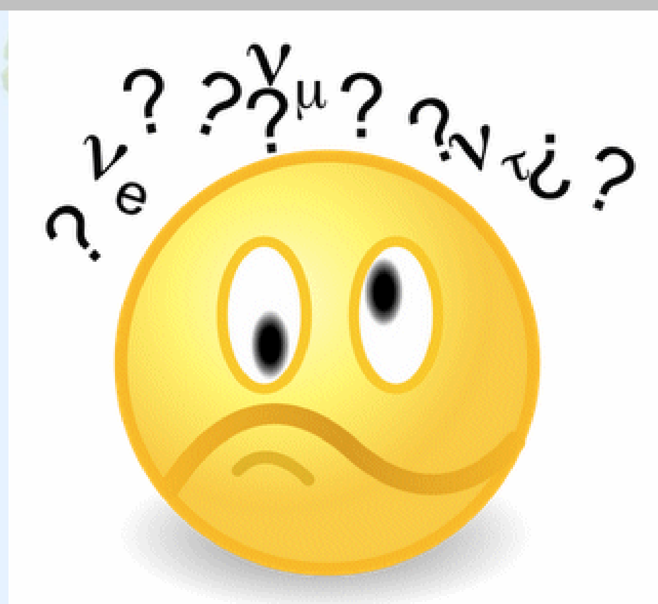
What's Not Wrong With Faster-Than-Light Neutrinos

Care and Feeding of Relativistic Measurements



Eric L. Michelsen (emichels/physics.ucsd.edu)
UCSD CASS Journal Club

Topics

The problem

The size of the "problem"

We don't need no stinking coordinates

What is synchronization?

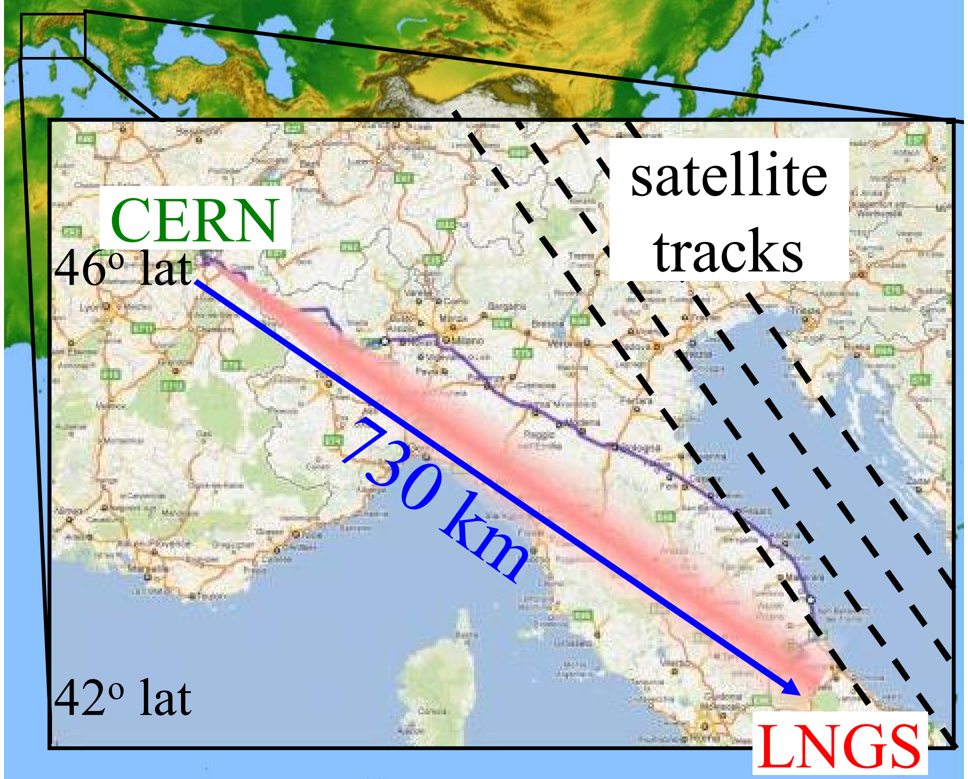
Rotating and orbiting systems

Common view synchronization

Why not use satellite frame?

The problem

- CERN→LNGS muon-neutrino (ν_μ) time-of-flight (TOF)
  - Neutrinos launched from Geneva to Gran Sasso
  - They're faster than light
- Separate clocks record launch and receive times
  - They better be well synchronized



References

1. It started with T. Adam + ~160 coauthors, arXiv:1109.4897v2 [hep-ex]
    - "We deliberately do not attempt any theoretical or phenomenological interpretation of the results."
2. Hypothesis by Elburg, arXiv:1110.2685v4 [physics.gen-ph]
    - Factor of 2 needed to agree with measurement
3. Comment by Assis, arXiv:1110.0047v1
    - Disputes factor of 2
4. Hypothesis reworked by Ramakrishna, arXiv:1111.1922v2, to essentially same result as [2]
5. Conceptual framework: Grøn, Ø, Am. J. Phys., 10/1975

The size of the "problem"

- 60 ns "deficit" (18 m) (e.g. 60 ± 6.9 ± 7.4 [4])
  - Compared to light
  - Varies a few ns with reduction algorithm
  - 6.2σ significance
  - 2.5×10^{-5} (big!)
- Epoch delta: < 3 ns
- Flight distance uncertainty
  - 730534.61 ± 0.20 m [1] => ± 0.7 ns
  - In 2.4 ms flight time [4] => 3×10^{-7}

- Uncorrected GPS clock discrepancy
  - 38 μs/day => 4×10^{-13}

Coordinates?

- ~~We don't need no stinking coordinates~~
- ~~We don't need no reference frames, either~~
- ~~We have formulas!~~
- ~~Just plug in numbers and start integrating~~

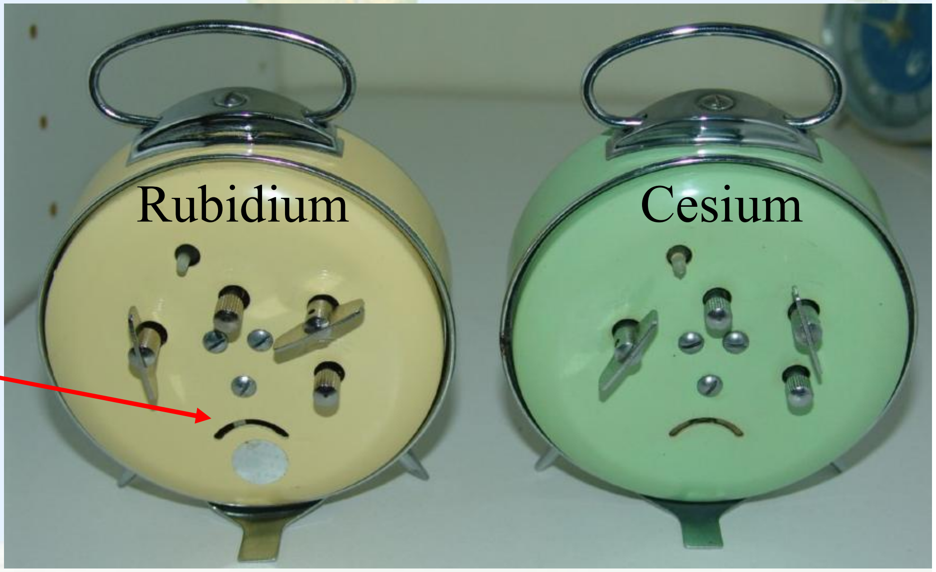
$$\Phi(R_s) = -\int_{R_\oplus}^{R_s} -9.81\left(\frac{R_\oplus}{r}\right)^2 dr = -9.81 R_\oplus{}^2\left[\frac{1}{R_s} - \frac{1}{R_\oplus}\right] = 4.75\times 10^7 \text{ m}^2/\text{s}^2$$

$$\Phi(R_s)/c^2 = 5.28\times 10^{-10} \quad \textit{or} \quad 45.6\ \mu\text{s/day}$$

"... without a proper reference frame, no form of geodesy is possible."
--http://www.gpsdancer.com/2.html

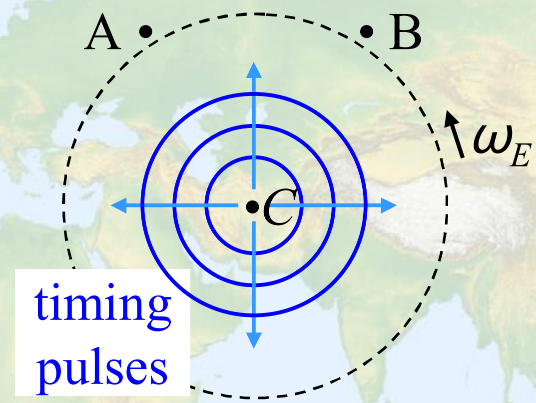
What is clock synchronization?

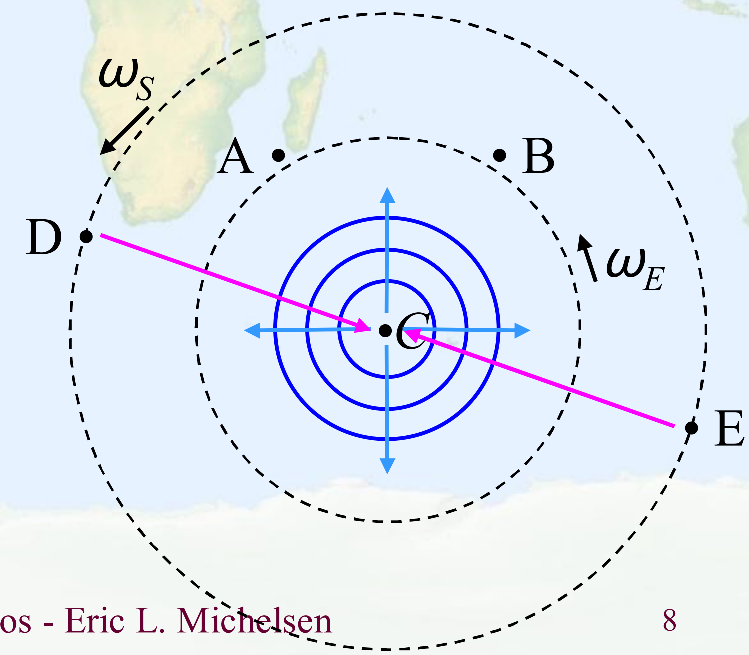
- Two parts to synchronization, both harder than they look:
  - Rate synchronized
    - As measured by whom?
  - Epoch synchronized
    - Simultaneous, according to whom?
- Can we synchronize two (non-inertial) earth clocks for all time?
- Yes
  - Any clock with a stationary (time independent) metric can be rate synchronized by a simple change of speed
  - Any clocks can be offset to have a common origin



Rotating and orbiting systems

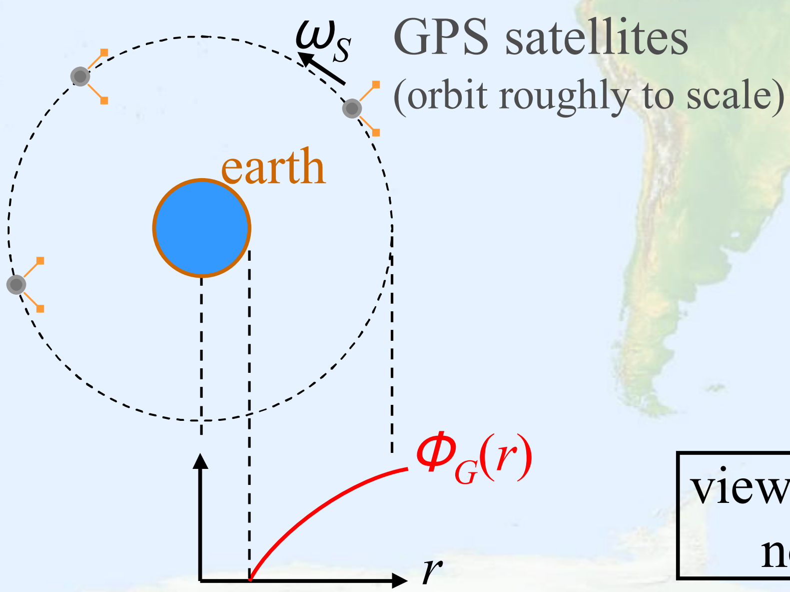
- Cindy, at center, is inertial and non-rotating
  - Point of maximal symmetry: provides a conceptual reference
- By axial symmetry, all orbiting clocks run at same speed
- Clocks are rate adjusted to broadcasts from center
- Multiple orbiting layers of different ω can be synchronized
  - Time signals can be echoed through Cindy
  - One system-wide time-coordinate
  - Proper time and time-coordinate are different
- Clocks are epoch synchronized by accounting for propagation delay from center
- All observers now agree on simultaneity
- There is *never* any SR time dilation between orbiters on different layers, despite their changing relative motion



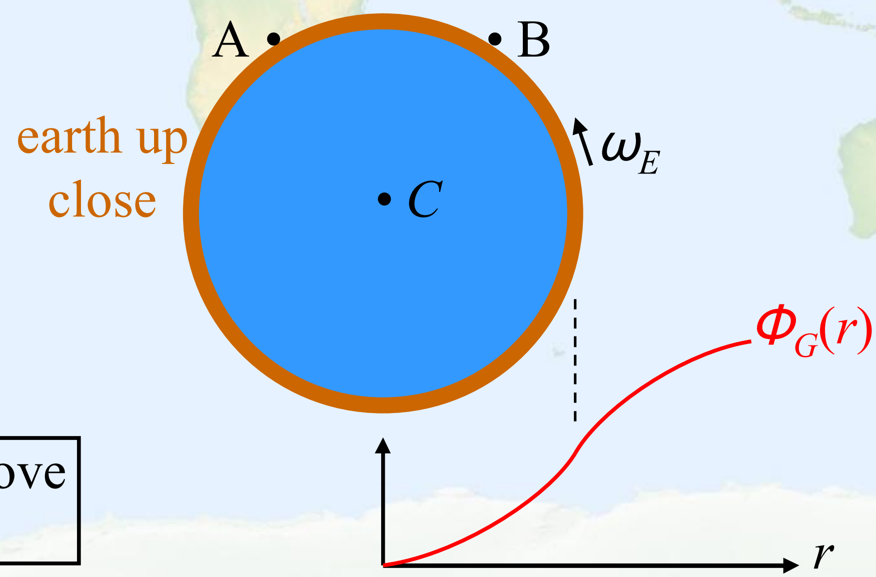


The earth needs a reference frame

- Clocks run faster at higher gravitational potential
  - But that's OK
- "Cindy" is at center of the earth
  - And not rotating (with respect to distant stars)

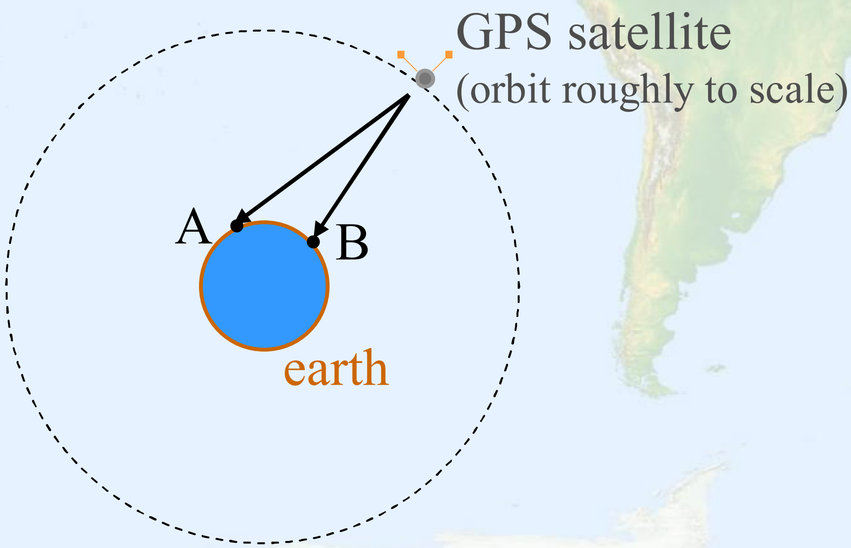


view from above north pole



Common View Synchronization

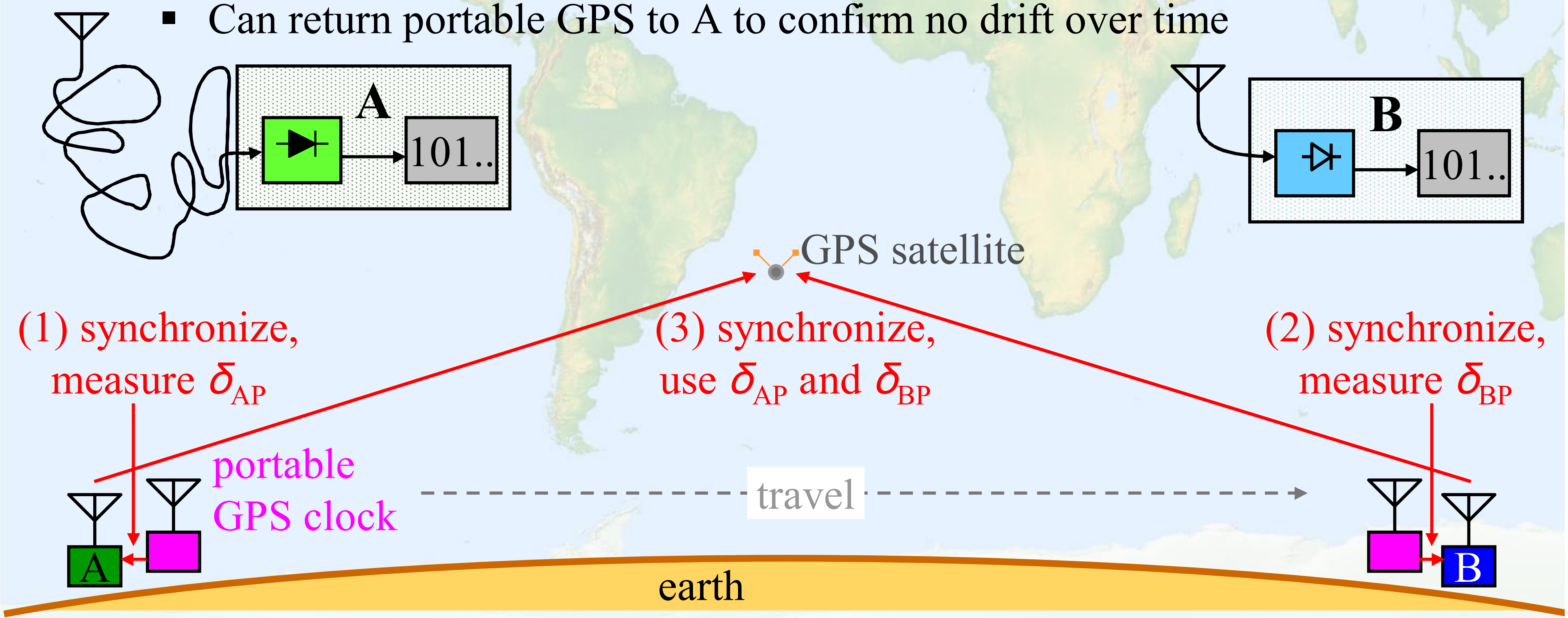
- Epoch Synchronization
  - Two earth stations receive the same satellite simultaneously
  - Cancels most atmospheric variation
  - Receivers adjust for propagation delay, in earth frame
  - < 3 ns error



We choose the GPS time coordinate so that it matches proper time on earth

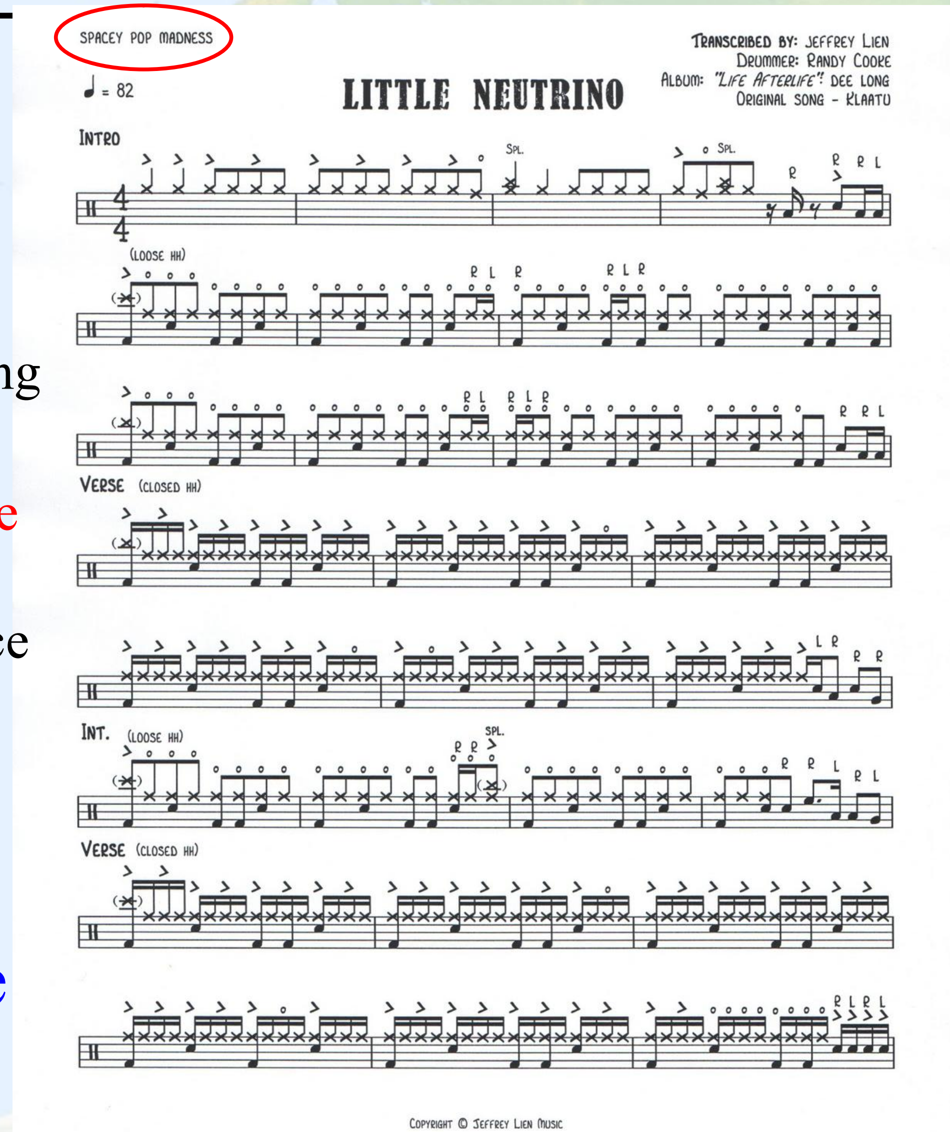
Get real: adjusting for variable delays

- Even between identical systems, the antenna cable and electronics have different delays
  - Portable GPS receiver calibrates these to each other
  - 3 step synchronization process: (1) A to P, (2) B to P, (3) A to B
  - Can return portable GPS to A to confirm no drift over time



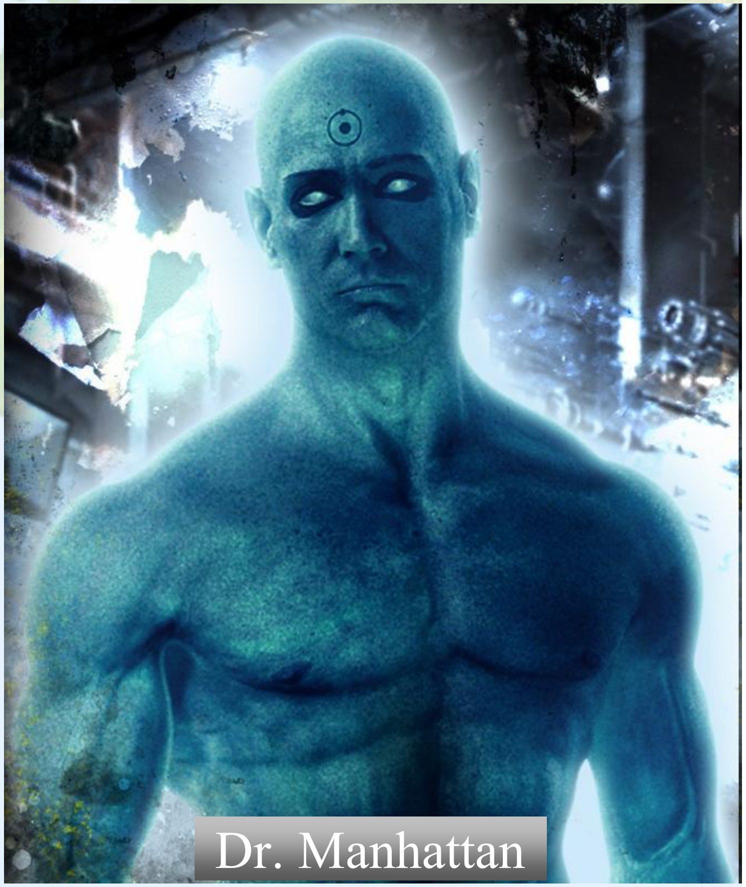
Why Not Use Satellite Frame?

- We could, but it's harder
  - However, it *is* inertial (freely falling)
  - Earth clocks move at constant gravitational potential, but varying speed
  - Earth clocks are not epoch or rate synchronized to satellite MCRF (momentarily comoving reference frame)
- NB: GPS-disciplining an earth clock does *not* make it run in the satellite frame of reference



Conclusion

- There is a reference frame with stationary metric that includes the earth's surface and GPS satellite clocks
  - Thus clocks can be synchronized
- There may be a measurement error in OPERA neutrino TOF, but it is not due to:
  - GPS synchronization method
  - SR time dilation
  - Gravitational potential time dilation
  - Non-inertial frames



Other numbers

- Sagnac effect: 2.2 ns
- GPS satellite motion: 3,900 m/s
  - $\gamma = 1 + 8.5\times10^{-11}$
  - H = 20,200 km, or R = 26,600 km
  - Propagation delay < 0.1 s (< 0.089 s)

Pair o' clocks paradox

- Two synchronized clocks (observers) can measure a 3rd clock differently
  - The MCRF is only valid for infinitesimal distances
  - It can fail dramatically for far away things, such as the rate of a far away clock
  - Suppose an MCRF and merry-go-round observer have synchronized clocks
    - They both look at the same, central clock
    - The orbiter says the clock runs fast, while the MCRF says it runs slowly
- In this case, synchronization is *not* transitive
  - The orbiter uses *one* clock to measure rate of central clock...
  - But the MCRF uses *two* separate clocks to measure its rate