Gravitational Redshift and Tests of Local Position Invariance

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Einstein Equivalence Principle

(1) Trajectories of freely-falling test bodies independent of structure or composition (WEP)

(2) Outcome of non-gravitational experiment in local, freely-falling frame independent of frame velocity (LLI)

(3) Outcome of non-gravitational experiment in local, freely-falling frame independent of time or place performed (LPI)

Gravitational redshift

Change in wavelength of light due to difference in gravitational potential energy:

$$Z = \frac{\Delta \nu}{\nu} = -\frac{\Delta \lambda}{\lambda} = \frac{\Delta U}{c^2}$$

Light loses energy when climbing uphill!

Einstein (1916): "An atom absorbs or emits light of a frequency which is dependent on the potential of the gravitational field in which it is situated."

How big is the effect?

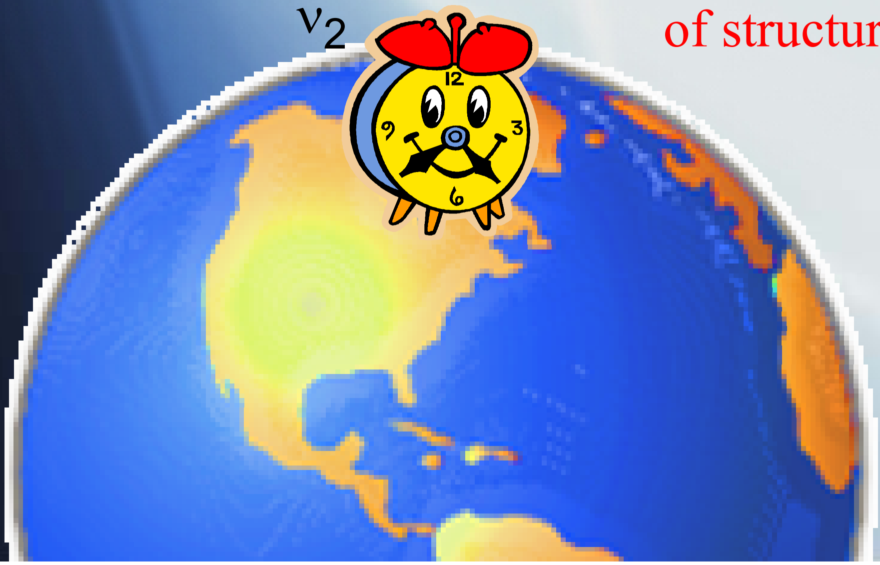
- GPS satellites move at 14,000 km/hr, 20,000 km above the earth
- Time dilation effect: 7 μs slow per day
- Gravitational redshift effect: 45 μs fast per day
- Net shift: 38 μs fast per day compared to clocks on the ground (error of 10 km per day)

Source: http://www.physicscentral.com/writers/2000/will.html

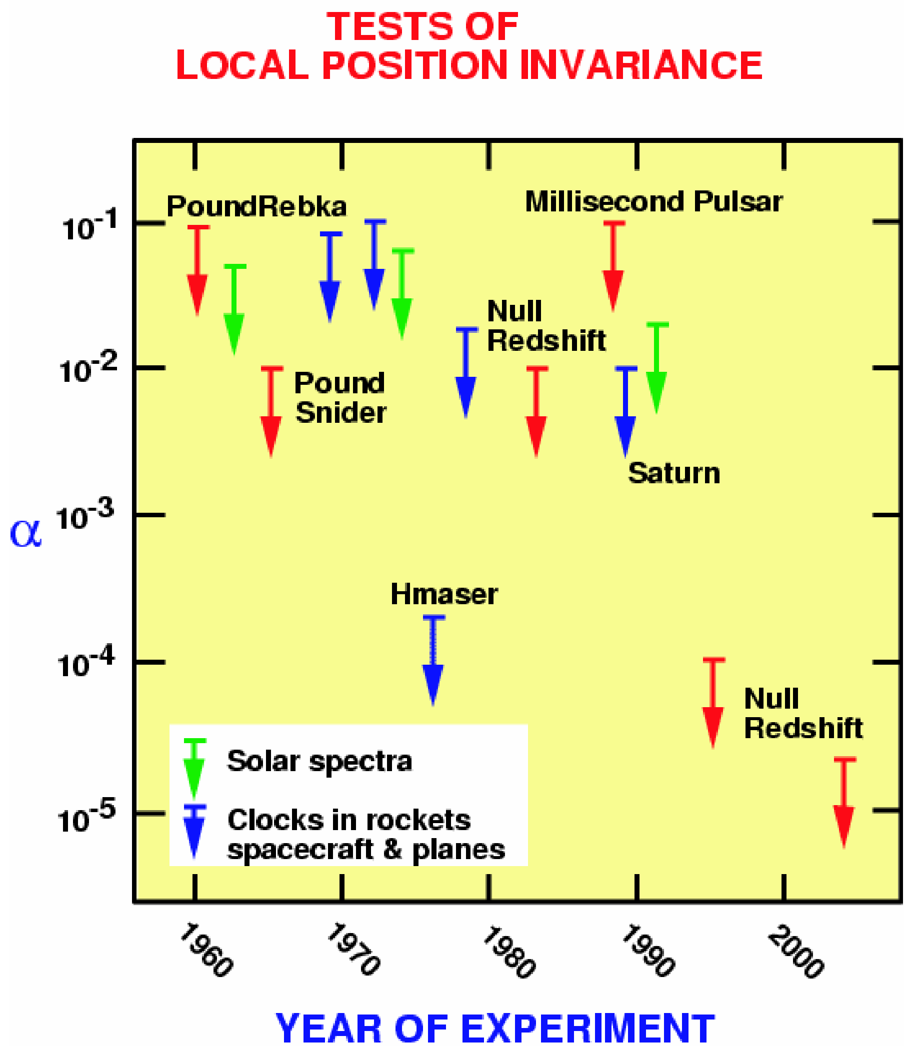
Why is this a test of LPI?

Identical clocks should have $\nu_1=\nu_2$ when measured in their respective local Lorentz frames, independent of location (and gravitational potential.)

A comparison of frequencies in one of these frames is a comparison of relative velocities of Lorentz frames, via Doppler shift of light (observed as gravitational redshift), independent of structure of clocks.



A deviation from the predicted frequency shift would indicate a dependence of some fundamental constant on position thus a violation of LPI and the EEP.



$$\Delta\nu/\nu = (1+\alpha)\Delta U/c^2$$

Source: Clifford Will
http://relativity.livingreviews.org/Articles/lrr-2006-3/index.html

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APPARENT WEIGHT OF PHOTONS*

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(Received March 9, 1960)

As we proposed a few months ago,[1] we have now measured the effect, originally hypothesized by Einstein,[2] of gravitational potential on the apparent frequency of electromagnetic radiation by using the sharply defined energy of recoil-free γ rays emitted and absorbed in solids, as discovered by Mössbauer.[3] We have already reported[4] a detailed study of the shape and width of the line obtained at room temperature for the 14.4-kev, 0.1-microsecond level in Fe^{57}. Particular attention was paid to finding the conditions required to obtain a narrow line. We found that the line had a Lorentzian shape with a fractional full-width at half-height of 1.13×10^{-12} when the source was carefully prepared according to a prescription developed from experience. We have also investigated the 93-kev, 9.4-microsecond level of Zn^{67} at liquid helium and liquid nitrogen temperatures using several combinations of source and absorber environment, but have not observed a usable resonant absorption. That work will be reported later. The fractional width and intensity of the absorption in Fe^{57} seemed sufficient to measure the gravitational effect in the laboratory.

As a preliminary, we sought possible sources of systematic error that would interfere with measurements of small changes in frequency using this medium. Early in our development of the instrumentation necessary for this experiment, we concluded that there were asymmetries in, or frequency differences between, the lines of given combinations of source and absorber which vary from one combination to another. Thus it is absolutely necessary to measure a change in the relative frequency that is produced by the perturbation being studied. Observation of a frequency difference between a given source and absorber cannot be uniquely attributed to this perturbation. More recently, we have discovered and explained a variation of frequency with temperature of either the source or absorber.[5] We conclude that the temperature difference between the source and absorber must be accurately known and its effect considered before any meaning can be extracted from even a change observed when the perturbation is altered.

The basic elements of the apparatus finally developed to measure the gravitational shift in frequency were a carefully prepared source containing 0.4 curie of 270-day Co^{57}, and a carefully prepared, rigidly supported, iron film absorber. Using the results of our initial experiment, we requested the Nuclear Science and Engineering Corporation to repurify their nickel cyclotron target by ion exchange to reduce cobalt carrier. Following the bombardment, in a special run in the high-energy proton beam of the high-current cyclotron at the Oak Ridge National Laboratory, they electroplated the separated Co^{57} onto one side of a 2-in. diameter, 0.005-in. thick disk of Armco iron according to our prescription. After this disk was received, it was heated to 900°-1000°C for one hour in a hydrogen atmosphere[4] to diffuse the cobalt into the iron foil about 3×10^{-5} cm.

The absorber made by Nuclear Metals Inc., was composed of seven separate units. Each

The Pound-Rebka experiment

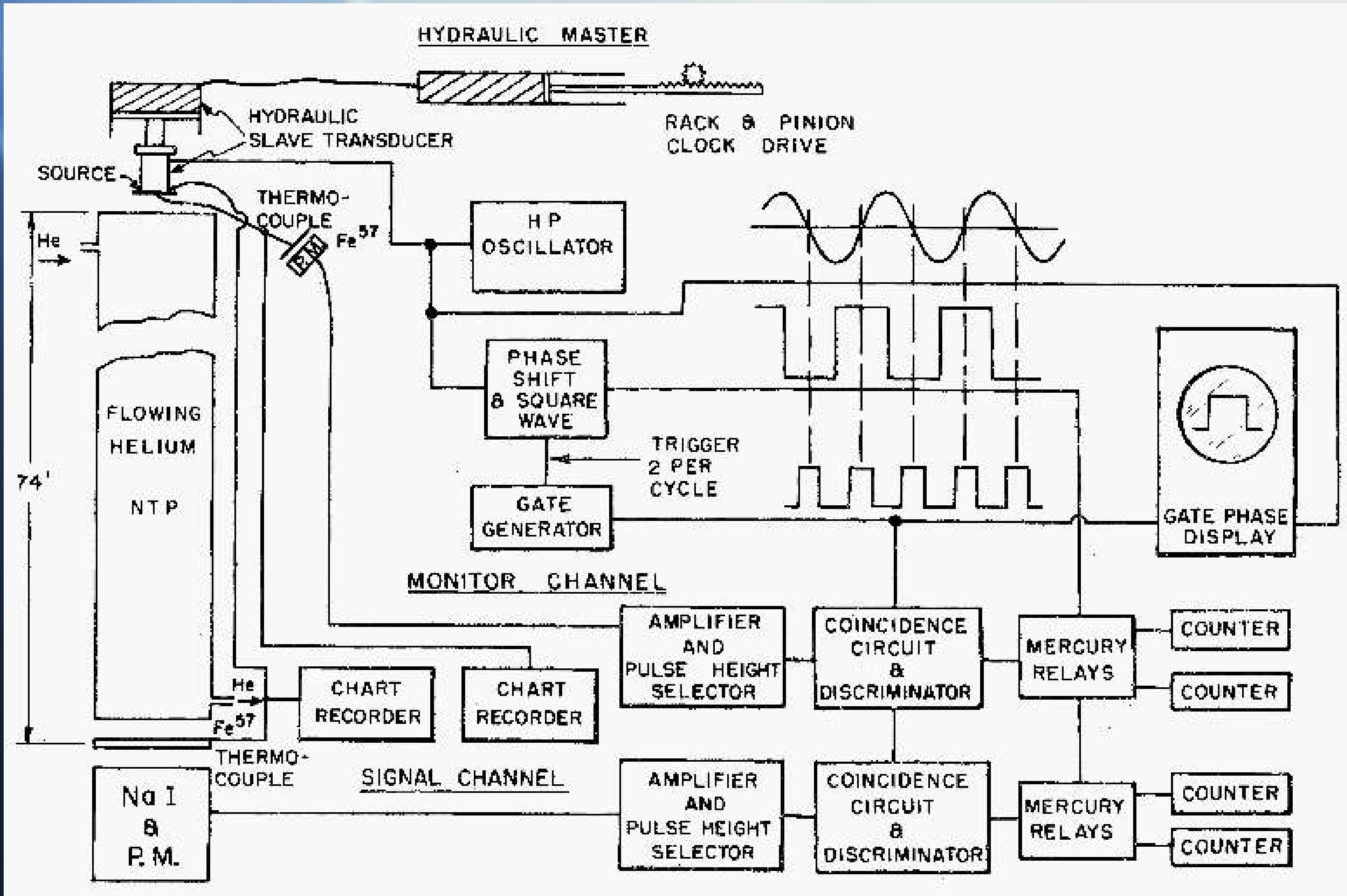


Table I. Data from the first four days of counting. The data are expressed as fractional frequency differences between source and absorber multiplied by 10^{15}, as derived from the appropriate sensitivity calibration. The negative signs mean that the γ ray has a frequency lower than the frequency of maximum absorption at the absorber.

Period	Shift observed	Temperature correction	Net shift
	Source at bottom		
Feb. 22, 5 p.m.	-11.5 ± 3.0	-9.2	-20.7 ± 3.0
	-16.4 ± 2.2[a]	-5.9	-22.3 ± 2.2
	-13.8 ± 1.3	-5.3	-19.1 ± 1.3
	-11.9 ± 2.1[a]	-8.0	-19.9 ± 2.1
	-8.7 ± 2.0[a]	-10.5	-19.2 ± 2.0
Feb. 23, 10 p.m.	-10.5 ± 2.0	-10.6	-21.0 ± 2.0
		Weighted average =	-19.7 ± 0.8
	Source at top		
Feb. 24, 0 a.m.	-12.0 ± 4.1	-8.6	-20.6 ± 4.1
	-5.7 ± 1.4	-9.6	-15.3 ± 1.4
	-7.4 ± 2.1[a]	-7.4	-14.8 ± 2.1
	-6.5 ± 2.1[a]	-5.8	-12.3 ± 2.1
	-13.9 ± 3.1[a]	-7.5	-21.4 ± 3.1
	-6.6 ± 3.0	-5.7	-12.3 ± 3.0
Feb. 25, 6 p.m.	-6.5 ± 2.0[a]	-8.9	-15.4 ± 2.0
	-10.0 ± 2.6	-7.9	-17.9 ± 2.6
		Weighted average =	-15.5 ± 0.8
		Mean shift =	-17.6 ± 0.6
		Difference of averages =	-4.2 ± 1.1

[a]These data were taken simultaneously with a sensitivity calibration.

Results

- Pound-Rebka measured a net fractional shift of $-(5.13\pm0.51)\times10^{-15}$ over 148 ft.
- Agrees with GR predicted value of -4.92×10^{-15} to within 10% uncertainty
- Revised Pound-Snider experiment in 1964 achieved 1% uncertainty

Space-Borne hydrogen maser (Gravity Probe-A, 1976)

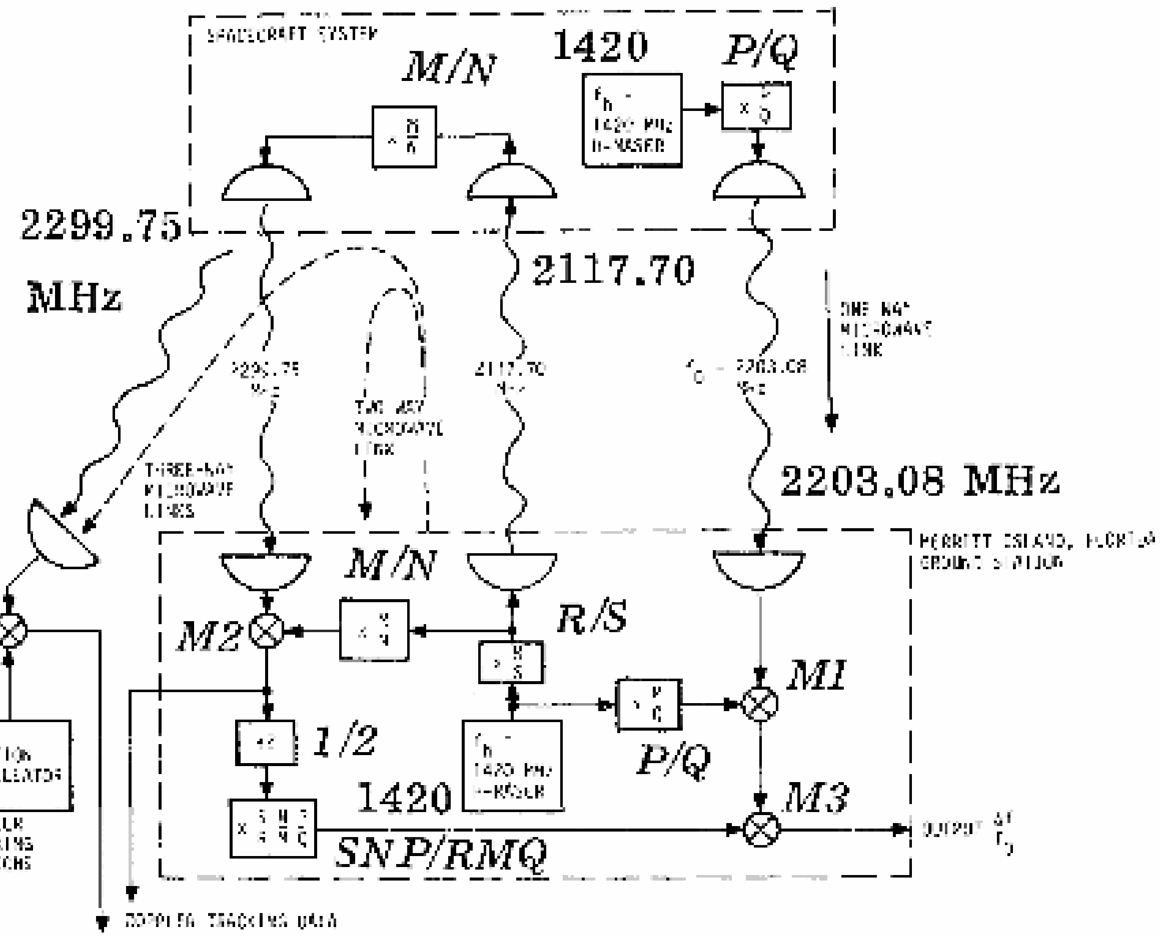


FIG. 1. Doppler cancellation and tracking system.

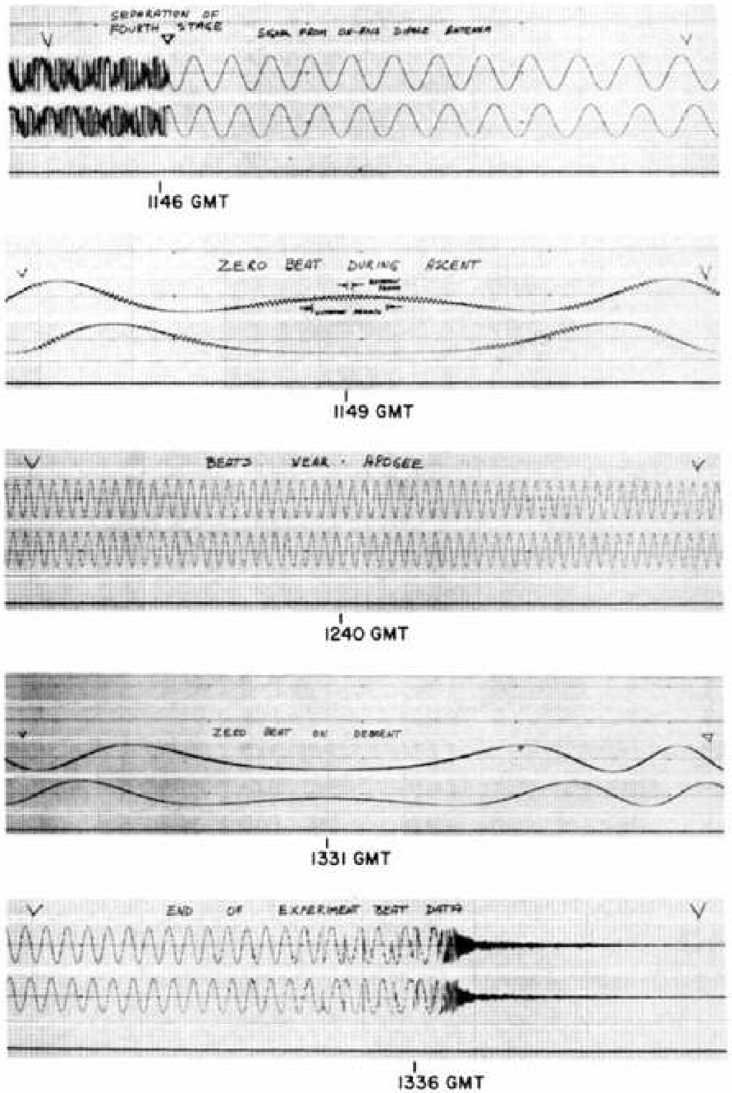


FIG. 2. Analog strip-chart recorder data at various times during the mission. (a) Signal from dipole antenna. The (inverted delta) markers indicate the time at which the fourth stage of the rocket separated. (b) Zero beat during ascent. The small interval indicated above the top trace is a rotation period; the longer interval below is a nutation period. (c) Beats near apogee. (d) Zero beat on descent. (e) End of experimental beat data.

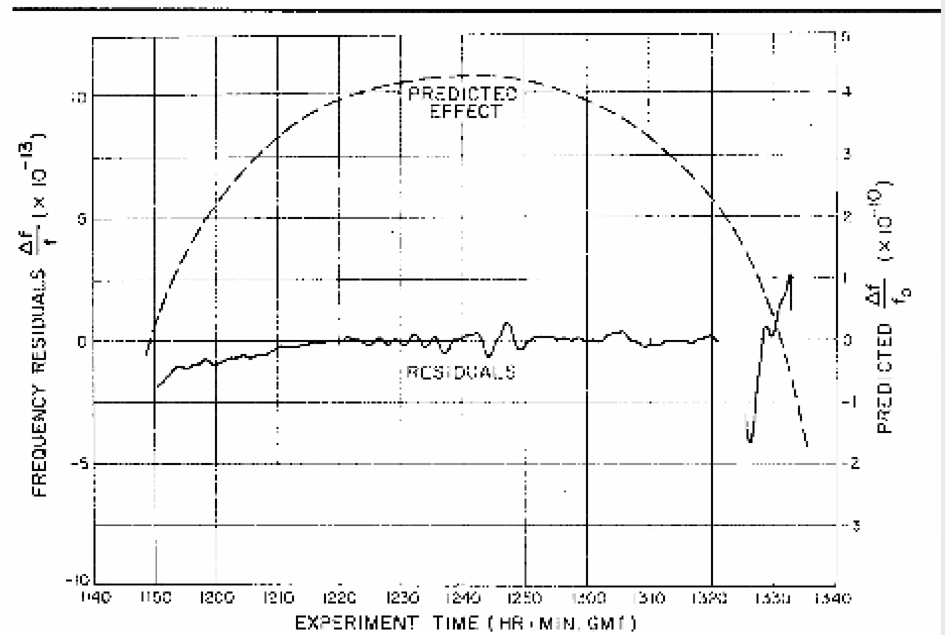


FIG. 3. Frequency residuals and predicted effect during mission.

$$\frac{\Delta f}{f_0} = \frac{\phi_s - \phi_e}{c^2} - \frac{\left|\vec{v}_e - \vec{v}_s\right|^2}{2c^2} - \frac{\vec{r}_{se} \cdot \vec{a}_e}{c^2}$$

GP-A results

- Measured frequency shift consistent with GR (combined effect of gravity and special relativity) to uncertainty of 7×10^{-5}
- To date the most precise traditional test of LPI

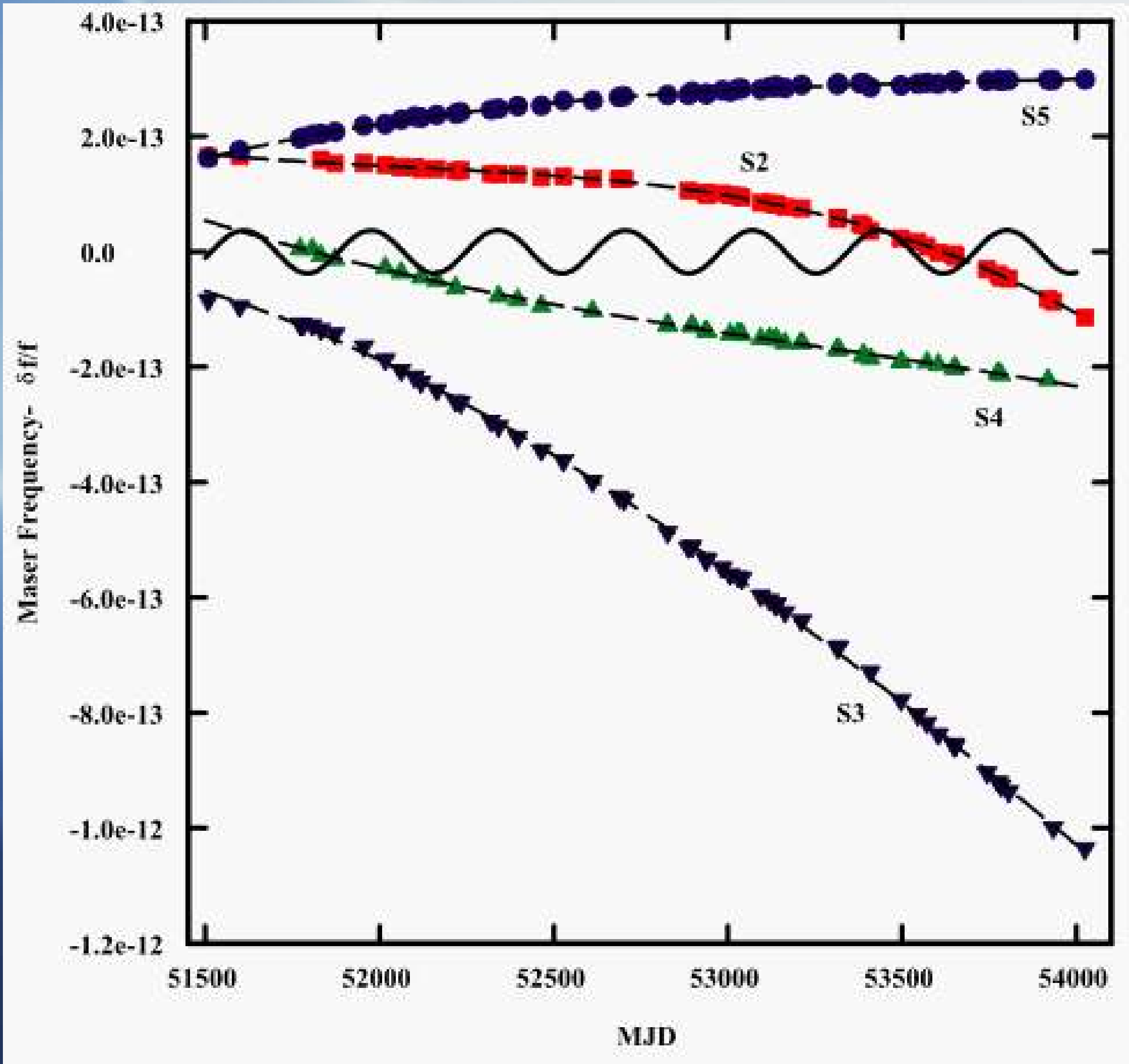
Null experiments

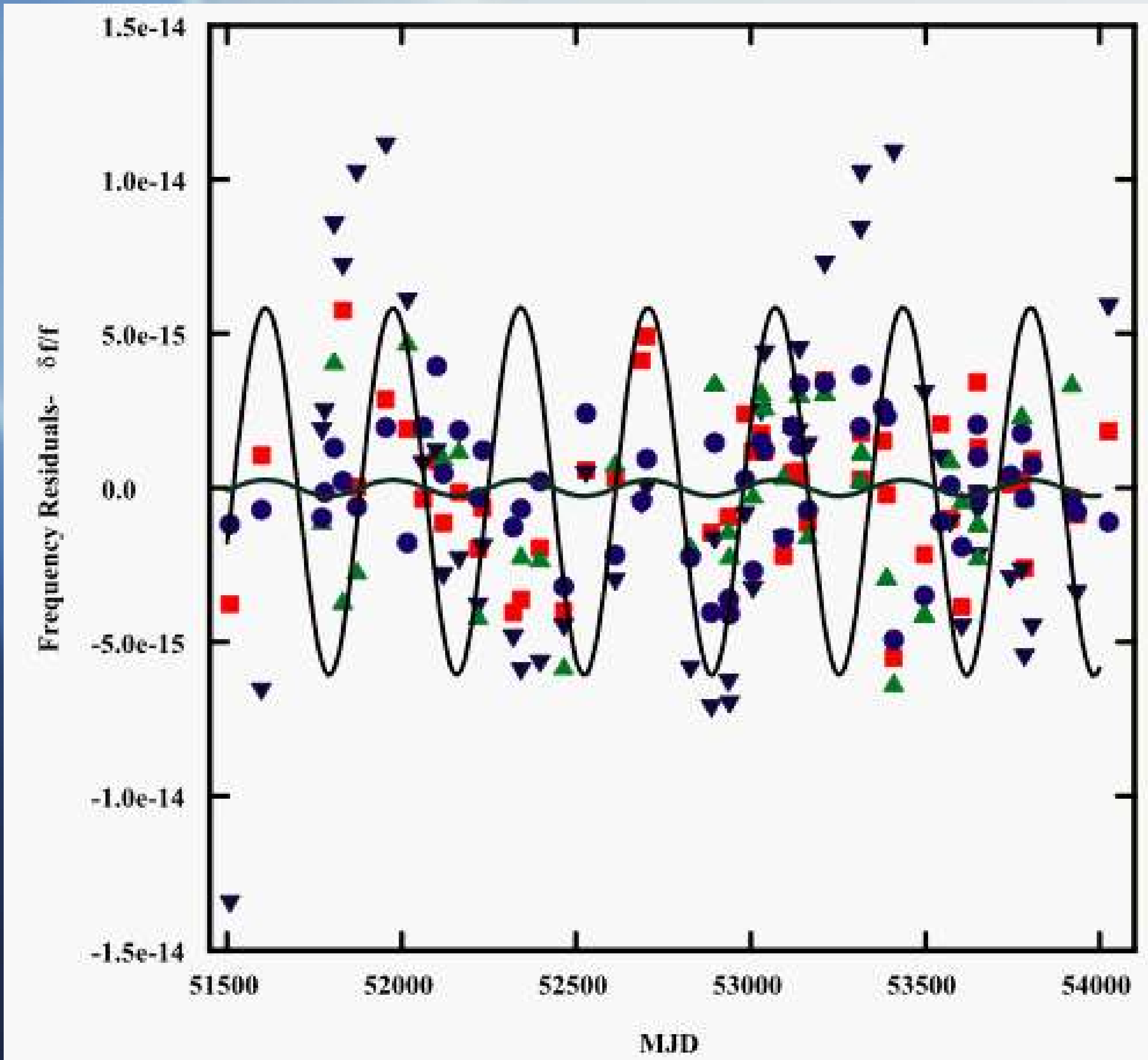
- Since GP-A, improvements in LPI violation have come from null-redshift experiments in which clocks of different composition are compared in a time-modulated gravitational field.
- 1978 Turneaure & al. (Stanford) used two 1.42 GHz hydrogen masers and three SCSO's at 8 GHz over 11 days while solar gravity varied (linearly by $3\text{x}10^{-12}$ per day from orbit, sinusoidally by $3\text{x}10^{-13}$ from rotation)

  Measured no deviation between the clocks, $|\alpha| < 1.7\text{x}10^{-2}$

Null experiments, cont.

- 1994 (Godone & al.) comparison of cesium and magnesium atomic clocks over 430 days, $|\alpha| < 7 \times 10^{-4}$
- 2002 (Bauch & al.) comparison of cesium clock with hydrogen maser over one year, $|\alpha| < 2.1 \times 10^{-5}$
- 2006 (Ashby & al.) comparison of four NIST hydrogen masers with cesium fountain clock standards from NIST, Germany, France, and Italy over 7 years…


4.0e-13
2.0e-13
0.0
-2.0e-13
-4.0e-13
-6.0e-13
-8.0e-13
-1.0e-12
-1.2e-12
Maser Frequency- δf/f
51500
52000
52500
53000
53500
54000
MJD
S5
S2
S4
S3



1.5e-14
1.0e-14
5.0e-15
0.0
-5.0e-15
-1.0e-14
-1.5e-14
Frequency Residuals- δf/f
51500
52000
52500
53000
53500
54000
MJD

The current best limit

$$|\alpha| < 1.4 \times 10^{-6}$$

Additional tests of LPI

- Gravitational redshift measured with solar spectra, pulsars, and oscillator clocks on spacecraft
- Time invariance of fundamental constants (current and past)