# Using GPS PPP To Test Relativity

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# Special Theory of Relativity, 1905

Source: http://www.crystalinks.com/bikeinstein.jpg

- All observers are equivalent.
  - They all think they are stationary
- All observers will measure identical values for the speed of light.

Therefore,

- Nothing can go faster than light
- Honorable observers will disagree about
  - What is stationary
  - How long length is
  - What is simultaneous
    - i.e. what came first
  - How fast time moves
- But a freshman can easily calculate what different observers will think they observed

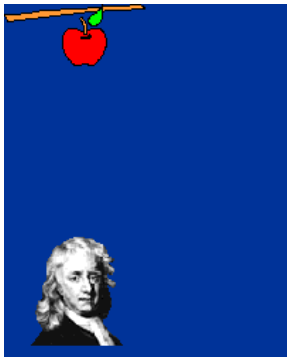
# And the freshman says:

A stationary observer will think a moving observer's

- Yardstick shrinks
- Mass is greater
- TIME RUNS SLOW
  - Therefore, the clocks will run slow
  - 2nd order Doppler Effect

Hafele-Keating Experiment, 1971 (USNO archive photo)

# Questioning Gravity

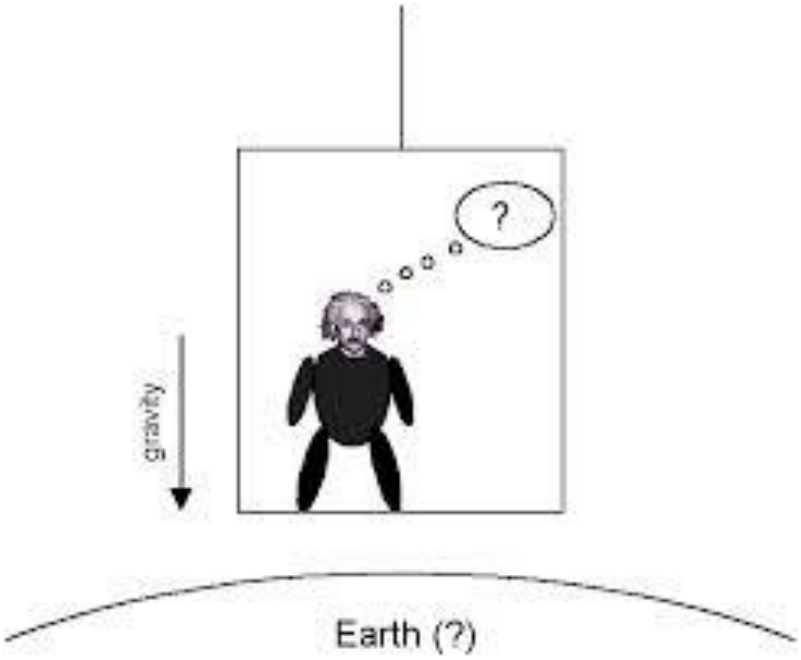


- How can gravity pass through empty space?
  - How can the Earth pull on an apple?
  - How can it pull on the Moon?
- Answer: the General Theory of Relativity

Newton from http://csep10.phys.utk.edu/astr161/lect/history/newtongrav.html

Moon from https://en.wikipedia.org/wiki/Moon

# Principle of Equivalence, 1907

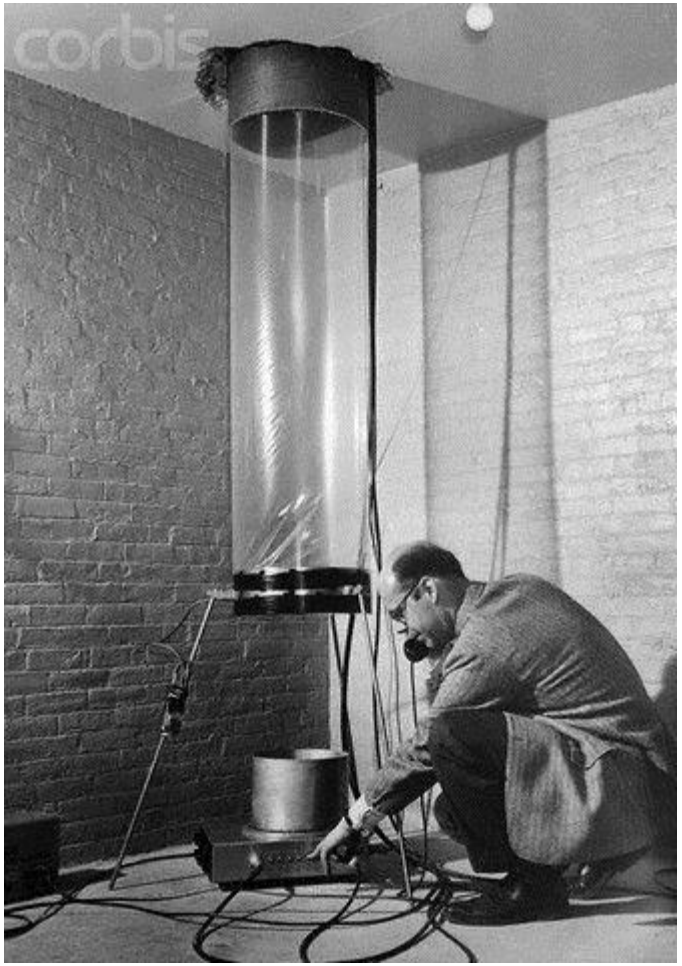



An observer cannot by local measurements, distinguish between an acceleration and a gravitational field.

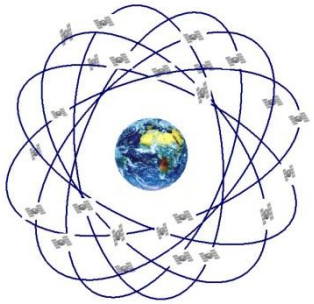


Graphic source: http://oldeloohuis.com/accelev.html

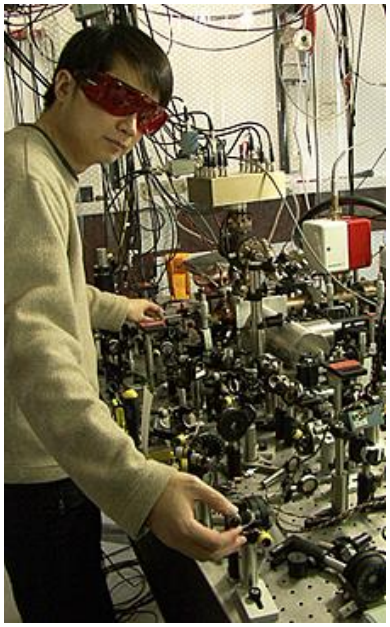
# The EEP explains the Gravitational Redshift




Harvard, 1959

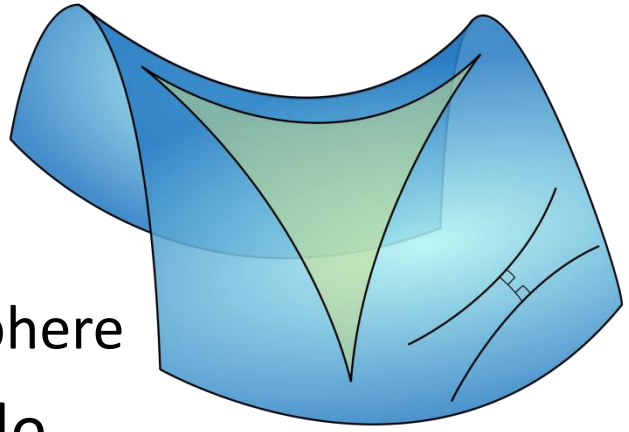


GPS, since 1978



NIST, 2010

# Curved Space



- Euclidian geometry does not apply
  - Plane geometry does not work on a sphere
- Things move straightest way possible
  - Principle of Least Action

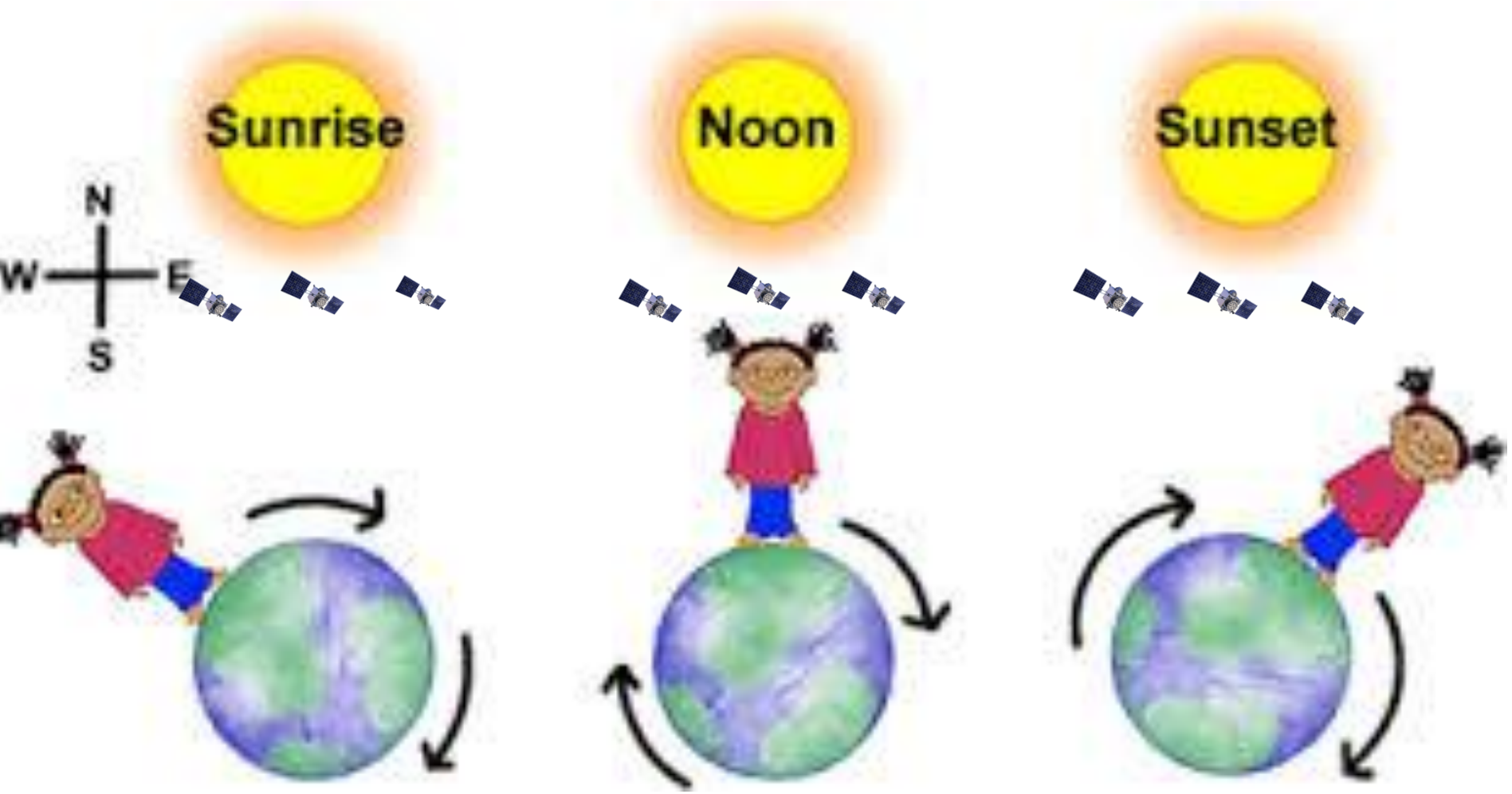
Source: Wikiedia

- Imagine a 2-dimensional ant walking around a sphere
  - She is going in a circle
  - She thinks gravity brought her back
  - You and Einstein realize that her space was curved.

Ant on globe from http://cosmology.carnegiescience.edu/https@cosmology.carnegiescience.edu/sites/cosmology.ciw.edu/files/images/ball1.png

# Many theorists predict EEP violations
## *the question is where and how*

We are closer to the Sun in the daytime,  so its gravity is stronger.



# Should the gravitational redshift from the Sun appear in GPS and ground clocks?

No, because all the clocks are, more or less, in free-fall about the Sun

- What about the Pound-Rebka & NIST experiments?
  - The equipment was tied to the stationary ground
  - An accelerating reference frame could replace gravity
    - But it saw the equipment as being accelerated by the ground
- Its different when everything moves together around the Sun

# Cancellation of Gravitational & 2nd-Order Doppler shifts

Solar gravitational redshift:

$\Delta f/f = GM_{sun}/(c^2 D_{sun}) = (GM_{sun} * r_{earth})/(c^2 D^2_{earth\text{-}sun})$

$= (6.674*10^{-11})*(1.988*10^{30})*(6.378\ 10^{6})/(3\ 10^{18} *1.496 *10^{11})^{2}$ mks units

$= 4.2 * 10^{-13} =$ *36 ns/day*

Second Order Doppler about Sun:

$\Delta f/f = -\frac{1}{2}\ v^2/c^2 = -GM_{sun}/(c^2 D_{sun}) =$ *-36 ns/day*

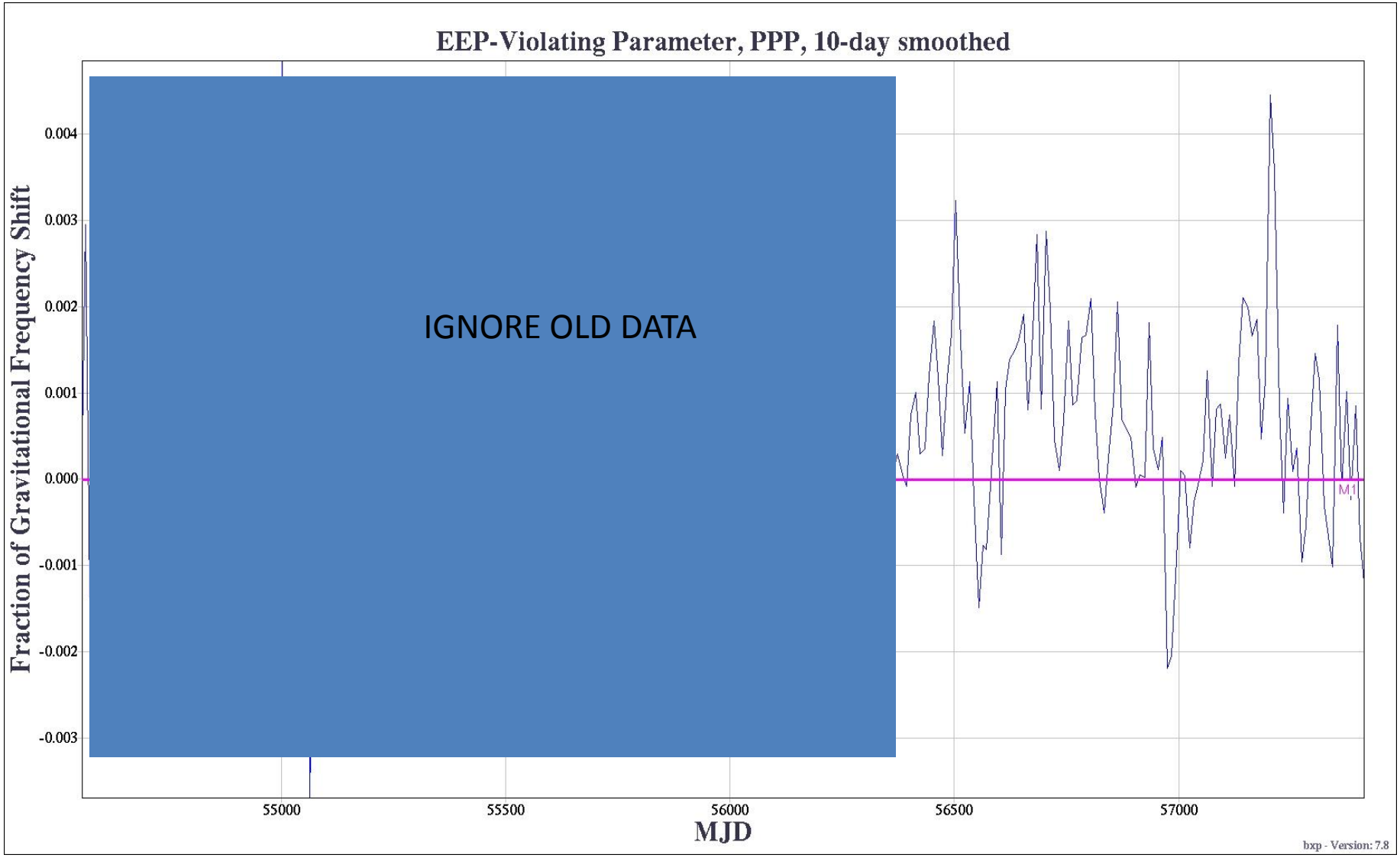
Relativity of Simultaneity extends cancellation over orbit

Ashby and Weiss (2013)

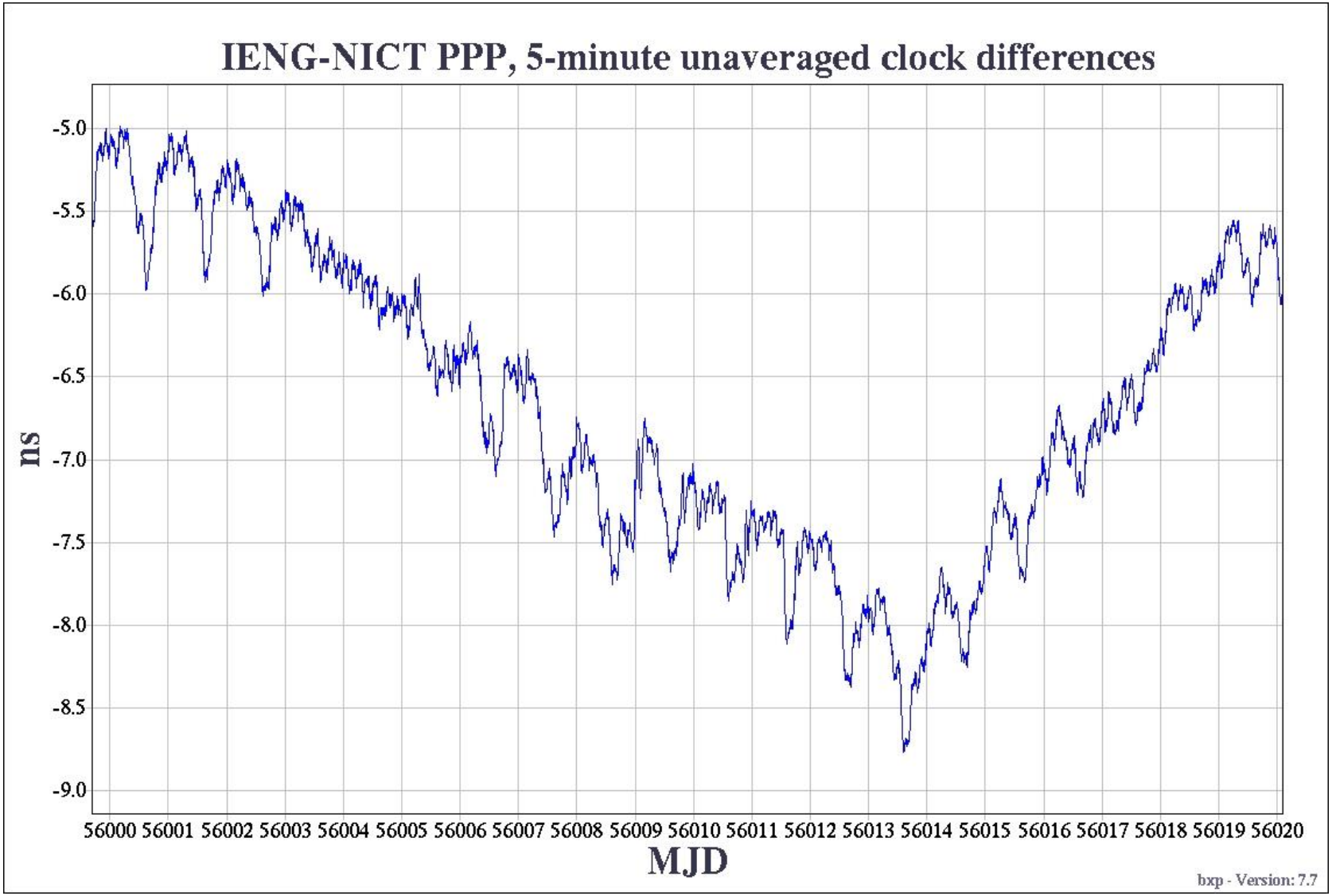
# GPS Precise Point Positioning (PPP)

- Search for frequency shift as fraction of solar gravitational red shift
  - Which is supposed to be cancelled by the Doppler
- Monthly solutions computed by BIPM
- Ten labs used (initially)
  - 4 in Europe, 4 in Asia, 2 in USA
  - Data going back as far as 2008
- Sensitive to model errors in satellites visible at each site
  - EEP violation on satellites ~4 times larger than on surface clocks
    - That's a good thing for this experiment

# PPP RESULTS


EEP-Violating Parameter, PPP, 10-day smoothed
IGNORE OLD DATA
Fraction of Gravitational Frequency Shift
0.004
0.003
0.002
0.001
0.000
-0.001
-0.002
-0.003
M1
55000
55500
56000
56500
57000
MJD
bxp - Version: 7.8

# Intermittent Diurnals In PPP (worst case, shown below, was excluded)



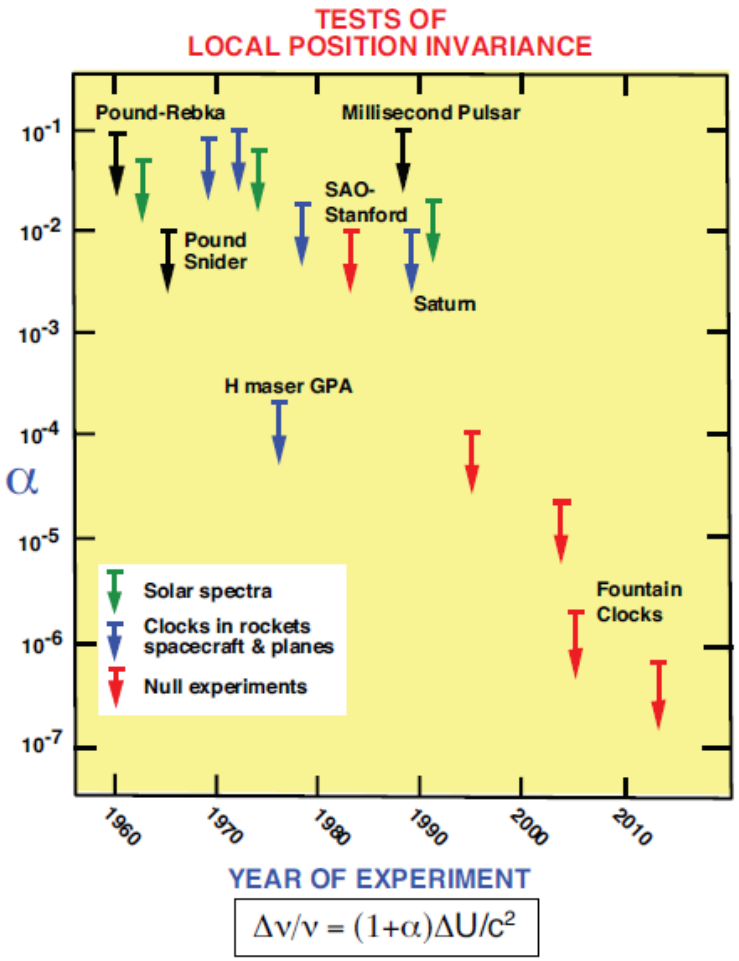
# Bottom Lines

| Technique | # Days | Covariance Source | EEP-violating Parameter | Statistical Uncertainty | Quadrature Parameter |
|---|---|---|---|---|---|
| TWSTT | 1538 | Data | $-2.2\ 10^{-4}$ | $\pm\ 2.4\ 10^{-3}$ | $5.0\ 10^{-4}$ |
| TWSTT | 1538 | Model | $1.4\ 10^{-3}$ | $\pm\ 2.4\ 10^{-3}$ | $5.5\ 10^{-3}$ |
| PPP | 2865 | Data | $7.4\ 10^{-4}$ | $\pm\ 1.1\ 10^{-4}$ | $4.4\ 10^{-4}$ |
| PPP | 2865 | Model | $7.9\ 10^{-4}$ | $\pm\ 8.9\ 10^{-5}$ | $7.8\ 10^{-4}$ |
| PPP | 1217 | Data | $6.8\ 10^{-4}$ | $\pm\ 1.1\ 10^{-4}$ | $2.8\ 10^{-4}$ |
| PPP | 1217 | Model | **$6.1\ 10^{-4}$** | **$\pm\ 9.2\ 10^{-5}$** | **$4.4\ 10^{-4}$** |

**Systematics $< 10^{-3}$**

**Formal Error $\sim 10^{-4}$**

# Tests of Local Position Invariance




This experiment
(distant clocks)

Nearby clocks
(different species)

**Figure 3:** Selected tests of local position invariance via gravitational redshift experiments, showing bounds on $\alpha$, which measures degree of deviation of redshift from the formula $\Delta\nu/\nu = \Delta U/c^2$. In null redshift experiments, the bound is on the difference in $\alpha$ between different kinds of clocks.

From Will, *Living Rev. Relativity*, **17** (2014), 4

# Future prospects involving Solar potential

- Everything getting better on Earth
  - PPP will be better
    - GPS => GNSS
    - Better hardware
      - Less environmental dependence, less multipath
  - Fiber-optics frequency transfer
- Circumsolar rocket probes
  - All they need is funding

# Time's Up

Source: http://www.dogoilpress.com/FDS-552996.html