flight Center. He is the analysis coordinator for the International Laser Ranging Service, a team member of the Gravity Recovery and Climate Experiment, and a co-principal-investigator for LARES. NASA and the National Geospatial-Intelligence Agency funded his work. (Photograph courtesy E. Pavlis)

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Ciufolini, I., E. Pavlis. 2004. A confirmation of the general relativistic prediction of the Lense-Thirring effect. *Nature* 431: 958–960, doi:10.1038/nature03007.

Pavlis, E. C. 2003. Geodetic contributions to gravitational experiments in space. In *Recent Developments in General Relativity: Genoa 2000*, eds. R. Cianci, et al., 217–233. Milan: Springer-Verlag.

For more information

NASA Crustal Dynamics Data Information System (CDDIS)
http://cddis.gsfc.nasa.gov

NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC)
http://podaac.jpl.nasa.gov

Gravity Recovery and Climate Experiment (GRACE)
http://www.csr.utexas.edu/grace/

Laser Relativity Satellite (LARES)
http://www.asi.it/en/activity/cosmology/lares

PO.DAAC GRACE Home
http://podaac.jpl.nasa.gov/grace/