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A Test of the Equivalence Principle Using a Space-Borne Clock[1]

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Abstract

An experimental verification of Einstein's equivalence principle has been made using an atomic hydrogen maser in a space probe attaining an altitude of 10,000 km above the earth's surface. At the present stage of the data reduction, confirmation is at the 2×10^{-4} level of accuracy. The experiment and the resulting data are described including a comment on the limits to the anisotropy of the velocity of light. We believe that this is the first direct, high-accuracy test of the symmetry of the propagation of light and a beginning in the use of high-accuracy clocks in space to measure relativistic phenomena.

§(1): *Introduction*

On June 18, 1976, a Scout D rocket was launched from Wallops Island, Virginia, carrying an atomic hydrogen-maser oscillator system as the payload. The objective of this experiment was to measure directly the effect of the gravitational potential on the frequency of a proper clock, in this case a hydrogen maser. The frequency of signals from the oscillator was monitored on the ground at Merrit Island, Florida, by using two hydrogen masers as comparison oscillators. The first-order doppler shift in the signals was eliminated by a go-return transponder link to the payload, and the resulting data, representing the relativistic shifts, were recovered and recorded.

The equivalence principle predicts that the rate of a proper clock varies as $\Delta\phi/c^2$ where $\Delta\phi$ is the change in gravitational potential. In this experiment, a gravitational effect on the clock rate amounting to some 4.5 parts in 10^{10}

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was measured with an oscillator having a stability of about 1 part in 10^{14}. Therefore, to make the best possible use of the oscillator, we must account for all frequency and phase shifts at the 5×10^{-15} level in the fractional frequency stability $\Delta f/f$ of the system.

This essay is an outline of the experiment and a preliminary review of the data now available; the data-reduction process is still in progress at this time.

We wish to emphasize that this experiment was conducted by a large number of people and involved many different organizations. The program was managed by George C. Marshall Space Flight Center (MSFC) of the National Aeronautics and Space Administration (NASA), who was also responsible for designing and assembling the payload structure and testing it before launch. NASA's Goddard Space Flight Center performed the task of tracking and data acquisition, and NASA's Langley Research Center and the Vought Corporation were responsible for the vehicle. The Smithsonian Astrophysical Observatory provided the payload and ground-based clocks, the doppler-canceling electronics system, and the scientific leadership of the experiment.

§(2): *Experiment Description*

The basic concept of the experiment is simple [1]. By moving an oscillator with very good frequency stability (representing the "proper" clock of the traditional relativity tests) up and down in the earth's gravity field and by using phase-coherent microwave links, the rate of the probing oscillator was measured with reference to a highly stable earth-bound oscillator. Movement through the earth's gravity field was provided by a four-stage Scout D rocket system, which hurled the payload nearly vertically to a 10,000-km apogee altitude.

The main parts of the payload consisted of a hydrogen-maser oscillator, an *S*-band transmitter phase-locked to the maser, and an *S*-band transponder. The whole payload, weighing 57 kg, was spin stabilized to maintain its orientation in inertial space and was separated from the fourth (last) stage of the Scout propulsion system just after burnout. The *S*-band signals were received and transmitted from a common antenna located on the spin axis at the aft end of the payload.

For thermal and ionospheric reasons, the experiment was performed in daylight. Launch was at 11:41 GMT, and impact was at 13:37 GMT at lat. 29°.44 N, long. 47°.75 W. The ground track of the experiment is shown in Figure 1. The experiment was completed after a total time of 1 h, 58 min.

Fundamental to the experiment is the concept of a real-time doppler-canceling system, shown schematically in Figure 2. It consists primarily of three microwave links. A go-return link operating a phase-coherent microwave transponder supplied two-way doppler-frequency data in the form of a beat frequency $f_0 - f_0''$. We divided the beat by two and subtracted it from the maser