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USNO Marks 50 Year Anniversary of Breakthrough Relativity Experiment

In October 1971, an astronomer from the U.S. Naval Observatory (USNO) and a physicist from the Washington University in St. Louis performed a novel experiment to verify effects predicted by Albert Einstein's Special and General Theories of Relativity. By flying four cesium-beam atomic clocks around the world twice, once in an eastward and once in a westward direction, they hoped to measure small differences in the rates of the clocks when compared to similar devices that remained at the USNO.

Joseph C. Hafele, an assistant professor of physics at Washington University in St. Louis, first conceived of the experiment while preparing notes for a lecture. He realized that the precision and stability of then-current cesium-beam frequency standards should yield measurable results. All he needed was clocks and funding. A year after following fruitless leads, Hafele met Richard E. Keating, an astronomer at USNO, who had attended one of his lectures. Keating worked with atomic clocks in the Observatory's Time Service Department, and had connections with the Office of Naval Research (ONR).

Keating obtained $8,000 from ONR to conduct the experiment, most of which went to pay for airline tickets for their seats and those required for the four HP-5061A cesium clocks that accompanied them. The eastward trip began on October 4, 1971 and lasted 65.4 hours, of which 41.2 hours were spent in flight. The westward trip began on October 13 and lasted 80.3 hours, of which 48.6 hours were in flight.

According to Special Relativity, the eastward-moving clocks would lose time (i.e. run slower) compared to the stationary reference clocks at USNO; the westward-moving clocks would gain time (run faster). In addition, General Relativity predicted that the clocks at a higher gravitational potential (altitude) would run faster.

Combining the two effects, theory predicted that the eastward-moving clocks would lose 40 +/- 23 nanoseconds (ns) compared to the "rest" clocks at USNO, while the westward-moving clocks would gain 275 +/- 21 ns. Hafele and Keating measured results of a 59 +/- 10 ns loss for the eastward trip and a 273 +/- 7 ns gain for the westward trip. Their results were published in the journal *Science*, Vol. 177 (July 14, 1972).

Fifty years later the pioneering work of Hafele and Keating's experiment is repeated on a daily basis at the USNO. A primary part of the Observatory's mission is to provide the time-scale reference to the Global Positioning System (GPS). Each of the satellites in the GPS constellation carries a number of cesium and rubidium frequency standards, and USNO's Precise Time Department measures the rates of each clock on each satellite every day, comparing them to the ensemble of dozens of atomic clocks that constitute the Observatory's "Master Clock".

Since each satellite orbits the Earth twice per day at an altitude of 20,200 km (12,550 miles), the effects of both Special and General Relativity first measured by Hafele and Keating have now become a routine part of the solution that leads to determining precise positioning information and time distribution for GPS users around the world.

Joseph Hafele (left), Richard Keating, and their HP-5061A cesium clocks prepare for one of their two round-the-world flights, October 1971