Relativity on Earth

Chris Williams
Student 1607421
HET 605

3rd April 2003

Almost everybody who has studied physics, read a mass-market science magazine, or visited an Internet science forum is aware of Einstein's theories of relativity. In 1905 Einstein published the Special Theory (hereafter SR) that presented an elegant approach to explaining some of the more puzzling experimental results of the 19th century electromagnetic experiments. Not content with that achievement, Einstein published his General Theory (GR) in 1915, extending the concept of relativity to encompass gravitation. Einstein did not concentrate on tweaking existing theory to suit the experimental data of the day, rather he looked for an elegant framework that could encompass all of the phenomena of electromagnetism and gravity.

Despite Einstein's lack of reference to experiment his theories are testable. Numerous tests are possible for predicted effects such as: time dilation, length contraction, and Doppler shifts from SR, and gravitational lensing, time dilation, and reddening from GR. Many of the experiments rely on astronomical or astrophysical observations, but some tests of both SR and GR are possible within the confines of Earth and its immediate surrounds. This essay will describe several Earthly experiments that have been performed to validate Einstein's work.

Equivalence Principle

Einstein's relativity is based upon two postulates. The first of these, the so-called equivalence principle, requires that the laws of nature are the same in all reference frames. Reference frames were considered by Einstein to be equivalent if, relative to one another, they were in a state of uniform motion (SR) or acceleration (GR, could be zero). Gravitation is treated as an accelerated frame of reference. Implicit in this principle of equivalence is that the gravitational mass, which appears in Newton's gravitational equation ($F = \mathcal{G}Mm/r^2$), and inertial mass, which appears in Newton's third law ($F = ma$), of an object are intimately linked and constant in ratio regardless of object. If the long assumed mass equivalence could be disproved, the first postulate would be violated and relativity would be in need of revision. In 1890, Roland Eötvös performed just such a test using a delicately constructed and aligned torsion balance, Figure 1. Equal masses of dissimilar materials were mounted on the ends of the torsion balance arm, and the alignment was such that the Earth's rotation would cause the balance to twist if the ratio of inertial and gravitational masses were not the same between materials. Eötvös successfully demonstrated equivalence within a few parts in 10^9. The Eötvös experiment has been repeated to great accuracy many times since the release of Einstein's work, and the equivalence principle remains intact.

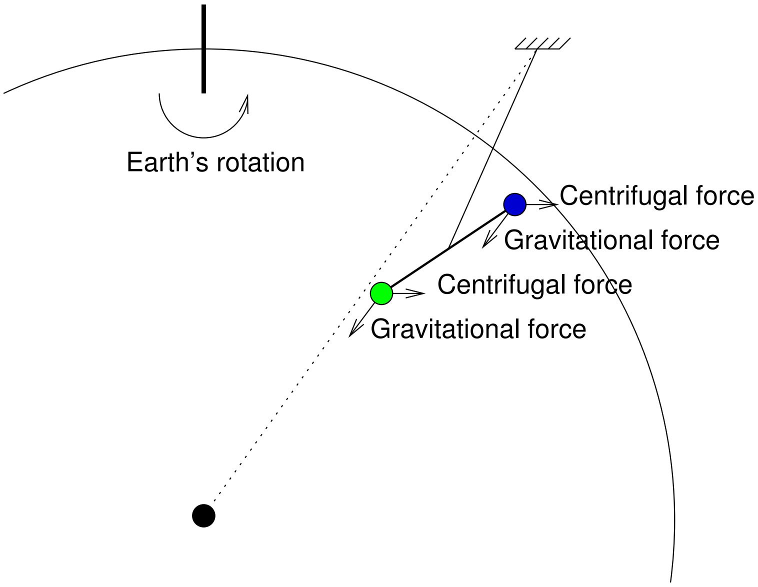


Figure 1: Eötvös experiment. Torsion balances are very sensitive to differences in forces that are not parallel to the support wire. Twisting is monitored using light reflected from a mirror attached to the beam. Centrifugal forces mean the support does not hang directly downward so that gravitational forces are not parallel to the support. If the gravitational and inertial (centrifugal) forces differ between masses the balance will twist, and swapping the masses would result in an opposite twist. No such twisting was observed. Adapted from [1, pp. 30]

Time Dilation and Contraction

One of the prime consequences of relativity is that there is no concept of absolute time: a concept deeply embedded in Isaac Newton's and derived physics. According to SR, identical clocks in constant, unaccelerated motion with respect to each other should run at different rates. The moving clock runs slower than the clock held by the observer. The introduction of GR also provided a time dilation effect caused by differing locations within a gravitational field. The clock with higher gravitational potential, i.e. further from the centre of the Earth, should run more quickly. The effective difference is absolutely tiny when the motion is slow or gravitational field is weak, explaining why it was not previously noted, but rapidly increases in significance as the velocity or field strength increases.

A classic test of time dilation was performed by Hafele and Keating in 1971 [2, 3]. The experiment used exceptionally accurate caesium beam atomic clocks, a reference set at the US Naval Observatory (USNO), and four mobile versions in commercial airliners. The four mobile clocks were sent around the world, first eastward and then westward. If relativity was correct the mobile clocks would show differences in time-keeping to their USNO counterparts, and to a notional clock at rest with respect to a frame of reference in which the Earth orbited the Sun at approximately uniform velocity. In the Hafele and Keating experiment the time differences arise from two sources:

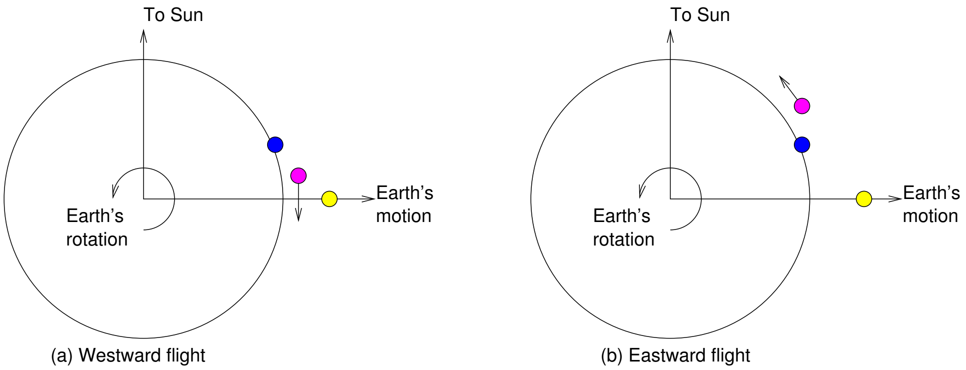
- Relative motion of the reference and mobile clocks. This contribution is predicted by SR and is responsible for asymmetry eastward versus westward. Asymmetry arises because both the aircraft and USNO clocks are in motion relative to the the frame of reference and to the notional inertial clock moving with the frame (Figure 2).

- Placement of the mobile clocks in a weaker gravitational field by virtue of the cruising altitude of commercial aircraft. The contribution of this component is a gain of the same order of magnitude as the relative motion component, but is symmetrical east versus west.

Theoretical predictions based on the actual flight paths of the clocks were for a loss of 40 ± 23 nanoseconds and gain of 275 ± 21 nanoseconds on eastward and westward trips respectively.

The mobile clocks were synchronised to the USNO reference and sent on an eastward journey around the world. Upon return the mobile clocks had lost 59 ± 10 nanoseconds with respect to the USNO reference clocks. The experiment was repeated with the clocks making a westward circuit of the Earth and returning with a gain of 273 ± 7 nanoseconds on the USNO reference clocks. The experimental data clearly match the predictions very well, supporting the presence of both forms of relativistic time dilation.

In 1976 a further test of time dilation was performed by Vessot, Levine and others [4] using a hydrogen maser clock on board a Scout D rocket. The hydrogen maser clock was used to control an oscillator providing a transmission at 2203 megahertz, accurate to 1 part in 100 billion. Vessot et. al. implemented an elaborate system of up-link and down-link signals from the rocket to eliminate Doppler shifts induced by the high speed motion of the



(a) Westward flight (b) Eastward flight

Figure 2: Hafele and Keating experiment asymmetry. The USNO (blue), aircraft (magenta), and notional inertial clock (yellow) started at t=0 on the horizontal axis, and the diagram is for some time afterwards. (a) On the westward flight the aircraft is moving away from the inertial clock more slowly than the USNO and is slowed less than the USNO clocks. Therefore, the airborne clock is gaining time on the ground-based clock. (b) On the eastward flight the aircraft clock is moving away from the inertial clock faster than the USNO clock and is therefore slowed more than the USNO clock. The airborne clock is losing time with respect to the USNO clock.

spacecraft, leaving only time dilations caused by gravitation and motion. The rocket was sent on a two hour sub-orbital trajectory approximately 10000 km into space before returning to Earth. During the unpowered portion of the flight the clock signal was measured by an Earth station to determine any subtle changes in frequency, and the spacecraft position was accurately tracked to provide a reference.

The experiment collected a large amount of data that took several years to analyse. Immediately after the rocket booster was jettisoned, time dilation was dominated by relative motion effects because the space craft was still relatively close to Earth and moving at speed. As the altitude increased, and speed decreased, the gravitational effects grew to dominate the declining relative speed effects. As the craft reached its highest point only gravitational effects were present because relative speed became zero. The ballistic return to Earth changed the balance once again toward relative motion effects. At the end of the analysis, the experimental data match predictions made using relativity to within seven thousandths of one percent.

Gravitational Red-shifting

The presence of gravitationally induced wavelength changes in light as it moves between locations of high an low gravitational potential is predicted by GR. Wavelength is predicted to increase (red-shift) when climbing to higher potential, and decrease when moving to lower gravitational potential (blue-shift). This effect was demonstrated experimentally in 1960 by Robert Pound and Glen Rebka [5]. The measurement apparatus was established in an elevator shaft of the Jefferson Tower physics building at Harvard University. The predicted wavelength change over the tower's approximate 22 m (72') height is in the order of two parts per 10^{15}. Prior to 1958 such a small change would be undetectable due the natural spread of emission wavelengths from Pound and Rebka's chosen gamma ray emitter (^{57}Co, a radioactive cobalt isotope). The Mössbauer effect, a discovery that earned Mössbauer the joint 1961 Nobel Prize in Physics, enabled Pound and Rebka to build emitter and receiver pairs that were monochromatic within 1 part in 10^{12} thereby making the experiment possible. Rather than attempting to directly measure the minute wavelength change, the emitter was moved back and forth at a slow, accurately measured velocity relative to the receiver. The velocity induced Doppler shift ensured that the desired signal was above noise thresholds, and the asymmetry between upward and downward movements betrayed the signal. The experiment was performed with the emitter at the bottom of the shaft and receiver at the top, and vice versa. The result was a gravitational wavelength shift within 10% of the predicted value.

The gravitational shift measurement of Pound and Rebka was improved upon by Pound and Snider in 1965 [6]. Using various methods to reduce systematic error, the result was 0.9990 ± 0.0076 times the theoretic prediction.

Conclusion

This essay has looked at a few key tests of predictions made by relativity, and of the underlying assumptions on which the theory is built. The principle of equivalence, in respect of mass, has support from the Eötvös experiment. Time dilation due to relative motion has been supported by physical transportation of high accuracy clocks by Hafele and Keating, and Vessot et. al. These experiments also confirmed the existence of gravitationally induced time dilation. Gravitational red-shifting, as predicted by GR, has been confirmed in the experiments of Pound, Rebka, and Snider. All of these experiments have been repeated, in varying guises, and remain in agreement with relativity. Einstein's theories of relativity have stood the challenge of experimental testing for nearly one hundred years.

References

[1] C. M. Will. *Was Einstein Right? Putting General Relativity to the Test.* Oxford University Press, 2 edition, 1993.

[2] J. C. Hafele and R. E. Keating. Around-the-World Atomic Clocks: Predicted Relativistic Time Gains. *Science*, 177:166–168, July 1972.

[3] J. C. Hafele and R. E. Keating. Around-the-World Atomic Clocks: Observed Relativistic Time Gains. *Science*, 177:168–170, July 1972.

[4] R. F. C. Vessot, M. W. Levine, F. E. M. Mattison, E. L. Blomberg, T. E. Hoffman, G. U. Nystrom, B. F. Farrell, R. Decher, P. B. Eby, C. R. Baugher, J. W. Watts, D. L. Teuber, and F. D. Wills. Test of Relativistic Gravitation with a Space-Borne Hydrogen Maser. *Physical Review Letters*, 45:2081–2084, December 1980.

[5] R. V. Pound and G. A. Rebka. Apparent Weight of Photons . *Physical Review Letters*, 4:337–341, April 1960.

[6] R. V. Pound and J. L. Snider. Effect of Gravity on Gamma Radiation. *Physical Review*, 140:788–803, November 1965.