

# *Project GREAT (2005)*

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General Relativity Einstein / Essen  
Anniversary Test

G<sup>2</sup>REAT

Tom Van Baak  
*tvb@LeapSecond.com*

PTTI 2006  
Washington DC

# Introduction

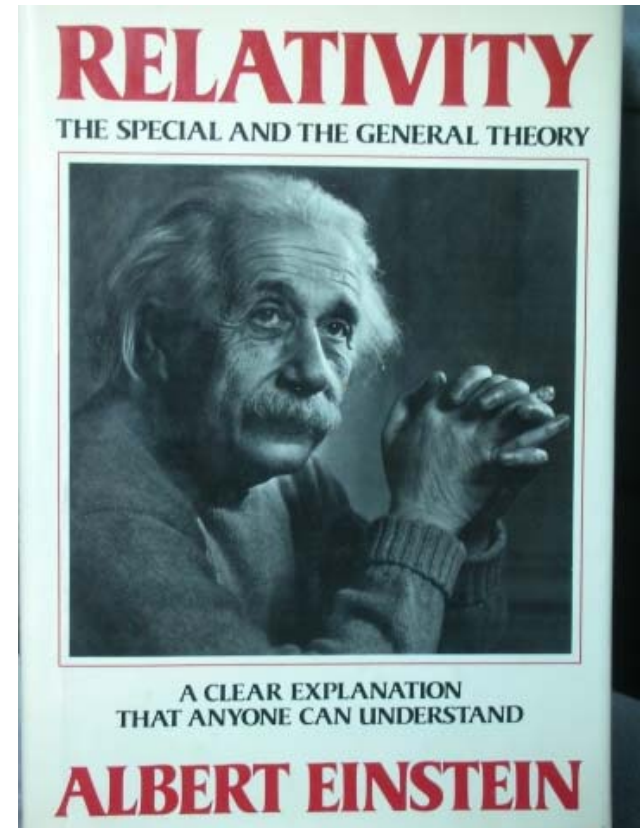
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- Project GREAT in 2005
  - Attempt to prove the theory of relativity
  - Take cesium clocks up a mountain
  - Do clocks really speed up or slow down?
- Celebrate 100<sup>th</sup> anniversary of 1905
  - Albert Einstein's "Annus Mirabilis"
- Celebrate 50<sup>th</sup> anniversary of 1955
  - Louis Essen's NPL cesium clock

# Albert Einstein

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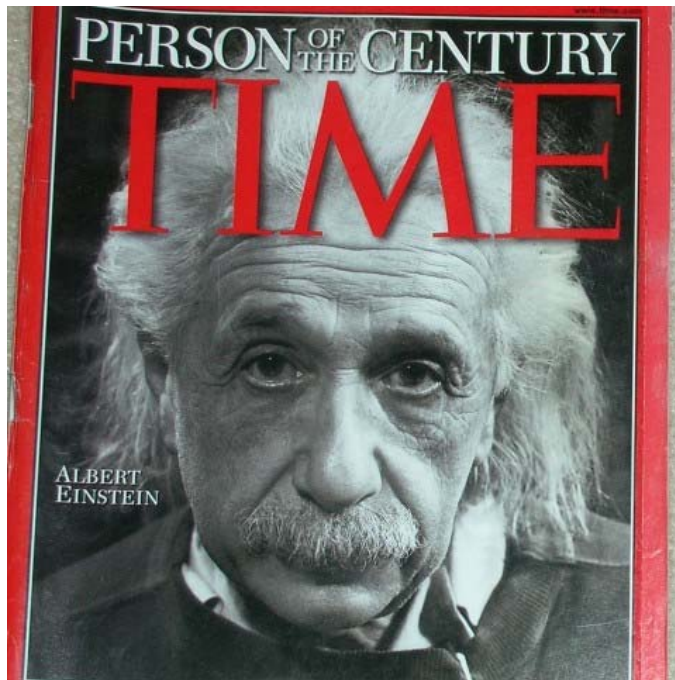
- Who was Einstein?
  - Need I say more...
  - Theory of relativity
  - Time is not absolute
  - SR, GR, space-time
  - Bold predictions
  - Later confirmed
  - Enormous influence



# Einstein and 2005

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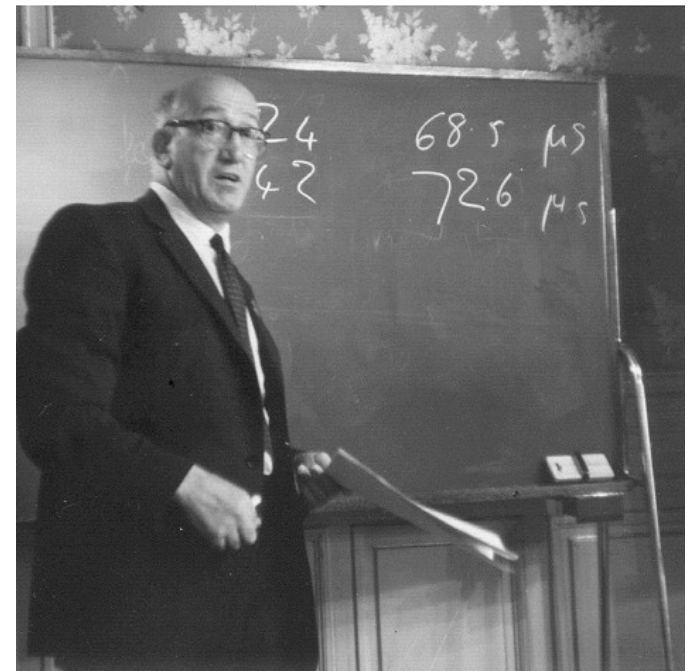
- 100<sup>th</sup> anniversary of relativity: books, magazines, radio, TV, web sites, "Physics Year", lectures...



# Louis Essen

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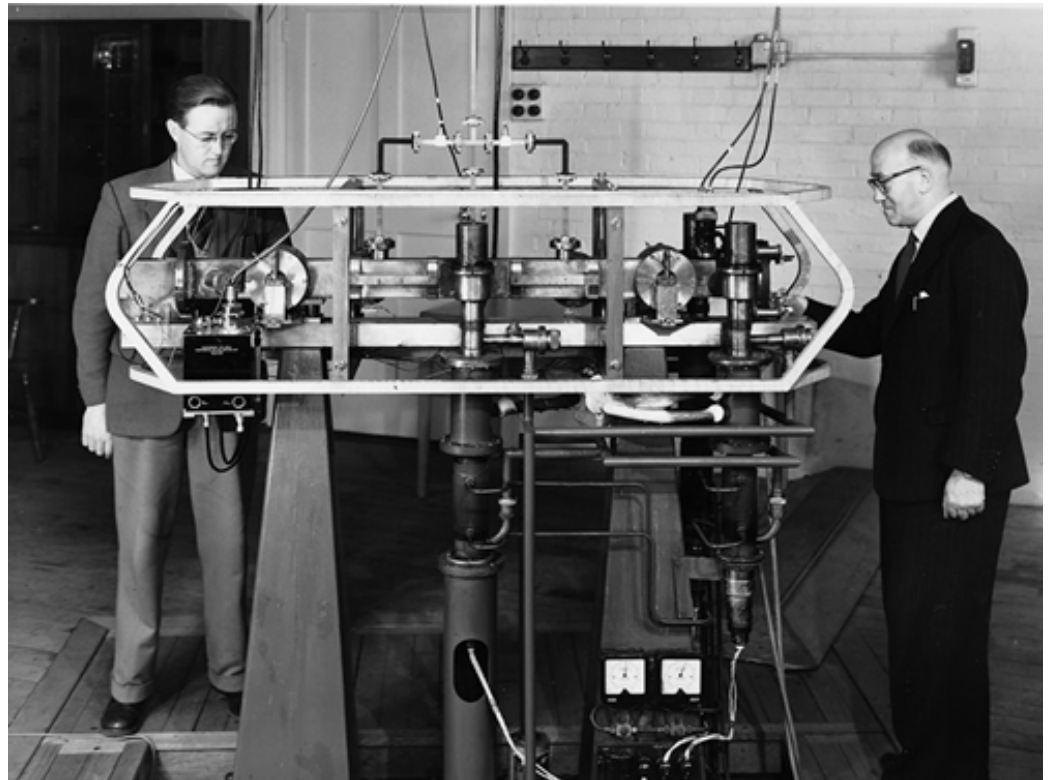
- Who was Essen?
  - First Cesium Clock
  - Joint NPL USNO project to calibrate atomic time against astronomical time
  - 9 192 631 770 Hz
  - Book: "Famous for a second"



# Essen and 2005

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- 50<sup>th</sup> anniversary of atomic time
- NPL Caesium



Jack Parry and Louis Essen  
Photo from [www.npl.co.uk/essen/](http://www.npl.co.uk/essen/)

# Cs Second

- 1954...1958
- How long is a second?

comparison between the cesium beam at Teddington and the moon camera at Washington. From an analysis of the various factors involved we have adopted a probable error of  $\pm 20$  cps.

We find, thus, the transition frequency of cesium  $(4, 0) \rightarrow (3, 0)$  at zero magnetic field is

$$\nu_E = 9\,192\,631\,770 \pm 20 \text{ cycles per second (of E.T.) at 1957.0.}$$

The mean epoch is specified because there is a possibility that the gravitational and atomic time scales may not be the same, and may change secularly. Future determinations of  $\nu_E$  will decide this question.

VOLUME 1, NUMBER 3

PHYSICAL REVIEW LETTERS

AUGUST 1, 1958

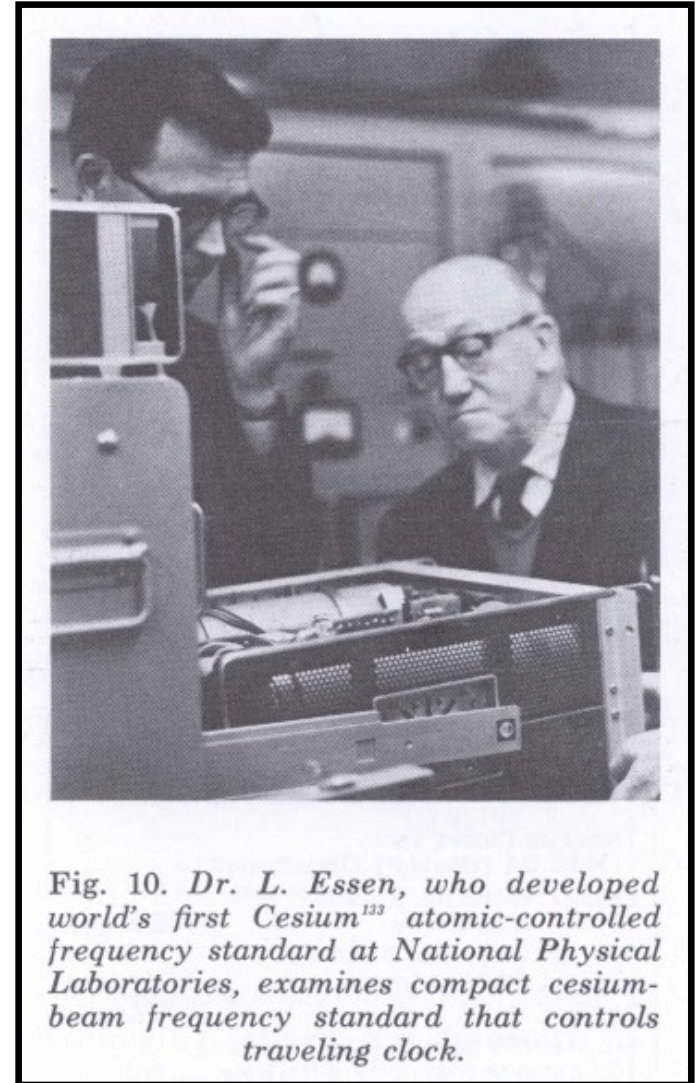
Table I. Results for  $\nu_E$  obtained from four different sets of data.

	Means	$\Delta H$ (sec)	$\nu_E - \bar{\nu}_U$	$\nu_E$	$\Delta T''$ (sec/yr <sup>2</sup> )
1.	$\Delta T_\theta$ , 1954.25-1958.25	+1.146	-121	9 192 631 761	+ 0.17
2.	$\Delta T_0$ , 1955.25-1958.25	1.085	-115	767	+ 0.10
3.	$\Delta T_C$ , 1954.25-1958.25	1.035	-110	772	+ 0.12
4.	$\Delta T_C$ , 1955.25-1958.25	0.966	-102	780	+ 0.17

# Louis Essen

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- 10 years later ...
- Essen at NPL with a HP 5060A "Flying Clock"





# Flying Clocks in the 1960's

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- Starting in 1964 with HP 5060A
- Portable transistorized cesium clock
- Hundreds of clock trips
- Remote synchronization to  $\mu\text{s}$  levels
- See HP Journals: 1964, 65, 66, 67
- 1965 world-wide time synchronization
- Paved the way for flying clock relativity experiments in the 1970's

# Relativity and Clocks

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- High-level summary:
  - Clocks run slower if they move at high velocity (SR)
  - Clocks run slower in the presence of greater gravity (GR)
  - Clocks lose time traveling East (Sagnac)
- This implies:
  - According to general relativity, stationary clocks on mountains run faster.

# And so... 2005

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- General  
  R  
  E  
  E  
  A  
  T  
  Test
- Project GRE<sup>2</sup>AT

# Chapter 2

- Flying clock experiments

# 1971 Hafele & Keating

- PTTI, vol 3, 1971
- Time, Oct 18, 1971
- Science, Jul 14, 1972



Table 1. Observed relativistic time differences from application of the correlated rate-change method to the time intercomparison data for the flying ensemble. Predicted values are listed for comparison with the mean of the observed values; S.D., standard deviation.

Clock serial No.	$\Delta\tau$ (nsec)	
	Eastward*	Westward
120	- 57	277
361	- 74	284
408	- 55	266
447	- 51	266
Mean		
± S.D.	- 59 ± 10	273 ± 7
Predicted		
± Error est.	- 40 ± 23	275 ± 21

\* Negative signs indicate that upon return the time indicated on the flying clocks was less than the time indicated on the MEAN(USNO) clock of the U.S. Naval Observatory.

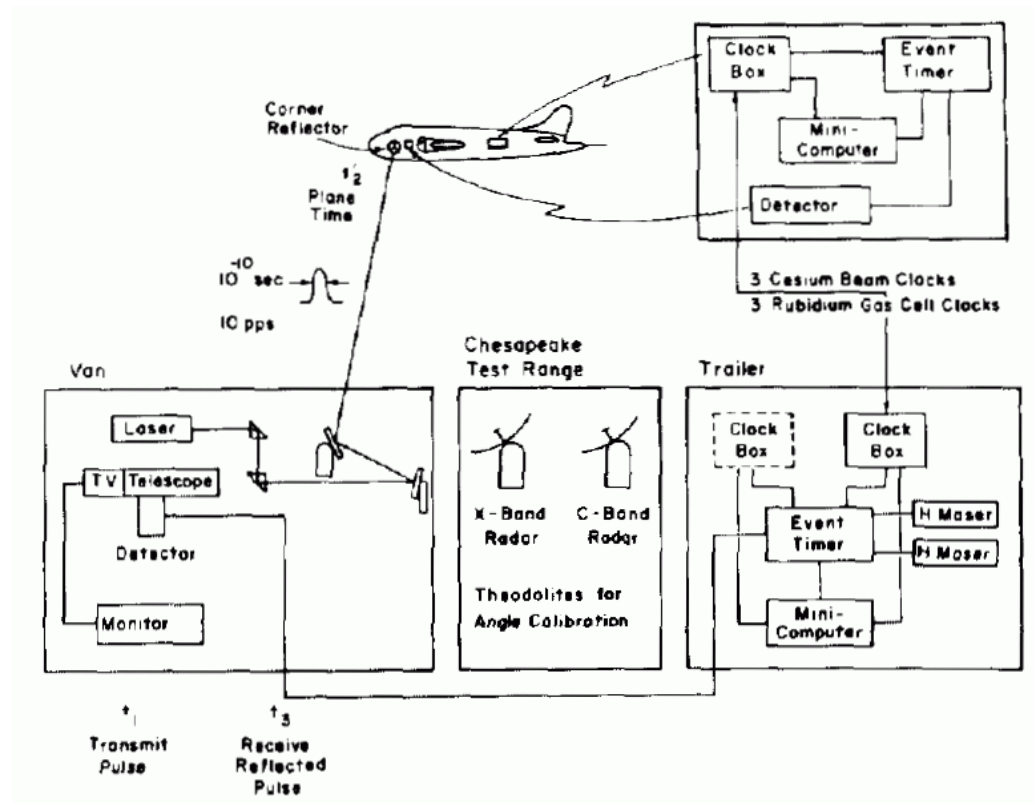
# Hafele & Keating

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- Round-the-world (EW/WE) flying clocks
- Hafele thought there would be effect
- Keating didn't (was open to finding out)
- Many scientists were "certain"
- Results were stunning: all 4 clocks showed difference between EW and WE
- Relatively simple, cheap experiment

# 1975 C.O. Alley

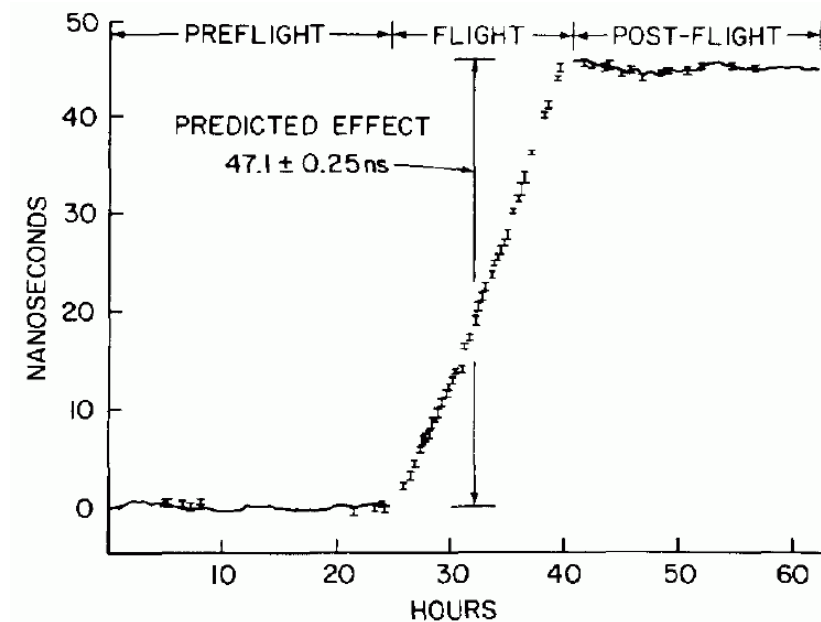
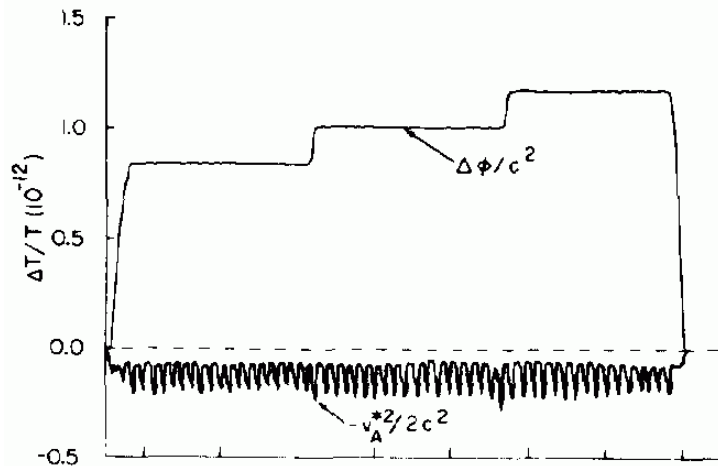
- Multiple flights
- P3C airplane
- Chesapeake Bay
- Environment
- Multiple clocks
  - 3 Cs, 3 Rb, 2 HM
  - L.C. 5061A
- Laser link



# C.O. Alley

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- 3 different altitudes (25, 30, 35 000)
- 5 flights, 2 h, multiple clocks, 0.5%





# 1976 R.F.C Vessot & M. Levine

- H-maser up, up and away: 10,000 km!
- NASA, ground stations, up/down links
- GP-A amazing results, 0.0070%, 70 ppm

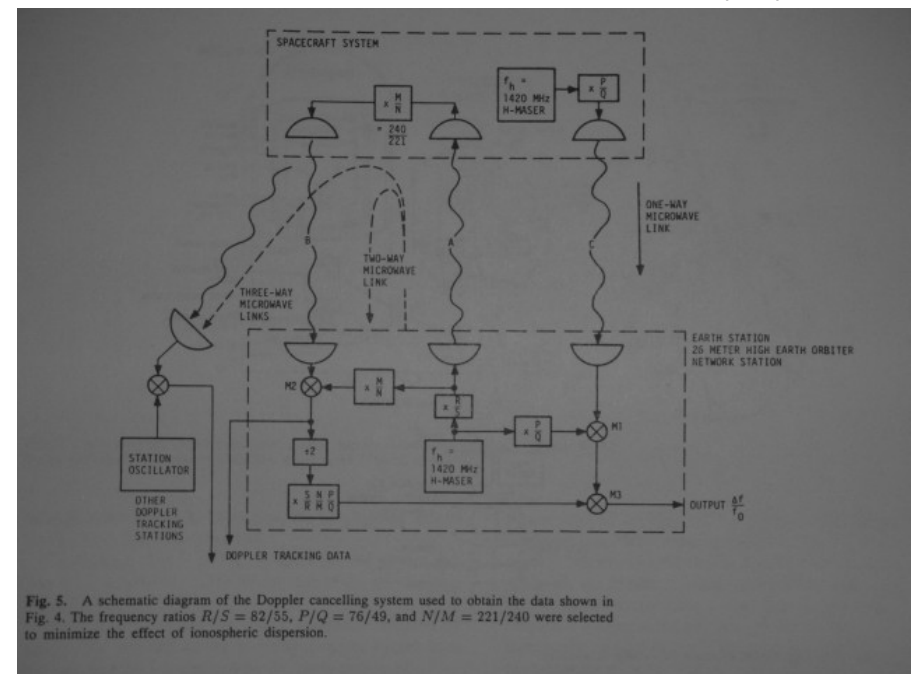
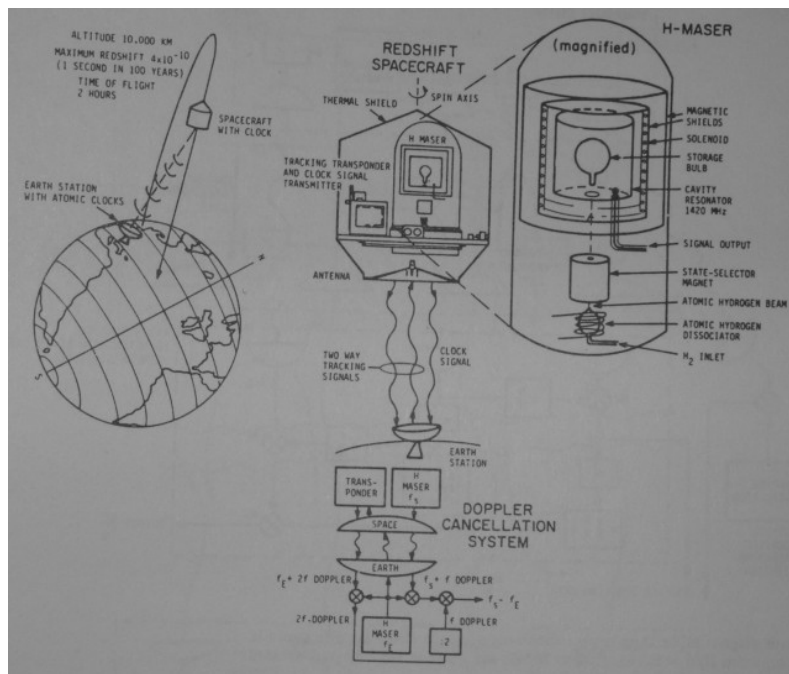
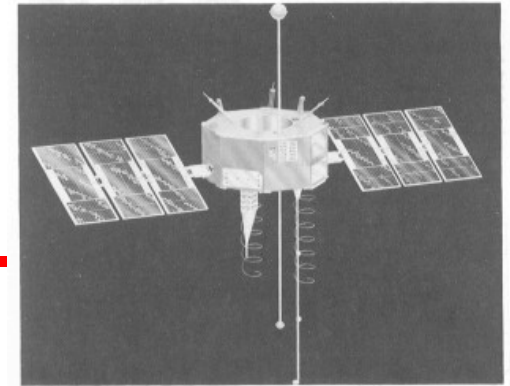
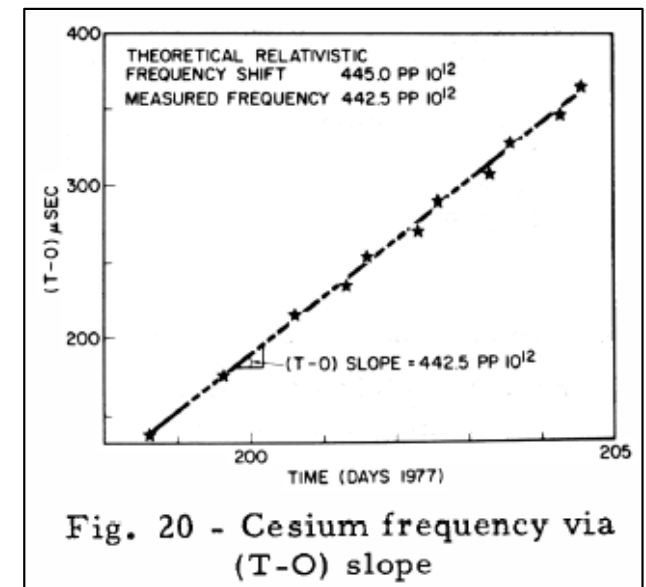
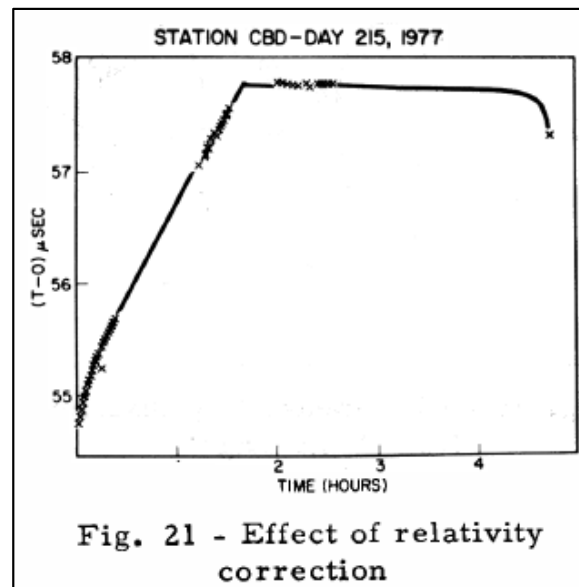
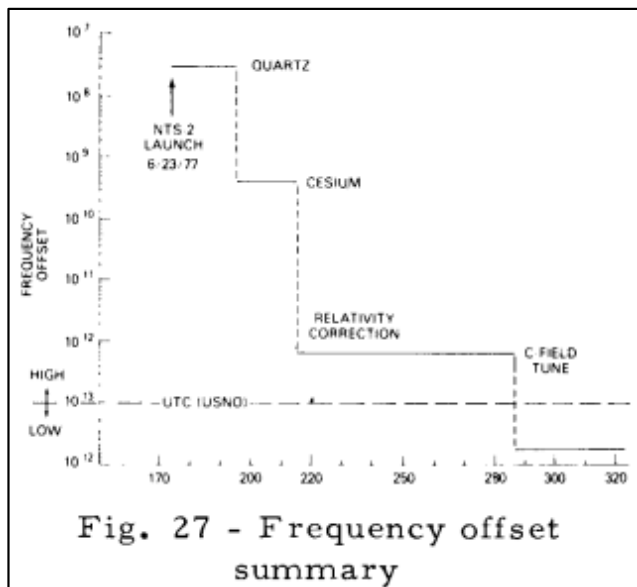


Fig. 5. A schematic diagram of the Doppler cancelling system used to obtain the data shown in Fig. 4. The frequency ratios  $R/S = 82/55$ ,  $P/Q = 76/49$ , and  $N/M = 221/240$  were selected to minimize the effect of ionospheric dispersion.

# 1977 NTS-2



- Navigation Test Satellite #2
- First NAVSTAR GPS, cesium in space
- Verify relativistic effects



# Recent relativity experiments

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- 1996 NPL & BBC - 25<sup>th</sup> anniversary of H&K with London (NPL) to Washington DC (USNO)
- 2000 T. Celano, TSC - military airplane, cesium clocks, comsat modems
- 2002 T. Celano, TSC - similar but with two-way communication, real-time corrections

# Recent relativity experiments

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- 2000-2002 - CRL (NICT) measured GR time dilation when moving several 5071A between low and high altitude facilities
- Also, many non-atomic clock relativity experiments are in progress
- GP-B, black holes, LIGO, ...

# Chapter 3

- The Big Idea

# Relativity at home?

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- Theory of relativity well confirmed
  - With planets, particles, atomic clocks
- But is it so extreme, so exotic, that only places like Harvard, USNO, JPL, or NASA can prove it?
- Or is it possible to perform a home experiment to confirm Einstein's prediction? This seems far-fetched.

# Relativity at home

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- Methods; take atomic clock
  - At high speed, or
  - To high altitude, or
  - On long eastward or westward trip, or
  - All the above
- Modes; transport using
  - Airplane
  - Rocket
  - Satellite

# Relativity at home

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- None of those methods work for me:
  - I don't have a plane
  - Rocket or satellite is out of the question
- But I do have:
  - Many atomic clocks
  - Nearby mountains
- So, use a mountain?





# Northwest Mountains

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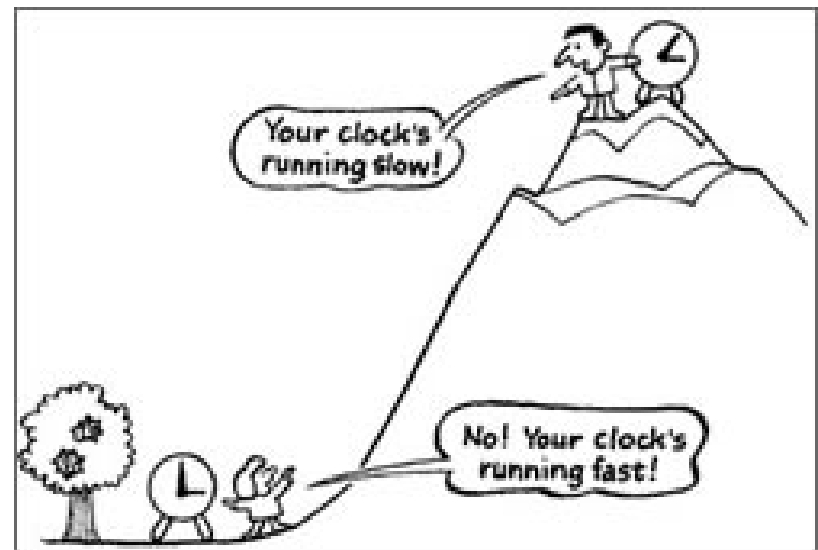
- (N) Mt Baker, Glacier Peak
- (S) Mt Rainer, Mt Adams, Mt St Helens
- (E) Olympic range, Cascade range...



# Back of Envelope Calculation

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- According to GR, clock frequency changes approximately by:  
 $\approx g \cdot \Delta h / c^2$
- On earth, this is  
 $\approx 1.09 \times 10^{-16} / \text{meter}$
- That's really small!
- Too small for me (or anyone) to measure



From NPL website

# $1.1 \times 10^{-16}$ is too small, but

---

- Say, you go up 1 km instead of 1 m  
 $\Delta f = 1.1 \times 10^{-13} = 0.11 \text{ ps/s}$
- And stay a whole day  
 $\Delta T = \Delta f \times 86400 \text{ s} = 9.5 \text{ ns}$
- 9 ns is "huge"; so this looks possible!
- The key to detecting time dilation: go high and stay long
- Sign is + (blue shift)

# The Big Idea

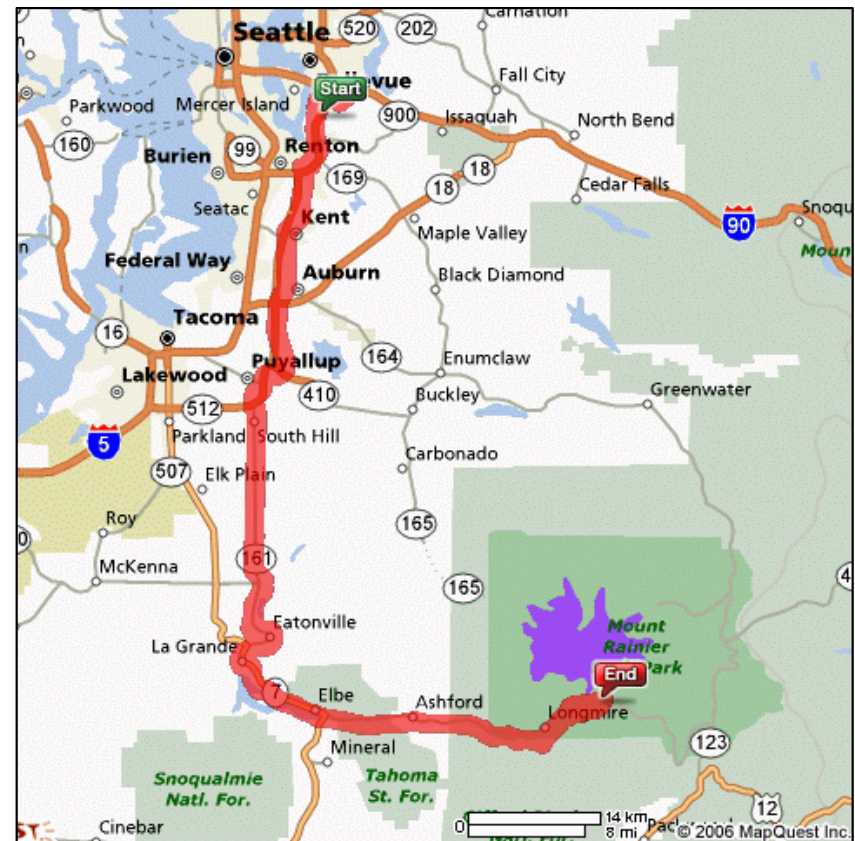
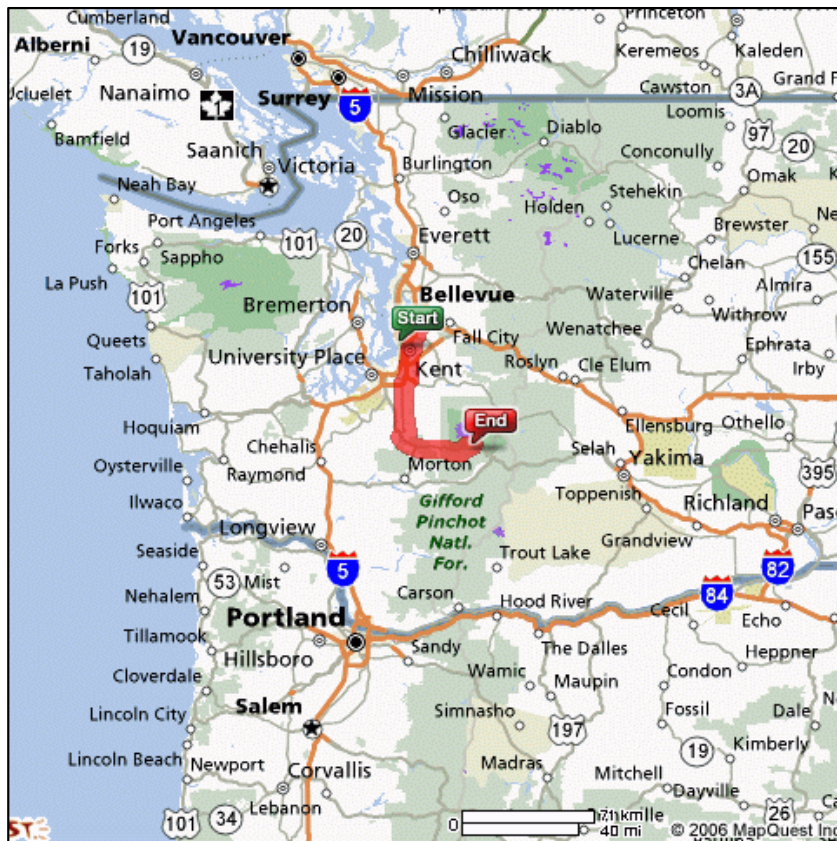
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- Take our 3 kids and 3 cesium clocks up Mt Rainier
- See if Einstein was right about gravity and time
- See if clocks really run faster up there



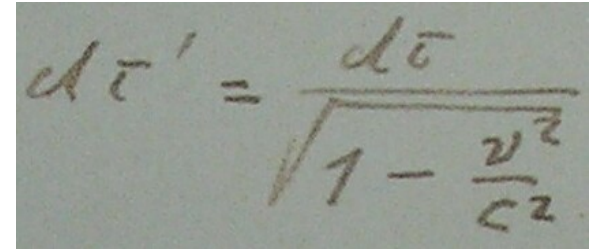
# Map: Seattle to Mt Rainier

- Just 100 miles away (~2½ hours)



# Math Detail

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$$d\tau' = \frac{d\tau}{\sqrt{1 - \frac{v^2}{c^2}}}$$

- To a first approximation, small  $v$ ,  $\Delta h$
- Kinematic:  $\Delta f_k \approx -\frac{1}{2}v^2/c^2$
- Gravitation:  $\Delta f_g \approx +g\Delta h/c^2$
- Sagnac:  $\Delta f_s \approx -\omega R^2 \cos^2(\phi) \cdot \lambda / c^2$
- Net  $\Delta f = \Delta f_k + \Delta f_g + \Delta f_s$
- Total  $\Delta T = \sum \Delta f \times T$

# Prediction: Sagnac Effect

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- $\cos^2$  factor is 0.5 for  $45^\circ$  vs. equator
- 200 ns for 40 000 km round-the-world
  - So 0.001x that for 40 km, or 200 ps
- No effect for N-S travel
- And no effect for same-path round-trip
- So ignore Sagnac effect

# Prediction: Velocity Effect

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- Automobile speeds are relatively low
  - 65 mph  $\approx$  96 fps  $\approx$  100 kph  $\approx$  30 m/s
- Actual trip is 100 miles and 2.5 hours
  - Average speed below 40 mph
- Worst case 30 m/s for  $10^4$  s
  - so  $\Delta f = 5 \times 10^{-15}$ , and  $\Delta T = -50$  ps.
- So ignore Velocity factor too!



# Prediction: Gravitational

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- Guess 40 to 48 hours
- Guess  $1640 - 300 = 1340$  meters
- $\Delta f = 1.5 \times 10^{-13}$ 
  - This  $\Delta f$  is very measurable with 5071A
- $1340 \text{ m} \times 40 \text{ hours}$
- $\Delta T \approx +20 \text{ ns}$ 
  - This  $\Delta T$  is very measurable with 53132A

# Time Dilation Examples

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Transport	Speed (km/h)	Altitude (km)	$\Delta f$	$\Delta T$
Walking	5	0	$\sim 0$	$\sim 0$ ps/h
Car	100	0	$-4 \times 10^{-15}$	16 ps/h 0.4 ns/d
Balloon	0	10	$+1.1 \times 10^{-12}$	+95 ns/d
Plane	900	10	$-3.5 \times 10^{-13}$ $+1.1 \times 10^{-12}$	-30 ns/d +95 ns/d
GREAT 2+2 h drive	100	0		60 ps
GREAT 40 h stay	0	1.340	$+1.5 \times 10^{-13}$	20 ns

# Summary - Calculations

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- "Many, High, Long"
- 3 best clocks (5071A/001)
- 1340 m (5400' - 1000') altitude
- Weekend (40 h)
- $1 \times 10^{-16}$  & 1340 m & 40h &  $\sqrt{3}$
- Estimate ~20 ns
- Estimated accuracy ~2 ns, 10%
- Time dilating at about 500 ps / hour

# Clocks on Mountains

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- Climb or drive?
- Plus batteries...



# Clocks on Mountains

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- Drive, of course
- This is America...



# One-way or Round-trip

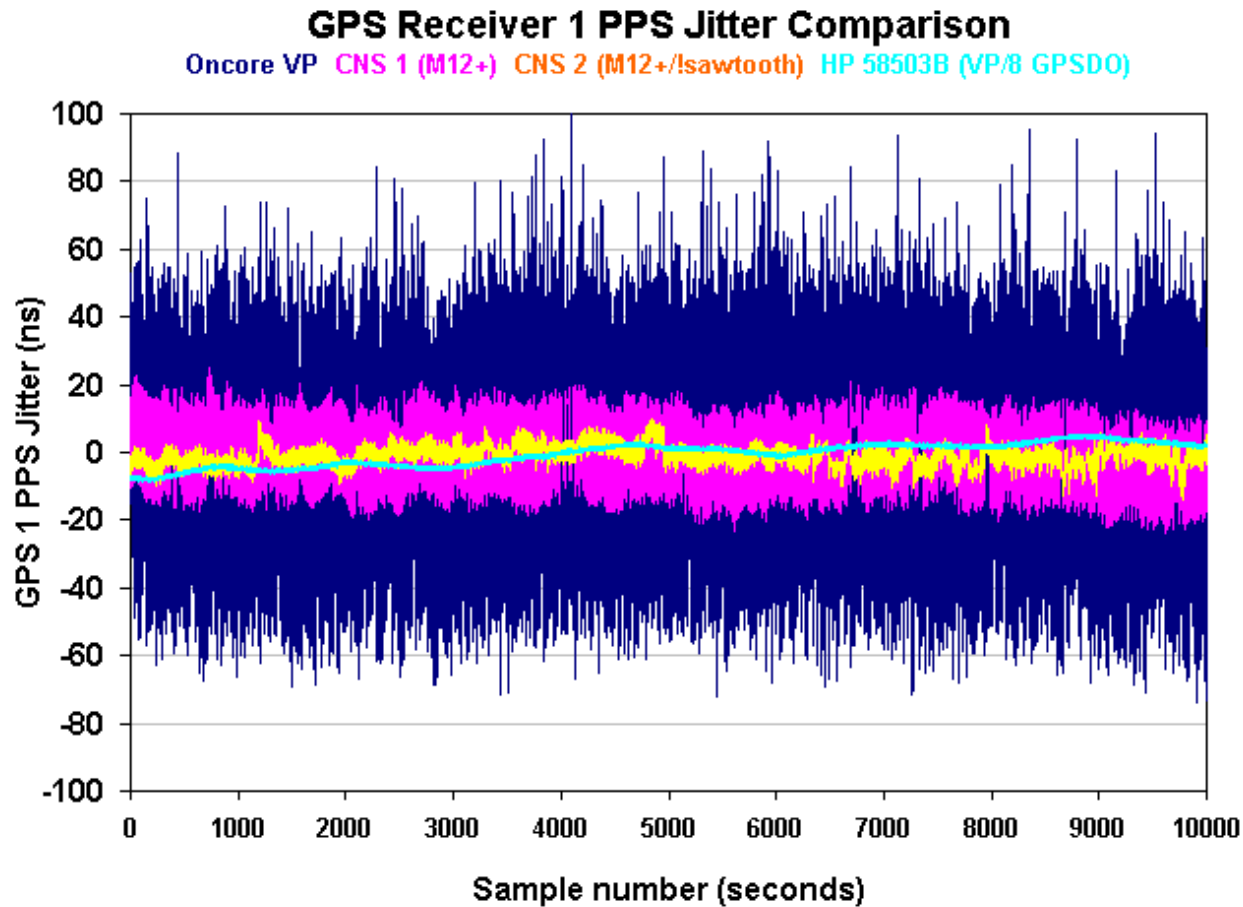
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- Clocks run slower on a mountain so:
  - Measure frequency of clock at home
  - Measure frequency of clock on mountain
- Measure against what?
  - How about GPS time & frequency
  - Need better than  $10^{-13}$  accuracy
  - Not with my GPS receivers

# GPS reference

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- Direct frequency measurement (GPS)



# Summary - Big Idea

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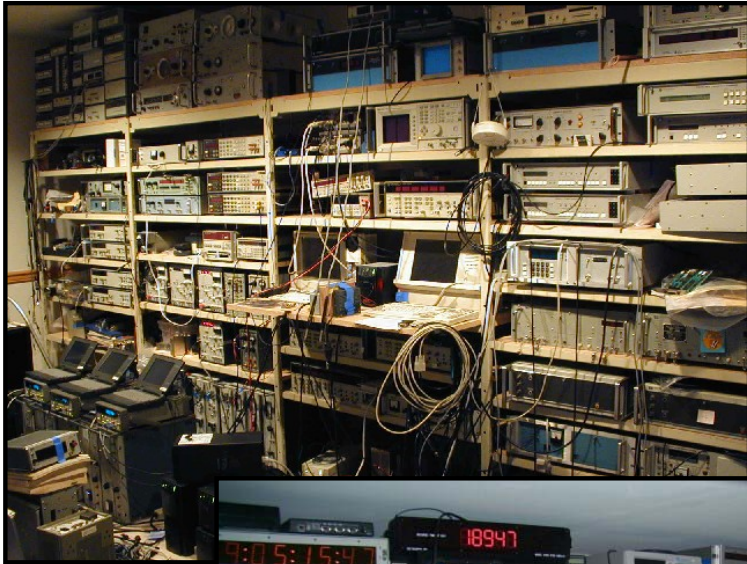
- 3 kids, 3 clocks, 1 family minivan
  - To 5400 feet
  - For 40 hours
  - Expect +20 ns
- Sync time/rate before trip
- Measure time/rate after trip
- Against reference; my "house standard"



# Chapter 4


- Home time lab

# Home Time Museum & Lab



# Where does it all come from?

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- Local aero/mil-surplus electronics
- Ham conventions; flea markets
- Used test equipment dealers
- Demo or refurbished models
- Friends, strangers; other "time-nuts"
- Sympathetic T & F companies
- And, of course,  !

# Surplus Time & Frequency

eBay: 5060A cesium beam atomic clock (item 190033321298 end time Sep-26-06 19:15:26 PDT)

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**5060A cesium beam atomic clock**

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Starting bid: **US \$100.00** Place Bid >

End time: **4 hours 47 mins**  
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Shipping costs: **US \$50.00**  
Standard Flat Rate Shipping Service

Ships to: United States

Item location: Sterling, VA, United States

History: [0 bids](#)

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Shipping costs: **US \$75.00 (discount available)**  
Standard Flat Rate Shipping Service

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Item location: silicon valley, United States

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IMMACULATE Condition! Competitive Offers considered!

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**Buy It Now** price: **US \$34,500.00**

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Back to My eBay Listed in category: Business & Industrial > Industrial Electrical & Test > Test

## Frequency Electronics Cesium Beam Standard/ Clock

You are signed in [Watch this item](#)



Starting bid: **US \$999.99** [Place Bid >](#)

End time: **Sep-27-06 20:00:00 PDT**  
(1 day 5 hours)

Shipping costs: Check item description and payment instructions or contact seller for details

Ships to: United States

Item location: Millersville, Maryland, United States

History: [0 bids](#)

You can also: [Watch this item](#)  
Get alerts via [Text message](#), [IM](#) or [Phone call](#)

Meet Seller Feed Members

Buy: 1. Clock 2. Le

eBay: Datum Austron GPS Rubidium Clock (item 130021839748 end time Sep-08-06 04:18:28 PDT)

File Edit View Favorites Tools Help

Back Forward Stop Home Search Favorites Refresh Print Mail

Address http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&item=130021839748

Google G Go Bookmarks 3 blocked Check

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Buy Sell My eBay Community Help

Back to My eBay Listed in category: Computing > Networking > Servers

## Datum Austron GPS Rubidium Clock

Bidding has ended for this item  
If you are a winner, [Sign In](#) for your status.

[Sell an item like this](#) or buy a similar item below.



Starting bid: **GBP 700.00**  
(Approximately US \$1,330.07)

Ended: **Sep-08-06 04:18:28 PDT**

Ships to: Worldwide

Item location: London, London, United Kingdom

History: [0 bids](#)

You can: [Email to a friend](#) | [Sell one like this](#)



# Surplus Time & Frequency

eBay: Efratom FRS-C 10MHz Rubidium Atomic Oscillator Standard (item 140031130392 end time Aug-30-06 20:00:00 PDT)

File Edit View Favorites Tools Help

Address http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&item=140031130392

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Buy Sell My eBay Community Help

Listed in category: [Business & Industrial](#) > [Industrial Electrical & Test](#) > [Test Equipment](#)  
 Also listed in: [Business & Industrial](#) > [Industrial Electrical & Test](#) > [Electrical Components](#)

**Efratom FRS-C 10MHz Rubidium Atomic Oscillator Standard**

You are signed in [Watch this item](#)



Starting bid: **US \$249.99** [Place Bid >](#)

**Buy It Now** price: **US \$299.99** [Buy It Now >](#)

End time: **Sep-28-06 12:09:33 PDT**  
(1 day 21 hours)

Shipping costs: Check item description and payment instructions or contact seller for details

Ships to: Worldwide

Item location: Phoenix, AZ, United States

History: [0 bids](#)

[View larger picture](#)

eBay: Ball Efratom Rubidium Oscillator 10 MHz FRK-L (item 120024221939 end time Aug-30-06 20:00:00 PDT)

File Edit View Favorites Tools Help

Address http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&item=120024221939

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Buy Sell My eBay Community Help

Listed in category: [Business & Industrial](#) > [Industrial Electrical & Test](#) > [Test Equipment](#)  
 Other Parts

**Ball Efratom Rubidium Oscillator 10 MHz FRK-L**

**Bidding has ended for this item**  
 If you are a winner, [Sign In](#) for your status.

[Sell an item like this](#) or buy a similar item below.



Winning bid: **US \$184.50**

Ended: **Aug-30-06 20:00:00 PDT**

Shipping costs: Check item description and payment instructions or contact seller for details

Ships to: United States

Item location: Millersville, Maryland, United States

History: [13 bids](#)

**Meet the Seller:**  
 Feedback: [View](#)  
 Member since: [View](#)

**Buy it now:** [View](#)

# Surplus Time & Frequency

eBay: FTS 4040A Cesium frequency standard (item 300025844151 end time Sep-12-06 19:00:00)

File Edit View Favorites Tools Help

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Address http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&item=300025844151

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Buy Sell My eBay Community Help

Back to My eBay Listed in category: Business & Industrial > Industrial Electrical & Test > Test

## FTS 4040A Cesium frequency standard

**Bidding has ended for this item**  
If you are a winner, [Sign In](#) for your status.

[Sell an item like this](#) or buy a similar item below.



Winning bid: **US \$850.00**  
Make no payments for 3 months - [Apply](#)

Ended: **Sep-12-06 19:00:00 PDT**

Shipping costs: Check item description and payment instructions or contact seller for details

Ships to: United States, Canada

Item location: Manchester, New Hampshire, United States

History: [10 bids](#)

eBay: Stanford Research FS700 Frequency Standard (item 7598463962 end time Oct-05-06 10:20:00)

File Edit View Favorites Tools Help

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Address http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&item=7598463962

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Buy Sell My eBay Community Help

Back to My eBay Listed in category: Business & Industrial > Industrial Electrical & Test > Test

## Stanford Research FS700 Frequency Standard

10 MHz LORAN-C Frequency Standard with Antenna!

You are signed in [Watch It](#)

**Buy It Now** price: **US \$2,950.00**

Shipping costs: Check item description and payment instructions or contact seller for details

Ships to: Worldwide

Item location: Oceanside, CA, United States

You can also: [Watch this item](#)  
Get alerts via [Text message](#) or [IM](#)  
[Sell one like this](#)

**Listing and payment details:** [Show](#)

**Meet the seller:**  
Seller: [View Profile](#)  
Feedback: [View Feedback](#)  
Member since: [View](#)  
[View](#)  
[View](#)  
[View](#)

**Buyer's Choice:**  
1. [View](#)  
2. [View](#)  
3. [View](#)

# Surplus Time & Frequency

eBay: FTS 1000 ULTRA STABLE OSCILLATOR FREQUENCY STANDARD (item 290010852638 end tim

File Edit View Favorites Tools Help

Back Search Favorites

Address http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&item=290010852638

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Buy Sell My eBay Community Help

Back to My eBay Listed in category: Business & Industrial > Industrial Electrical & Test > Test

### FTS 1000 ULTRA STABLE OSCILLATOR FREQUENCY STANDARD

You are signed in [Watch this item](#)



**Buy It Now** price: **US \$757.25** [Buy It Now >](#)

Make no payments for 3 months - [Apply](#)

Shipping costs: **US \$12.00**  
Standard Flat Rate Shipping Service

Ships to: Worldwide

Item location: New York, United States

Quantity: 2 available

History: [Purchases](#)

You can also: [Watch this item](#)  
Get alerts via [Text message](#) or [IM](#)  
[Sell one like this](#)

[View larger picture](#)

eBay: FTS 1130 ULTRA STABLE OSCILLATOR FREQUENCY STANDARD (item 290021507967 end tim

File Edit View Favorites Tools Help

Back Search Favorites

Address http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&item=290021507967

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Buy Sell My eBay Community Help

Back to My eBay Listed in category: Business & Industrial > Industrial Electrical & Test > Test

### FTS 1130 ULTRA STABLE OSCILLATOR FREQUENCY STANDARD

You are signed in [Watch this item](#)



**Buy It Now** price: **US \$757.25** [Buy It Now >](#)

Make no payments for 3 months - [Apply](#)

Shipping costs: **US \$12.00**  
Standard Flat Rate Shipping Service

Ships to: Worldwide

Item location: New York, United States

You can also: [Watch this item](#)  
Get alerts via [Text message](#) or [IM](#)  
[Sell one like this](#)

[View larger picture](#)

Listing and payment details: [Show](#)

# Surplus Time & Frequency

eBay: FTS 6001 CESIUM MULTI CHANNEL PHASE COMPARATOR (item 290033007646 end time Oct 06 2006)

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Address http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&item=290033007646

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Buy Sell My eBay Community Help

Back to My eBay Listed in category: Business & Industrial > Industrial Electrical & Test > Test

## FTS 6001 CESIUM MULTI CHANNEL PHASE COMPARATOR

You are signed in [Watch this item](#)



**Buy It Now** price: **US \$575.00** [Buy It Now >](#)

[Make no payments for 3 months - Apply](#)

Shipping costs: **US \$22.75**  
Standard Flat Rate Shipping Service

Ships to: Worldwide

Item location: New York, United States

You can also: [Watch this item](#)  
[Get alerts via Text message or IM](#)  
[Sell one like this](#)

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Listing and payment details: [Show](#)

eBay: RUBIDIUM SYMMETRICOM EFRATOM LPRO-101 (item 290023487129 end time Sep-02-06 2006)

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Address http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&item=290023487129

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Buy Sell My eBay Community Help

Back to My eBay Listed in category: Business & Industrial > Industrial Electrical & Test > Test

## RUBIDIUM SYMMETRICOM EFRATOM LPRO-101

Bidding has ended for this item  
If you are a winner, [Sign In](#) for your status.

[Sell an item like this](#) or buy a similar item below.



Winning bid: **US \$255.00**  
[Make no payments for 3 months - Apply](#)

Ended: **Sep-02-06 23:00:32 PDT**

Shipping costs: **US \$10.00**  
Standard Flat Rate Shipping Service

Ships to: Worldwide

Item location: Chicago, IL, United States

History: [8 bids](#)

# Surplus Time & Frequency

eBay: OSCILLOQUARTZ AMPLIFIER MODULE for FREQUENCY STANDARD (item 290033007939 end t

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Buy Sell My eBay Community Help

Back to My eBay Listed in category: Business & Industrial > Industrial Electrical & Test > Test Equipment & Other Signal Generators

**OSCILLOQUARTZ AMPLIFIER MODULE for FREQUENCY STANDARD**

You are signed in [Watch this item](#)



**Buy It Now** price: **US \$1,230.00** [Buy It Now >](#)

[Make no payments for 3 months - Apply](#)

Shipping costs: **US \$45.00**  
Standard Flat Rate Shipping Service

Ships to: Worldwide

Item location: New York, United States

You can also: [Watch this item](#)  
[Get alerts via Text message](#) or [IM](#)  
[Sell one like this](#)

[View larger picture](#)

Listing and payment details: [Show](#)

eBay: STANFORD RESEARCH RUBIDIUM PRS10 FREQUENCY STANDARD (item 290021918472 end t

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Address http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&item=290021918472

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Buy Sell My eBay Community Help

Back to My eBay Listed in category: Business & Industrial > Industrial Electrical & Test > Test Equipment & Other Signal Generators

**STANFORD RESEARCH RUBIDIUM PRS10 FREQUENCY STANDARD**

**Bidding has ended for this item**  
If you are a winner, [Sign In](#) for your status.

[Sell an item like this](#) or buy a similar item below.



Winning bid: **US \$535.25**  
[Make no payments for 3 months - Apply](#)

Ended: **Aug-31-06 19:08:35 PDT**

Shipping costs: **US \$15.00**  
Standard Flat Rate Shipping Service

Ships to: Worldwide

Item location: New York, United States

History: [2 bids](#)

# Surplus Time & Frequency

eBay: OVENAIRE 1 MHZ OVEN - QUARTZ FREQUENCY STANDARD (item 7631007623 end time Oct-10 12:00 PM EDT)

File Edit View Favorites Tools Help

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Address http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&item=7631007623

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Buy Sell My eBay Community Help

Back to list of items Listed in category: Business & Industrial > Industrial Electrical & Test > T

### OVENAIRE 1 MHZ OVEN - QUARTZ FREQUENCY STANDARD

TESTED - GUARANTEED - FREE SHIPPING

You are signed in [Watch this item](#)



**Buy It Now** price: **US \$99.00** [Buy It Now >](#)

**Best Offer** [Make Offer >](#)

Shipping costs: **FREE**  
Other (see description)  
[\(more services\)](#)

Ships to: Worldwide

Item location: Rhodes Island, Greece

You can also: [Watch this item](#)  
Get alerts via [Text message](#) or [IM](#)

**Meet**  
Sellers  
Feedback  
Members

**Buy**  
1. C  
ε

eBay: CTS 10 MHz QUARTZ CRYSTAL OSCILLATOR FREQUENCY STANDARD (item 290010850492 end time Oct-10 12:00 PM EDT)

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Address http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&item=290010850492

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Back to list of items Listed in category: Business & Industrial > Industrial Electrical & Test > T

### CTS 10 MHz QUARTZ CRYSTAL OSCILLATOR FREQUENCY STANDARD

You are signed in [Watch this item](#)



**Buy It Now** price: **US \$47.25** [Buy It Now >](#)

Shipping costs: **US \$12.00**  
Standard Flat Rate Shipping Service

Ships to: Worldwide

Item location: New York, United States

Quantity: 4 available

History: [Purchases](#)

You can also: [Watch this item](#)  
Get alerts via [Text message](#) or [IM](#)  
[Sell one like this](#)

**Meet**  
Sellers  
Feedback  
Members

**Buy**  
1. C  
R

# Surplus Time & Frequency

eBay: QUARTZ CRYSTAL NATURAL PIEZOELECTRIC CLEAR (item 290010849821 end time Oct-20-06)

File Edit View Favorites Tools Help

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Address http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&item=290010849821

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Buy Sell My eBay Community Help

Back to My eBay Listed in category: Business & Industrial > Industrial Electrical & Test > Test

## QUARTZ CRYSTAL NATURAL PIEZOELECTRIC CLEAR

You are signed in [Watch this item](#)



**Buy It Now** price: **US \$45.00** [Buy It Now >](#)

Shipping costs: **US \$12.00**  
Standard Flat Rate Shipping Service

Ships to: Worldwide

Item location: New York, United States

You can also: [Watch this item](#)  
[Get alerts via Text message or IM](#)  
[Sell one like this](#)

**Meet the Seller**  
Feedback  
Member

**Buy:**  
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[Listing and payment details: Show](#)

eBay: RUBIDIUM ATOMIC CLOCK RESONANCE CELL FREQUENCY (item 290025555927 end time Sep-09-06)

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Address http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&item=290025555927

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Back to My eBay Listed in category: Business & Industrial > Industrial Electrical & Test > Test

## RUBIDIUM ATOMIC CLOCK RESONANCE CELL FREQUENCY

**Bidding has ended for this item**  
If you are a winner, [Sign In](#) for your status.

[Sell an item like this](#) or buy a similar item below.



Winning bid: **US \$0.99**

Ended: **Sep-09-06 12:18:23 PDT**

Shipping costs: **US \$4.75**  
Standard Flat Rate Shipping Service

Ships to: Worldwide

Item location: New York, United States

History: [1 bid](#)

**Meet the Seller**  
Feedback  
Member

**Buy:**  
[Close](#)  
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# Surplus Time & Frequency

eBay: Efratom Rubidium Portable Atomic Clock PC 10 (item 120025429658 end time Sep-03-06)

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Address http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&item=120025429658

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Buy Sell My eBay Community Help

Back to My eBay Listed in category: [Business, Office & Industrial](#) > [Electrical & Test Equipment](#) > [Generators](#)  
Also listed in: [Consumer Electronics](#) > [Radio Equipment](#) > [Ham Radio](#) > [Other](#)

### Efratom Rubidium Portable Atomic Clock PC 10

**Bidding has ended for this item**  
If you are a winner, [Sign In](#) for your status.

[Sell an item like this](#) or buy a similar item below.



Winning bid: **GBP 269.90**  
(Approximately US \$512.84)

Ended: **Sep-03-06 13:20:06 PDT**

Ships to: Worldwide

Item location: Henley-on-Thames, United Kingdom

History: [12 bids](#)

Winning bidder: [kalausi](#) (private)

eBay: Efratom 10 MHz Rubidium Frequency Standard COMPLETE! (item 200029512716 end time Sep-03-06)

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Address http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&item=200029512716

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Buy Sell My eBay Community Help

Back to My eBay Listed in category: [Business & Industrial](#) > [Industrial Electrical & Test](#) > [Test Equipment](#)

### Efratom 10 MHz Rubidium Frequency Standard COMPLETE!

You are signed in [Watch It!](#)



[View larger picture](#)

Current bid: **US \$202.50** [Place Bid >](#)  
[Reserve not met](#)

End time: **19 hours 8 mins**  
(Sep-27-06 10:01:51 PDT)

Shipping costs: Check item description and payment instructions or contact seller for details

Ships to: Europe, Australia, Asia, N. and S. America

Item location: Westford Massachusetts, United States

History: [9 bids](#)

High bidder: [timeok](#) (47 ★)

**Meet Seller**

Feedback: [Feedback](#)

**Buy It Now**

1. [Ch...](#)  
Sc



# Surplus Time & Frequency

eBay: Tracor 308A Rubidium Frequency Standard (item 200022971634 end time Sep-01-06 11:22:40 PDT)

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Address http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&item=200022971634

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Buy Sell My eBay Community Help

Back to My eBay Listed in category: Business & Industrial > Industrial Electrical & Test > Test

## Tracor 308A Rubidium Frequency Standard

**Bidding has ended for this item**  
If you are a winner, [Sign In](#) for your status.

[Sell an item like this](#) or buy a similar item below.



Sold for:	<b>US \$275.00</b>	Meet Seller Feedback Member
	Auction ended early with Buy It Now.	
Ended:	<b>Sep-01-06 11:22:40 PDT</b>	<ul style="list-style-type: none"> <li>▪ <a href="#">Relativity</a></li> <li>▪ <a href="#">Ask</a></li> <li>▪ <a href="#">Add</a></li> <li>▪ <a href="#">View</a></li> <li>▪ <a href="#">Visit</a></li> </ul>
Shipping costs:	<b>US \$25.00</b>	
	Standard Flat Rate Shipping Service	
Ships to:	United States	
Item location:	Amarillo, TEXAS, United States	Buy

eBay: 1988 Vintage Book "RELATIVITY" Einstein Brand New Mint (item 200029181391 end time Sep-01-06 13:58:29 PDT)

File Edit View Favorites Tools Help

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Address http://cgi.ebay.com/ws/eBayISAPI.dll?ViewItem&item=200029181391

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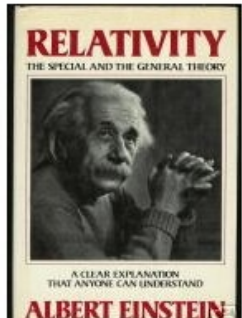
Buy Sell My eBay Community Help

Back to My eBay Listed in category: Books > Nonfiction Books

## 1988 Vintage Book "RELATIVITY" Einstein Brand New Mint

**Bidding has ended for this item**  
If you are a winner, [Sign In](#) for your status.

[Sell an item like this](#) or buy a similar item below.



Winning bid:	<b>US \$0.99</b>	Meet Seller Feedback Member
Ended:	<b>Sep-26-06 13:58:29 PDT</b>	
Shipping costs:	<b>US \$5.99</b>	<ul style="list-style-type: none"> <li>▪ <a href="#">Relativity</a></li> <li>▪ <a href="#">Ask</a></li> <li>▪ <a href="#">Add</a></li> <li>▪ <a href="#">View</a></li> <li>▪ <a href="#">Visit</a></li> </ul>
	(discount available) US Postal Service Parcel Post®	
Ships to:	Worldwide	
Item location:	Scottsdale, United States	
History:	1 bid	Buy

# Home Time Lab

---

- Not just dirt cheap clocks, but...
- Manuals, cables, connectors, power supplies, meters, GPIB, USB, software, GPS antennas, GPSDO, WWVB, Loran-C, clocks, displays, IRIG, TCG, frequency counters, TIC, phase comparators, etc.
- Most old, some new; possibly broken, often working. Buy 3, play Frankenstein.

# Museum of HP Clocks

---



06-Dec-2006

Project GREAT

59

# Requirements

---

- GR effect  $1.1 \times 10^{-16}$  / m
- $\Delta f = 1.5 \times 10^{-13}$
- If we want 10% accuracy
- We need a reference good to  $10^{-14}$

# Chapter 5

- A Powers of Ten tour

# Powers of Ten - Introduction

---

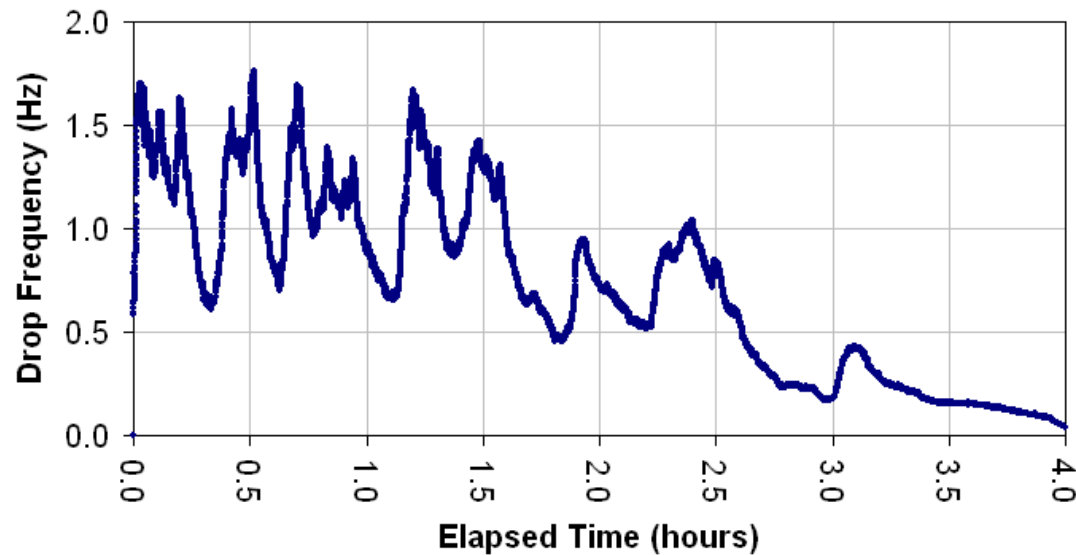
- A quick overview of clock accuracy
- What clocks keep poor time?
- What clocks keep best time?
- And many in between...

# $10^{-0}$ drip, drip

- Leak in ceiling
- 0.57 s ... 9.9 s
- 1.7 Hz ... 0.1 Hz



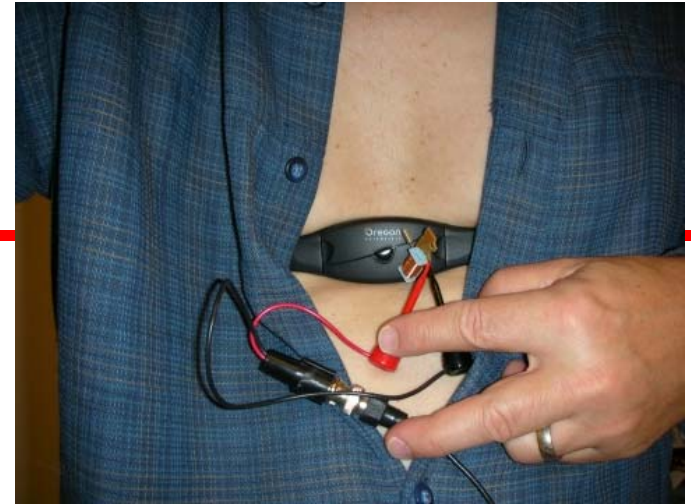
Kitchen Ceiling Water Drip  
8 PM 13-Nov-2006 PST (MJD 54052)



# $10^{-1}$ heart beat

---

- $10^{-1}$ , 0.1, 10%
- The original '1 PPS'
- Sometimes 2x, even 3x
- Much higher stability at night
- < 10% accuracy possible

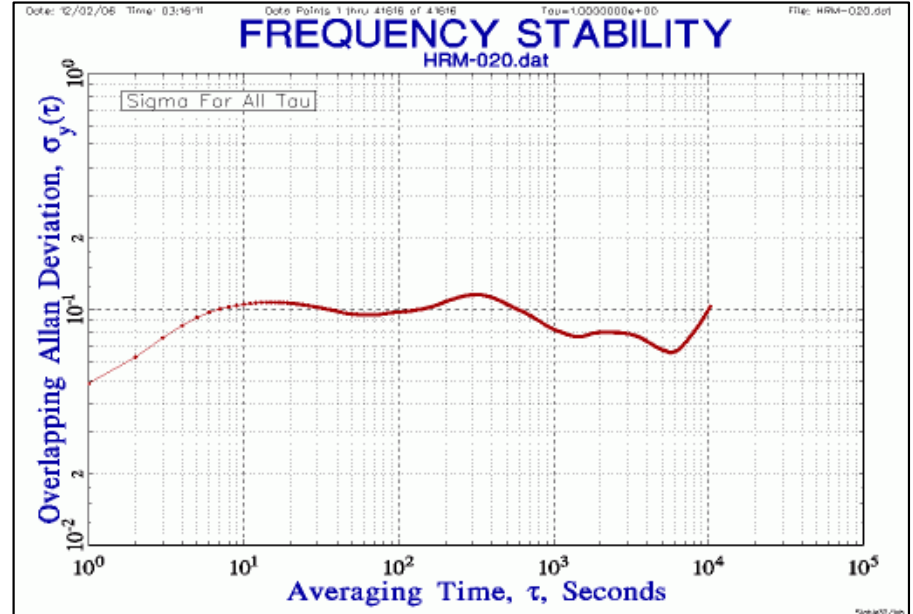
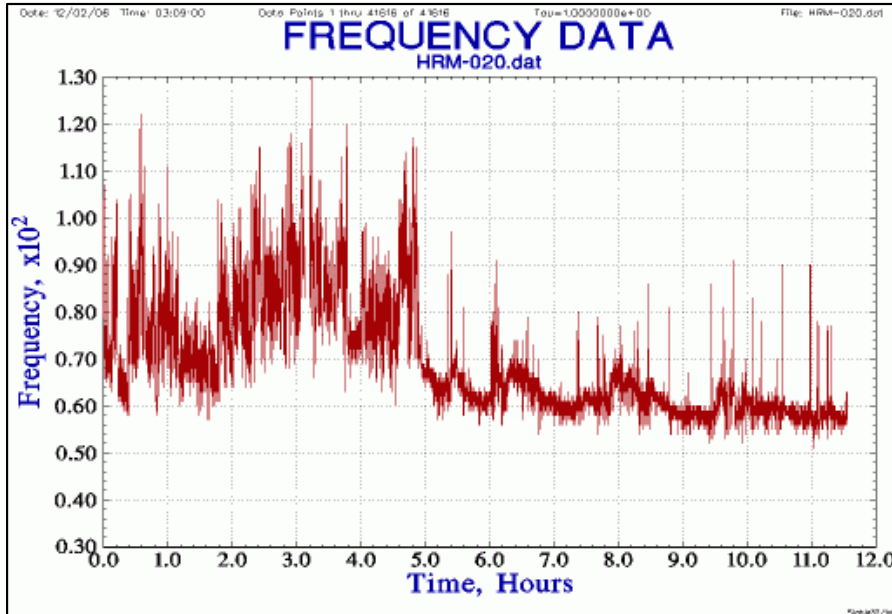


```
62.0  
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59.0  
60.0  
60.0  
61.0
```



# $10^{-1}$ heart beat

- 12 h frequency plot (evening/night)
- ADEV floor is  $10^{-1}$  from  $10^1$  to  $10^4$  s!
- (is this OK?)



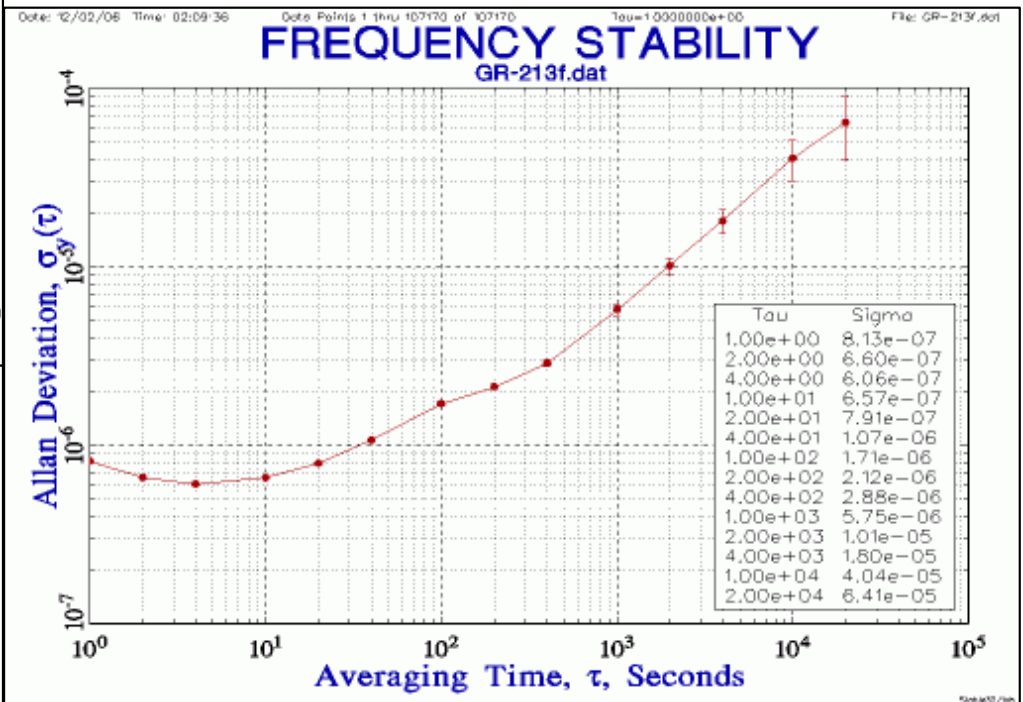
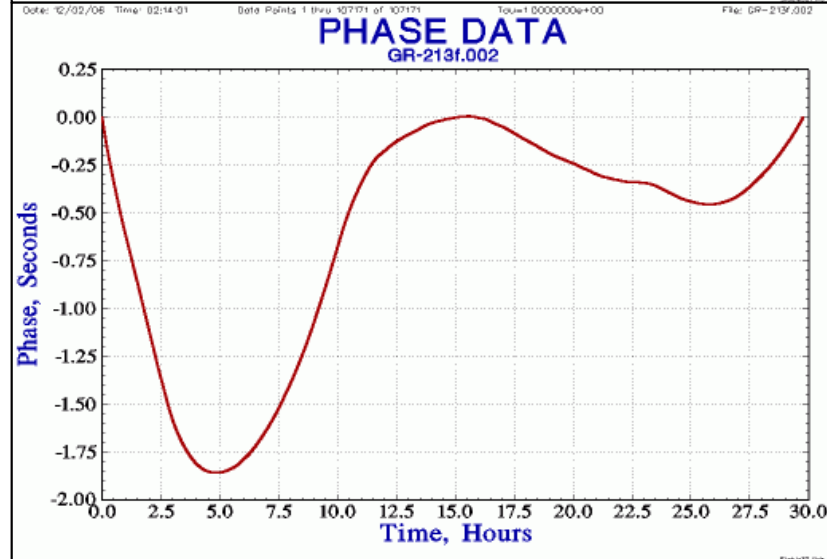
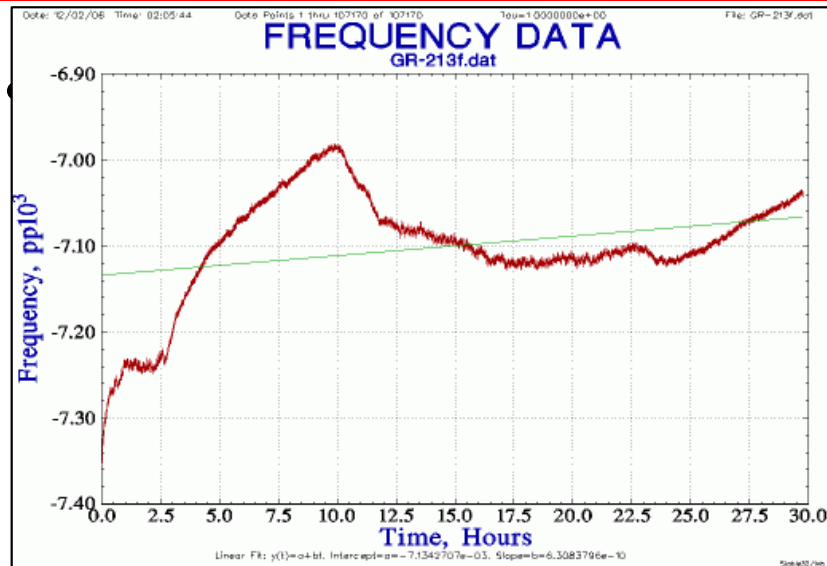
# $10^{-2}$ tuning fork oscillator

- 0.01, 1%
- General Radio Type 213 Audio Oscillator
- 1 'kc';  $f = \sim 992.8$  Hz
- $\pm 1.3$  mHz ( $60 \times 1$  s)
- Accuracy  $< 1\%$
- Count those 9's
- ADEV is  $10^{-6}$



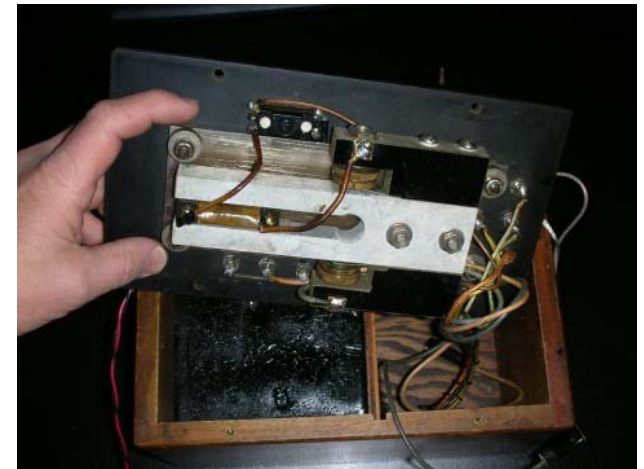
```
992.897,388,71 HZ
992.896,598,37 HZ
992.896,556,22 HZ
992.896,560,05 HZ
992.897,374,78 HZ
N : 60
STD DEV: 0.001,387,672 HZ
MEAN : 992.898,857,676 HZ
MAX : 992.901,768,32 HZ
MIN : 992.896,168,74 HZ
992.898,234,03 HZ
992.898,247,28 HZ
992.897,293,73 HZ
992.897,564,75 HZ
```

# $10^{-2}$ tuning fork oscillator



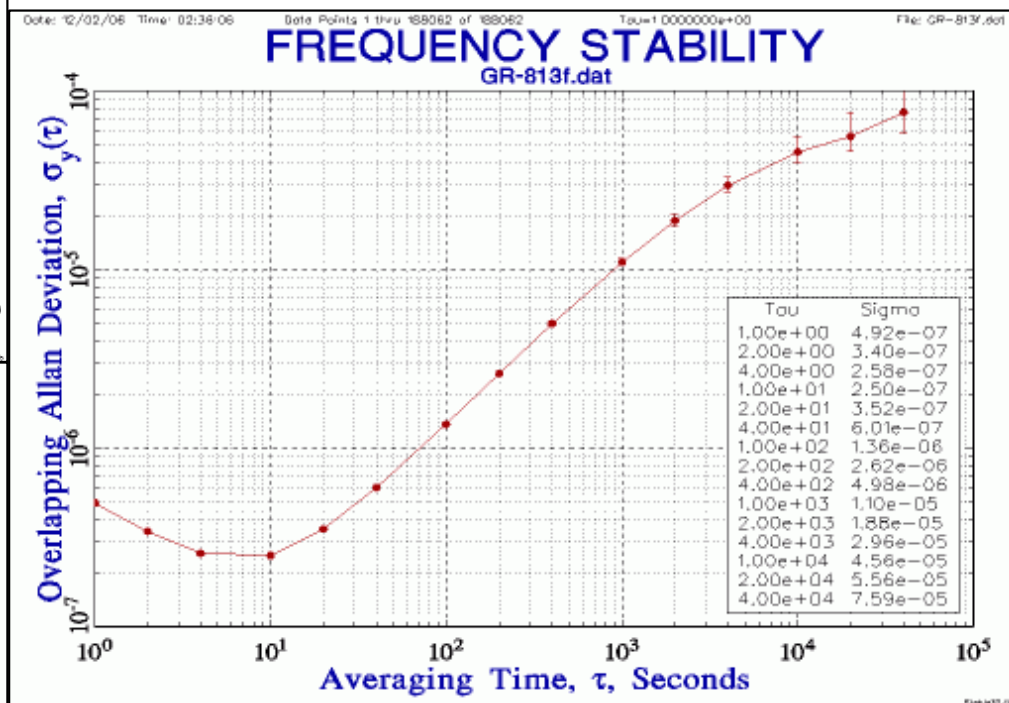
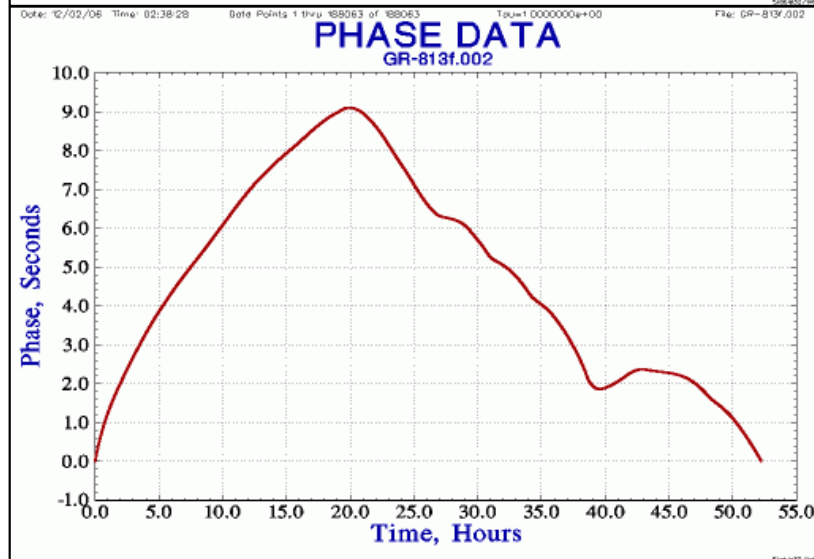
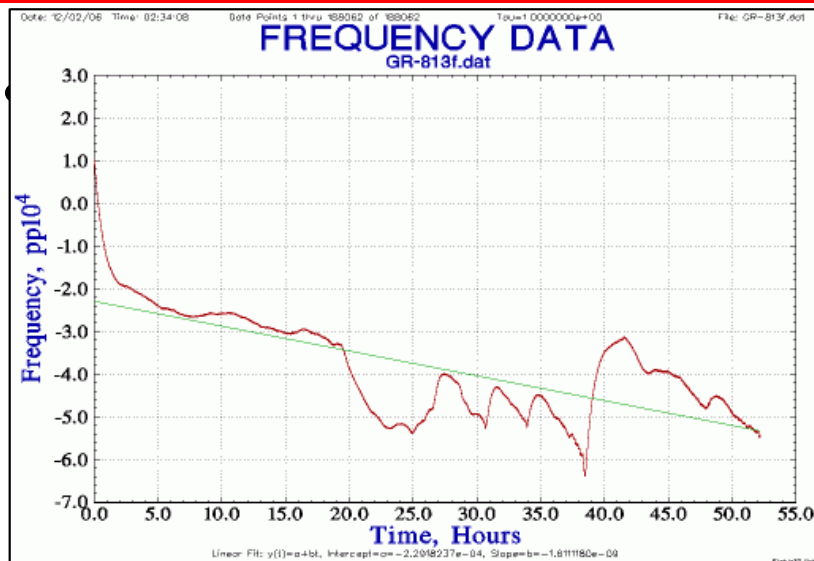
# $10^{-3}$ precision tuning fork

- 0.001, 0.1%, 1 ms/s
- General Radio Type 813
- 1 'kc' tuning fork
- $f = \sim 999.4$  Hz
- $\pm 400$   $\mu$ Hz (60  $\times$  1 s)
- Accuracy  $< 0.1\%$
- ADEV is  $10^{-7}$



```
999.463,938,97 HZ
999.463,932,59 HZ
999.464,159,16 HZ
999.465,063,84 HZ
999.463,826,22 HZ
999.464,577,00 HZ
N : 60
STD DEV: 478.778 uHz
MEAN : 999.464,134,273 HZ
MAX : 999.465,477,73 HZ
MIN : 999.463,290,13 HZ
999.464,657,58 HZ
999.464,554,46 HZ
999.464,006,05 HZ
```

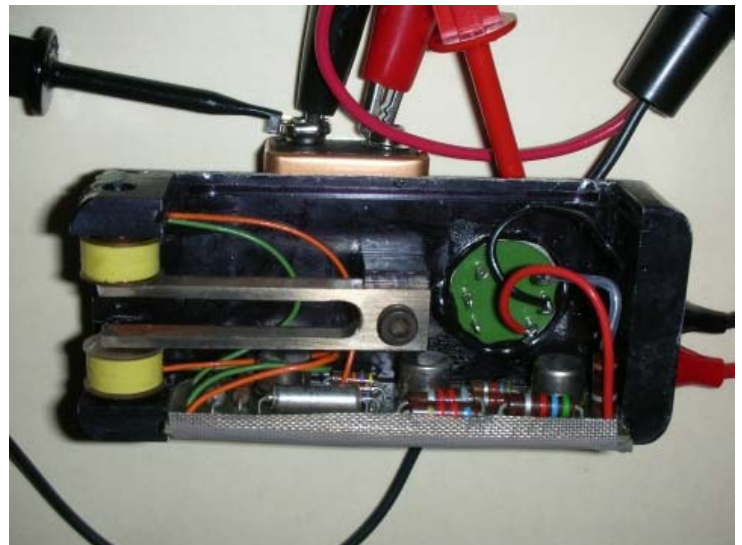
# $10^{-3}$ precision tuning fork



# $10^{-4}$ mechanical oscillator

- 0.01%, 100 ppm
- Mechanical oscillator
- "Four 9's"

```
999.907,211,67  HZ
999.907,250,33  HZ
999.907,273,16  HZ
999.907,311,01  HZ
999.907,250,27  HZ
999.907,345,09  HZ
N      : 60
STD DEV: 151.812  uHz
MEAN   : 999.907,159,334  HZ
MAX    : 999.907,404,05  HZ
MIN    : 999.906,840,54  HZ
999.907,392,20  HZ
999.907,415,25  HZ
999.907,354,85  HZ
```



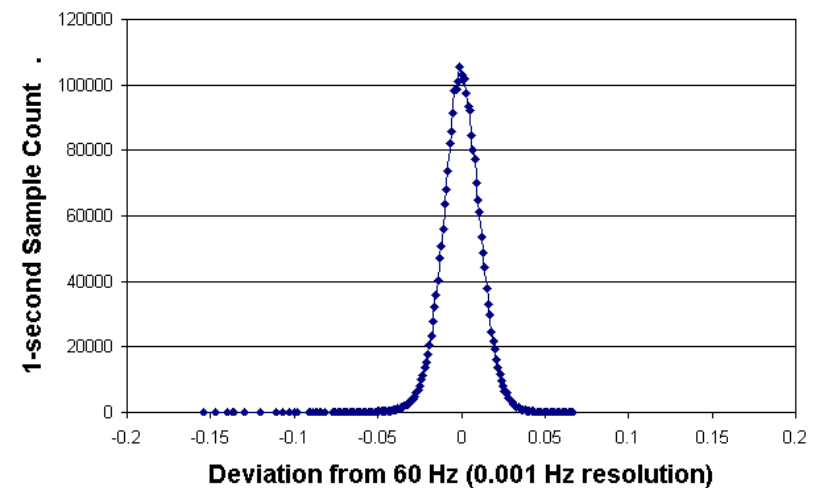
# $10^{-5}$ mains

- 0.001%, 10 ppm
- $60 \pm$  Hz

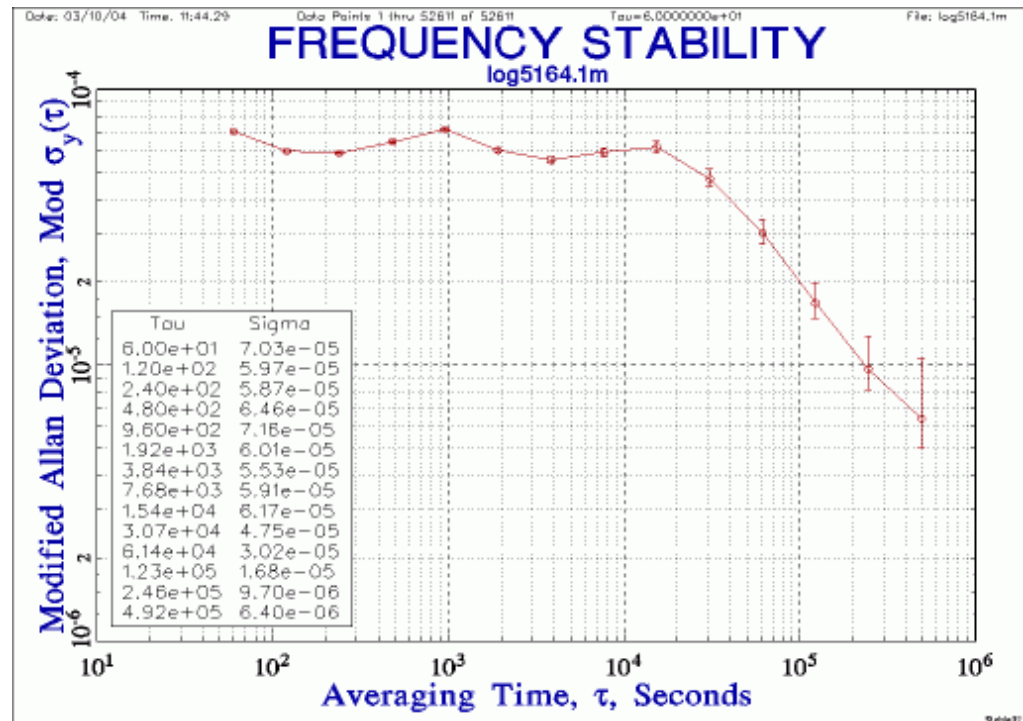
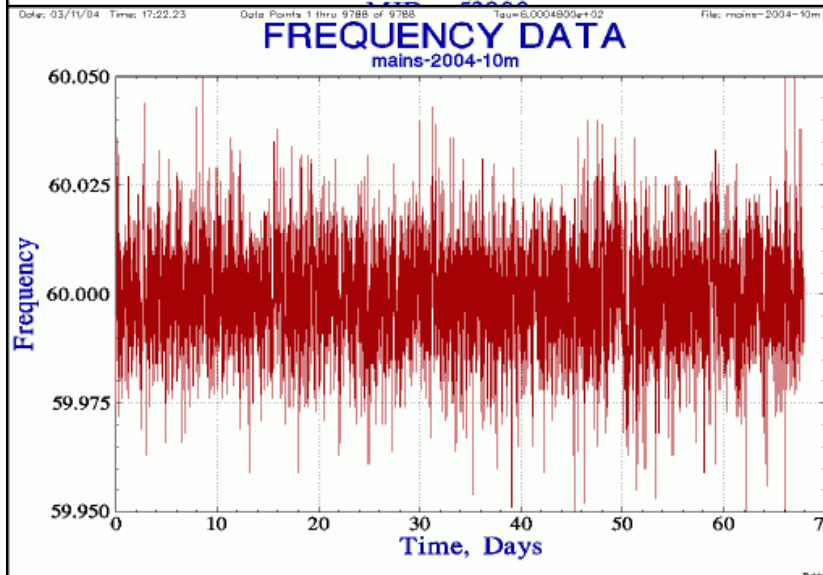
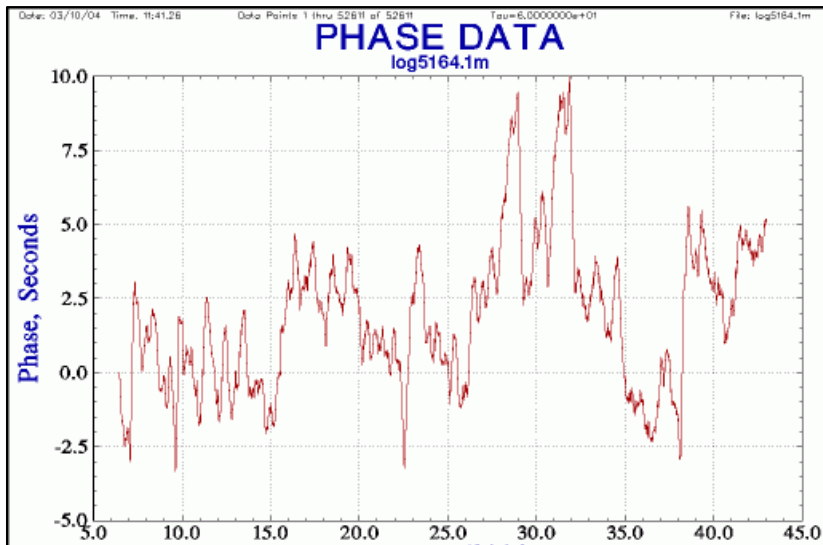
```
60.003,640,120,5 Hz
60.009,491,393,8 Hz
60.000,431,181,6 Hz
59.992,198,219,9 Hz
59.987,371,509,5 Hz
59.993,148,200,6 Hz
59.999,032,462,5 Hz
59.985,892,634,1 Hz
59.995,727,396,2 Hz
N : 36
STD DEV: 0.006,765,596,40 Hz
MEAN : 59.999,554,563,23 Hz
MAX : 60.010,390,980,5 Hz
MIN : 59.985,892,634,1 Hz
59.996,011,518,6 Hz
59.999,520,100,7 Hz
```



60 Hz Mains Frequency Deviation Histogram  
2.7 million one second samples (~1 month)



# 10<sup>-5</sup> mains





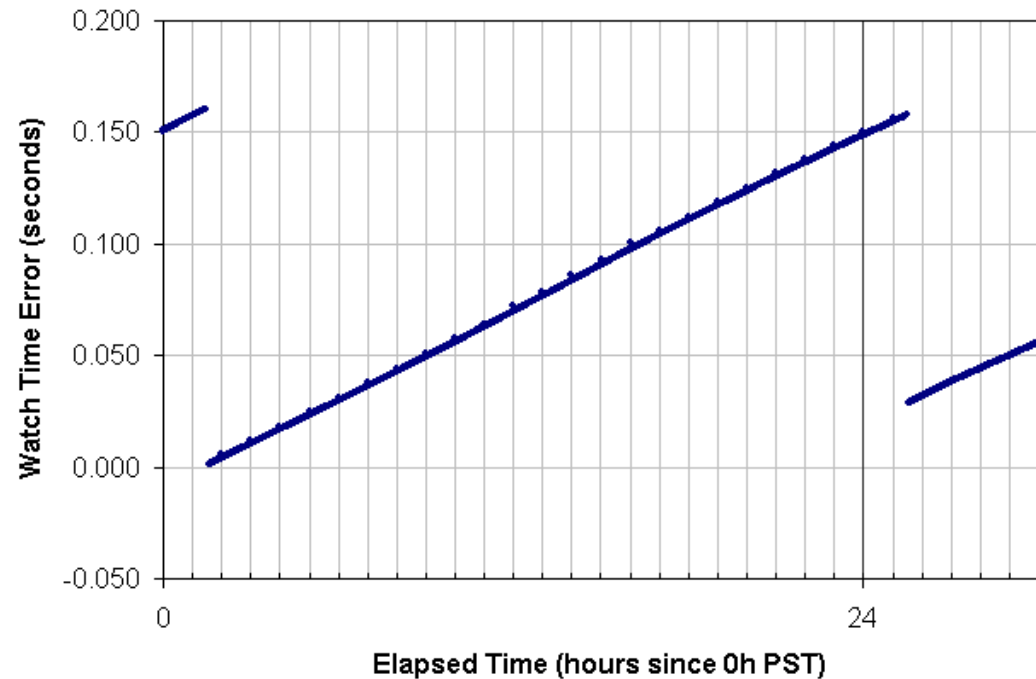
# $10^{-6}$ quartz watch (RC)

---

- 0.0001%, 1 PPM, 1  $\mu\text{s}/\text{s}$
- +160 ms/d = +1.85 ppm



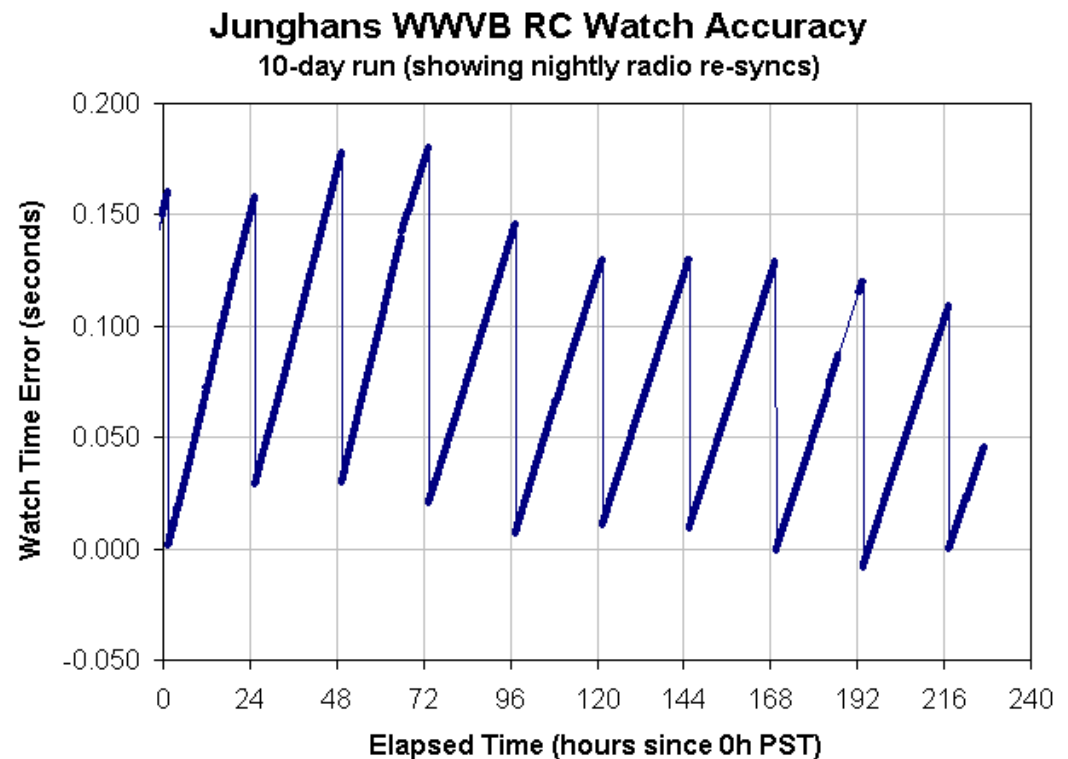
Junghans WWVB RC Watch Accuracy  
160 ms gain / 24 h = 1.8 ppm fast



# $10^{-6}$ quartz watch (RC)

---

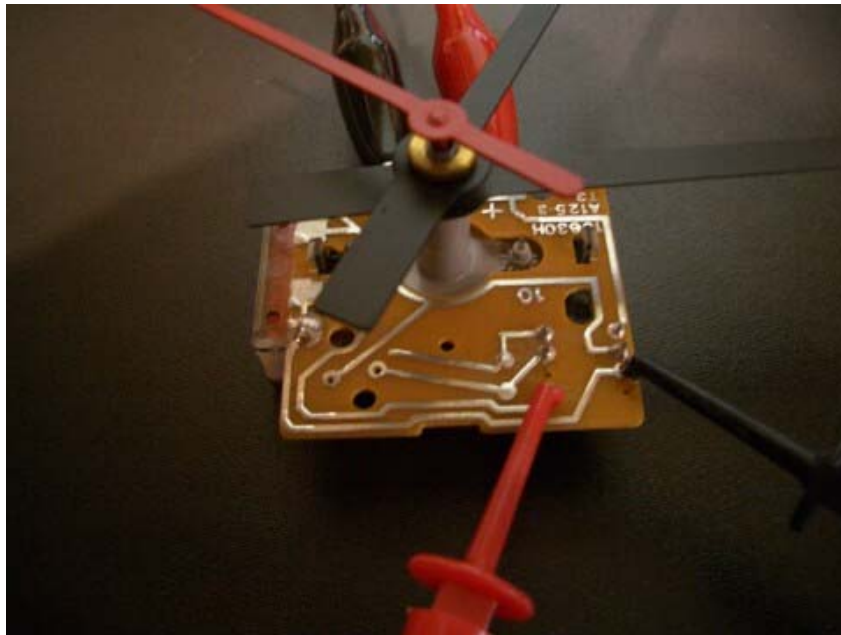
- Nightly WWVB radio sync (60 kHz)
- Look closely at 01:30 AM PST
- +1h +30m +15s
- Plot of 9 days
- Rate variations
- Sync variations



# Aside: Quartz Wall Clock

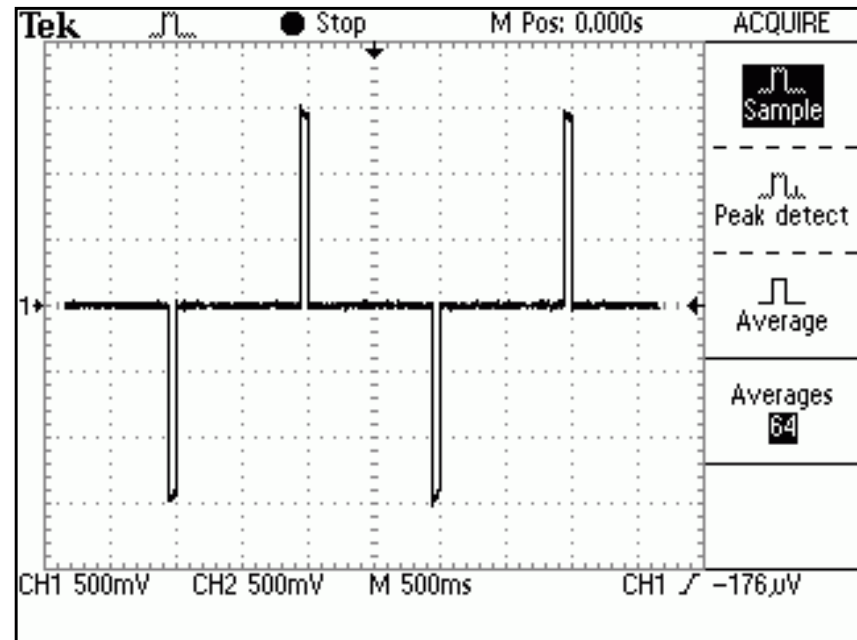
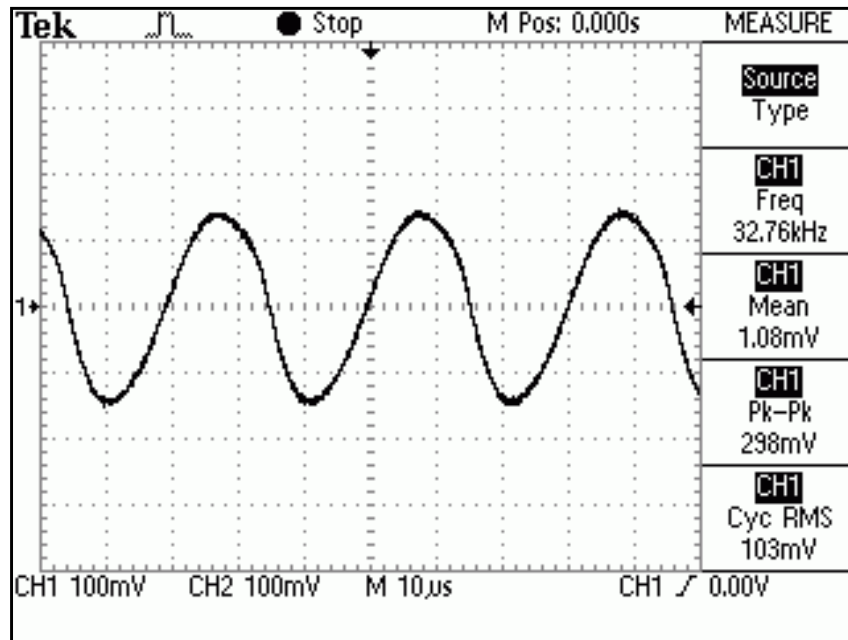
---

- Quartz crystal and divider/driver IC
- Stepper motor (180° per step)



# Quartz Wall Clock

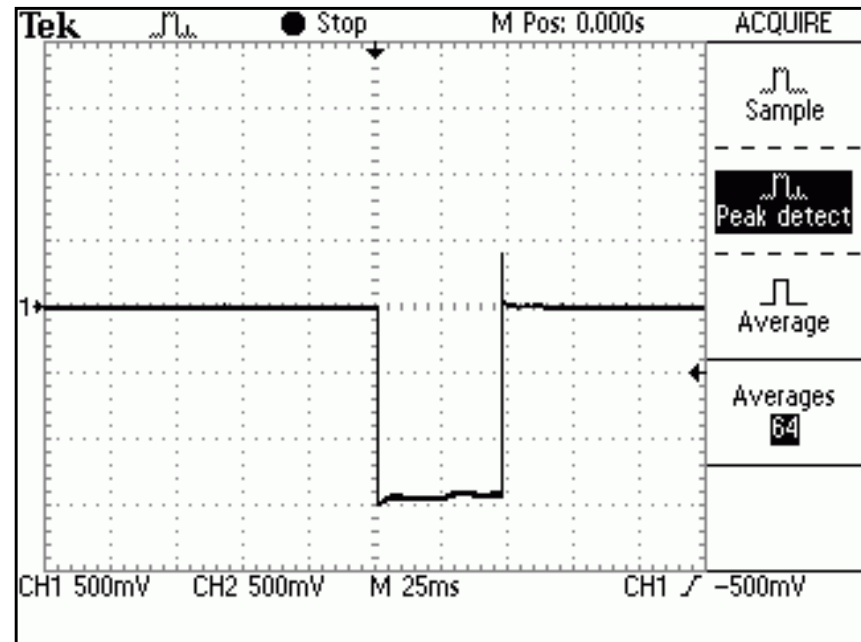
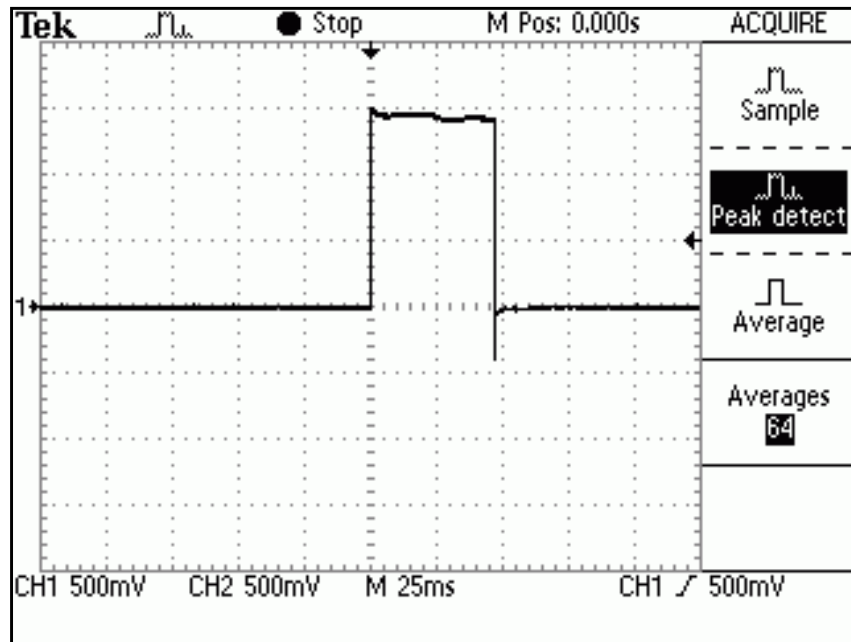
- 32 kHz oscillator
- 1 Hz stepper



# Quartz Wall Clock

---

- Polarity alternates
- Pulse size: 1.5 V x 50 ms



# Quartz Wall Clock

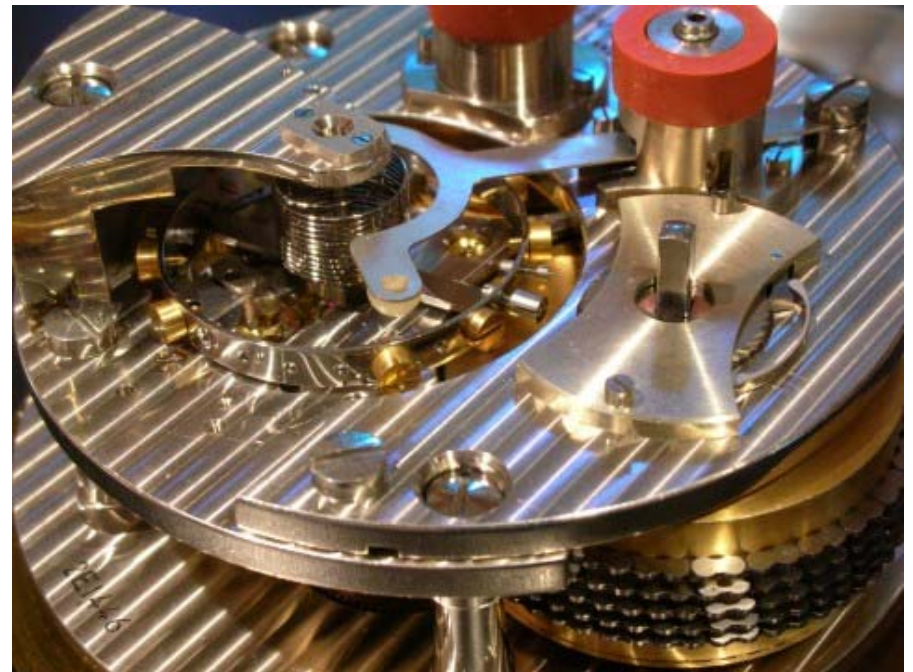
---

- Coil current:  $1.5 \text{ V} / 500 \text{ } \Omega = 3 \text{ mA}$
- Oscillator current:  $< 1 \text{ } \mu\text{A}$
- Pulse power ( $V \times A$ ):  $4.5 \text{ mW}$
- Pulse width:  $50 \text{ ms}$
- Clock Energy ( $P \times T$ ):  $4.5 \text{ mW} \times 50 \text{ ms}$   
 $= 225 \text{ } \mu\text{J} = 60 \text{ pico kWh}$
- AA battery ( $2850 \text{ mAh}$ ) =  $\sim 2 \text{ years}$

# $10^{-7}$ chronometer

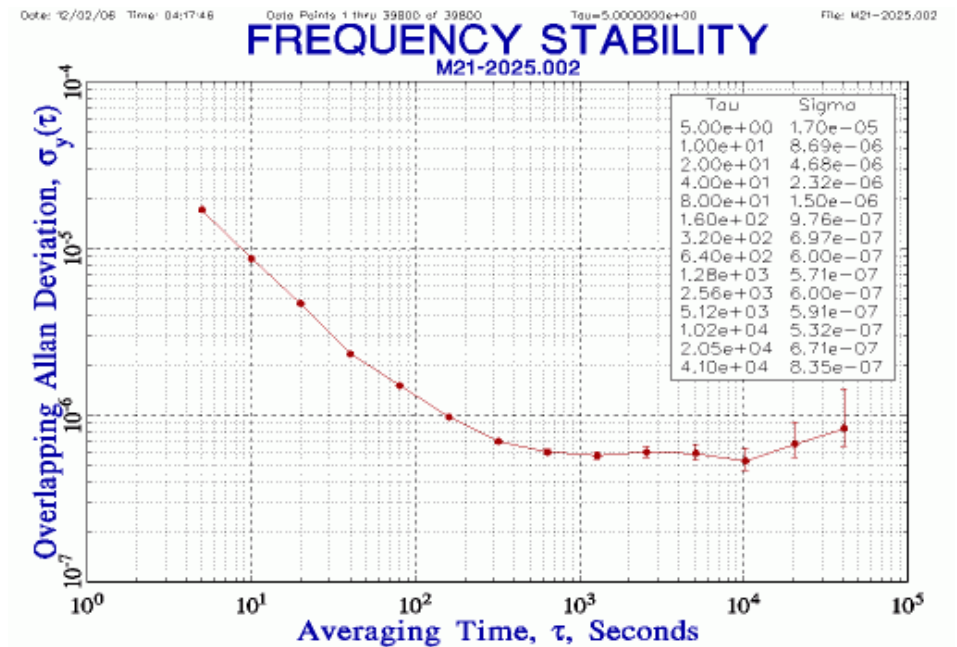
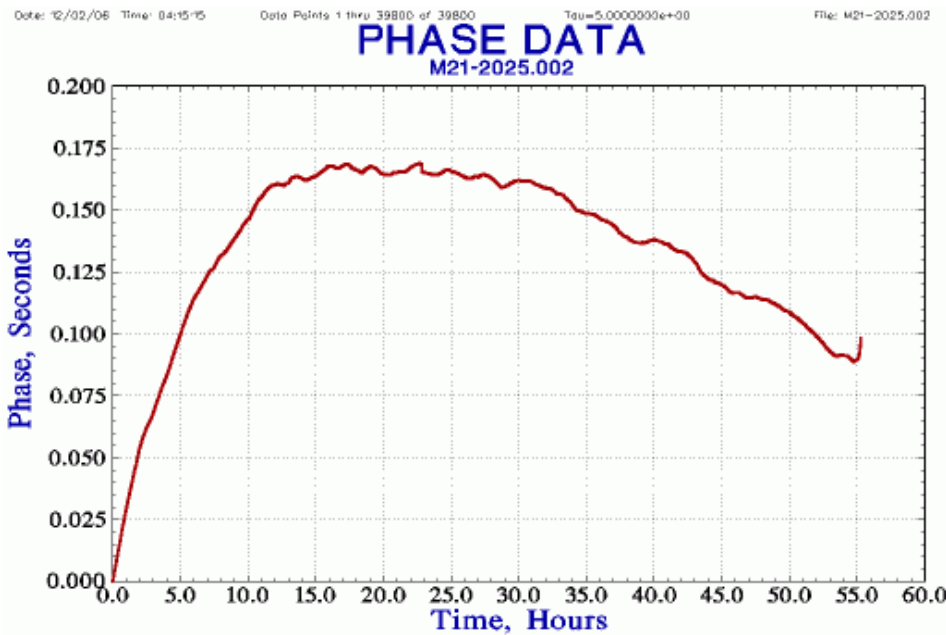
---

- 0.1 ppm
- Rated  $\frac{1}{4}$  sec/day deviation



# $10^{-7}$ chronometer

- ~55 hour runtime
- 200 ms phase residuals
- ADEV  $6 \times 10^{-7}$





# $10^{-7}$ chronometer

- From 1940's USN manual...
- Phase
  - Dial error
- Frequency
  - Daily rate
- Drift
  - Deviation in rate

COMPUTATION OF RATE

Date	Dial Error + = Fast - = Slow		Daily Rate + = Gain - = Loss	Mean Deviation in Daily Rate	Remarks
	Min	Sec			
Oct 1948					
3	+0	2			Started+Set
4	+0	2½	+½		
5	+0	2½	0	¼	
6	+0	3	+½	¼	
7	+0	3	0	¼	
8	+0	3½	+½	¼	
9	-	-	-	-	Not wound
10	+0	4	+¼	-	2 day avg.

(Mean daily rate = +1/4 second)

In Table I, there will be noted a column headed "Mean Deviation in Daily Rate." The

# $10^{-8}$ pendulum clock

---

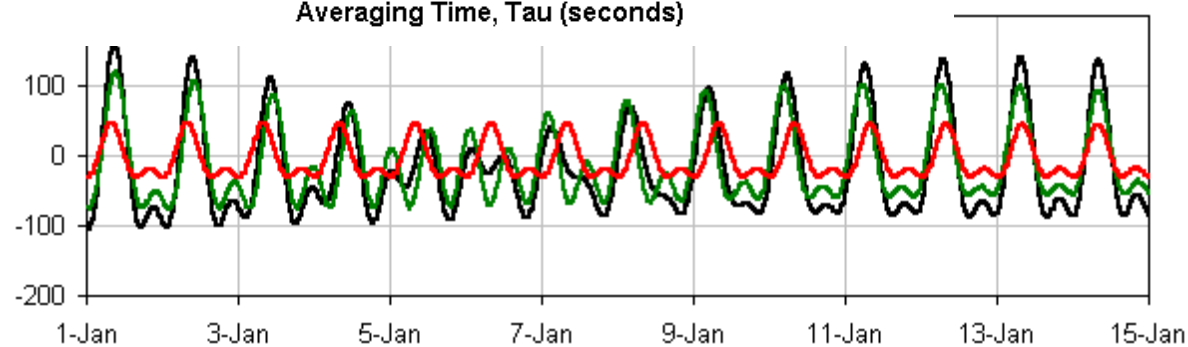
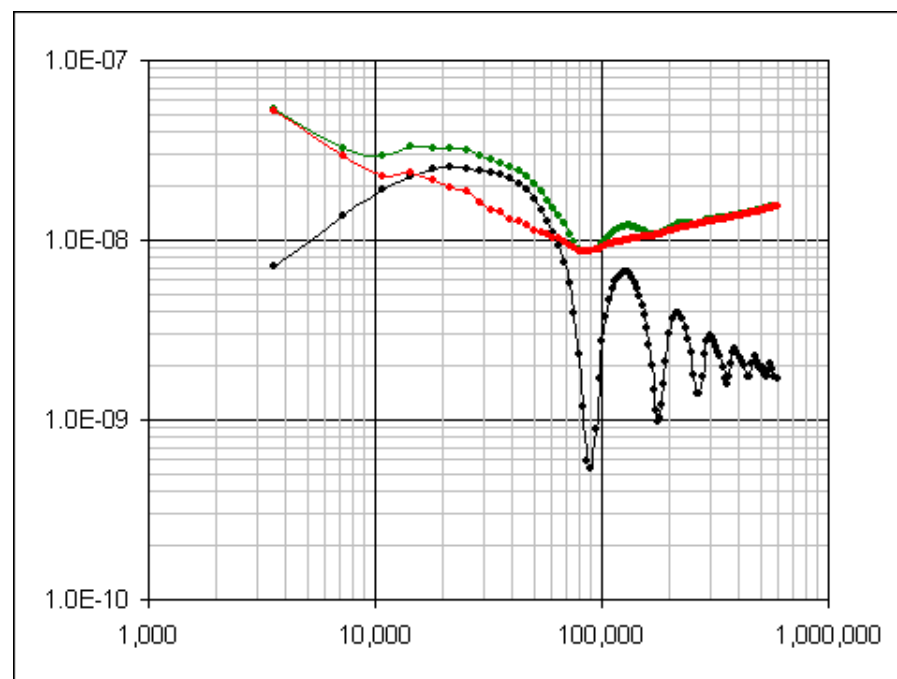
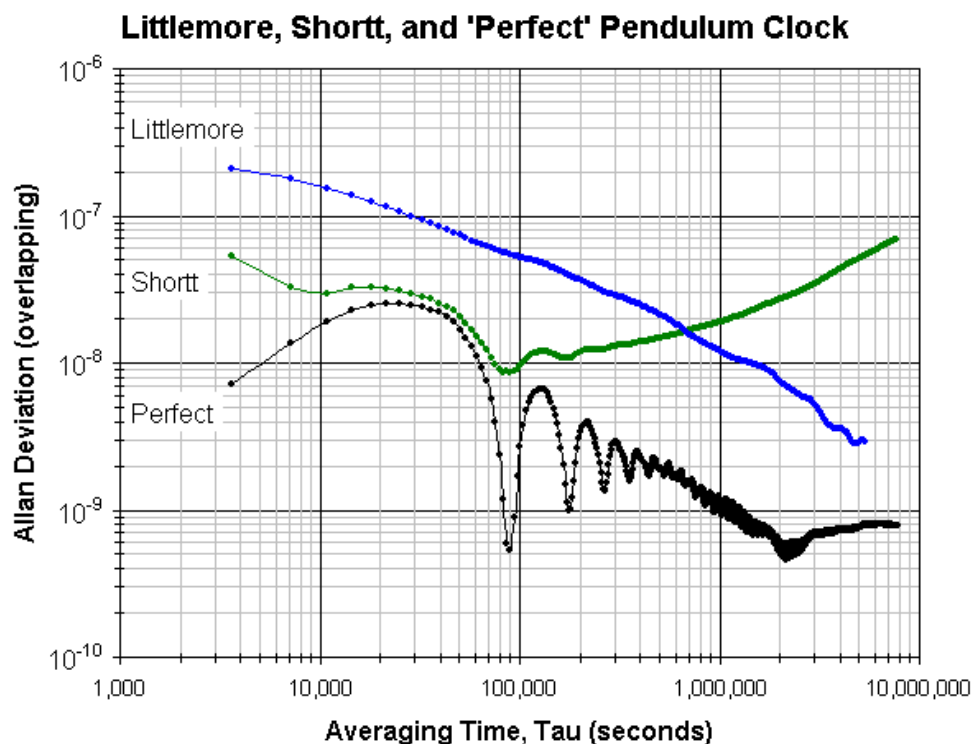
- 0.01 ppm, 10 ppb  
10 ns/s, 864  $\mu$ s/d
- Shortt,  
Fedchenko,  
Riefler,  
'Littlemore'



# $10^{-8}$ pendulum clock

- Amazing astronomical pendulum clocks
- Several centuries of understanding and perfection. Limitations addressed:
- Temperature, humidity, mass, friction, metallurgy, escapement, master/slave, vacuum, isochronous suspension, etc.
- When all factors solved, the best pendulum clock is just a good gravimeter

# $10^{-8}$ pendulum clock



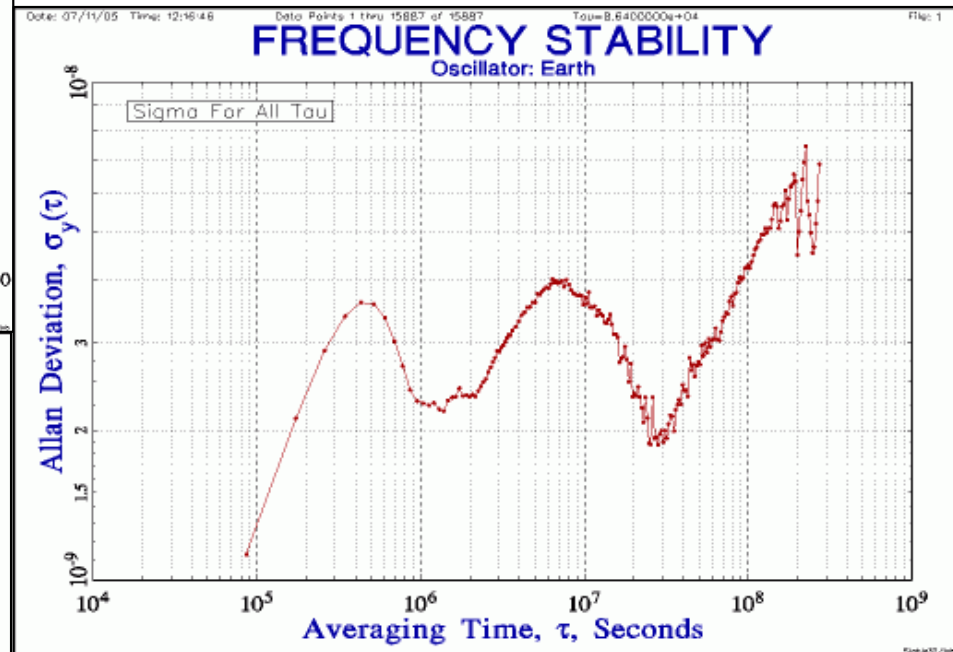
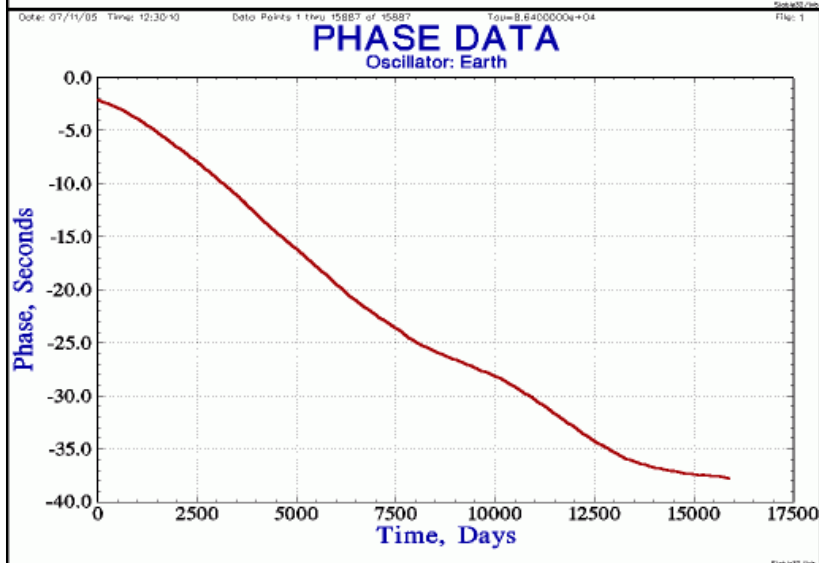
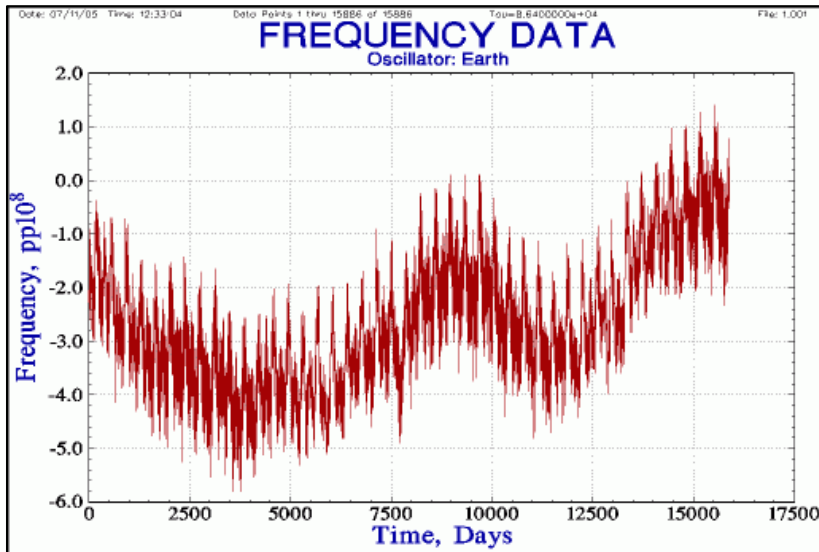
# $10^{-9}$ earth

---

- 0.001 ppm
- Slow by  $\sim 2$  ms per day
- Also somewhat irregular
- ADEV  $10^{-8} \sim 10^{-9}$
- Limited by core, weather, climate
- Also lunar/solar tides



# $10^{-9}$ earth



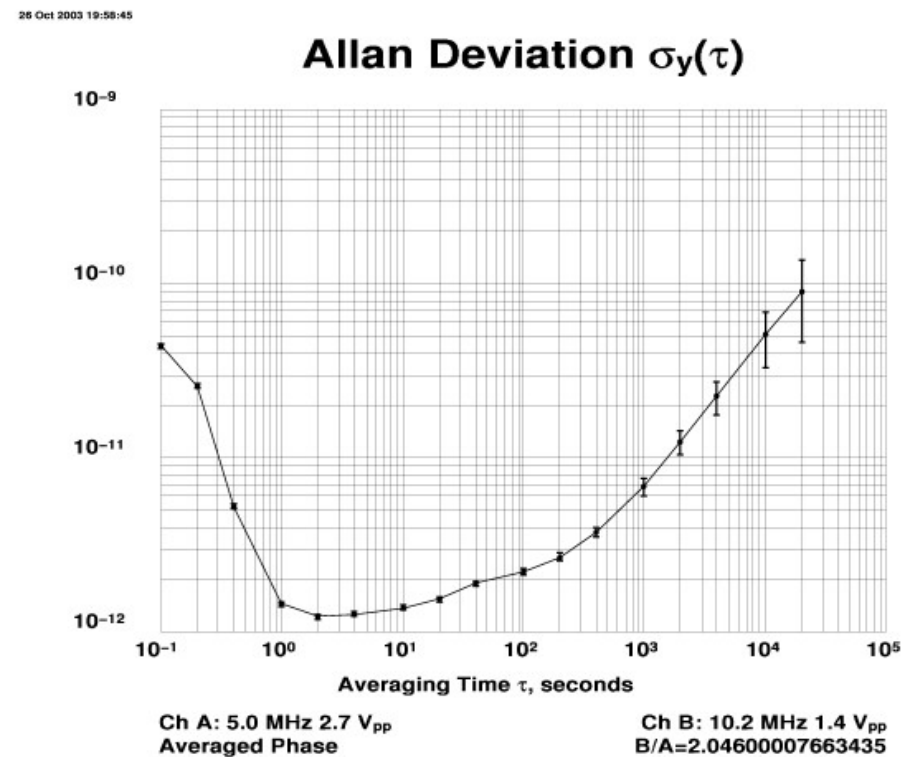
# $10^{-9}$ earth

---

- Earth as a frequency standard
- Suggested improvements:
  - Thoroughly clean, and dry with cloth
  - Remove surrounding gas and water vapor
  - Wait for core to cool before use
  - Re-align axis of rotation (wobbling)
  - Keep away from nearby moon (tides)
  - Keep away from sun (tempco)
  - Re-adjust rate (avoid leap seconds)

# $10^{-10}$ OCXO

- 0.1 ppb, 100 ps/s, 8.64  $\mu$ s/d
- $10^{-10}$ ... $10^{-13}$  short
- $5 \times 10^{-10}$ /d drift

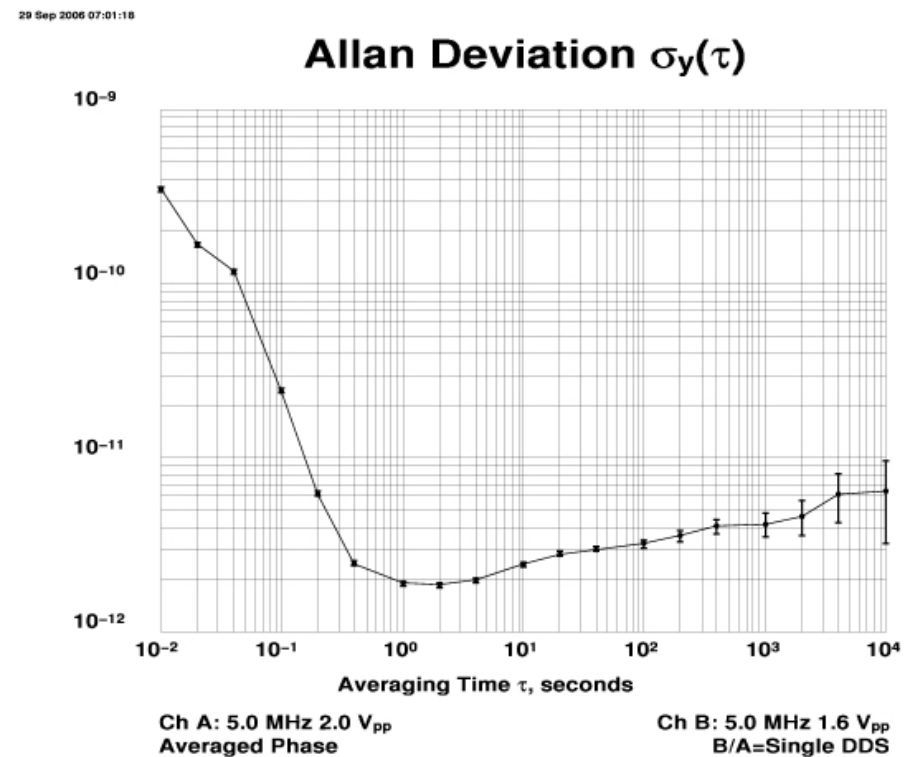


C:\tvb\Tscpl0e\Log94165.g1f



# $10^{-11}$ good ocxo

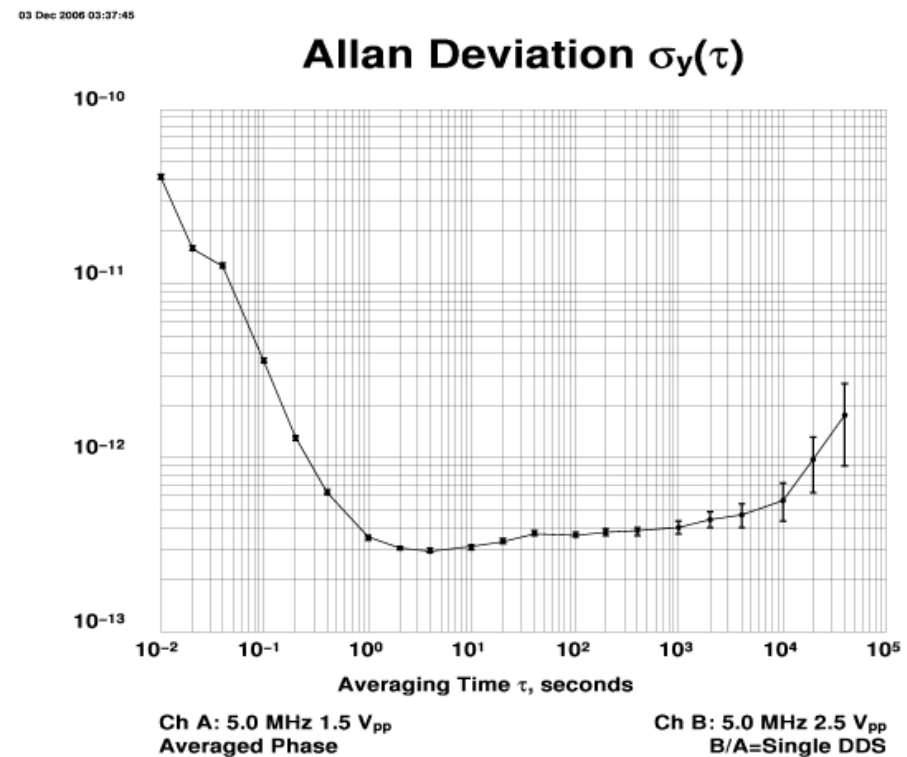
- 0.01 ppb, 10 ps/s, 864 ns/d ( $\sim 1 \mu\text{s/d}$ )
- $10^{-11} \dots 10^{-13}$  short
- $\sim 10^{-11}/\text{d}$  drift



C:\tvb\TSCPlot\Log29240.g1f

# $10^{-12}$ excellent ocxo

- 1 ppt, 1 ps/s, 86.4 ns/d (~100 ns/d)
- $\sim 10^{-13}$  short/mid
- $\sim 3 \times 10^{-12}$ /d drift



C:\tvb\Tscplot\Log29858.g1f

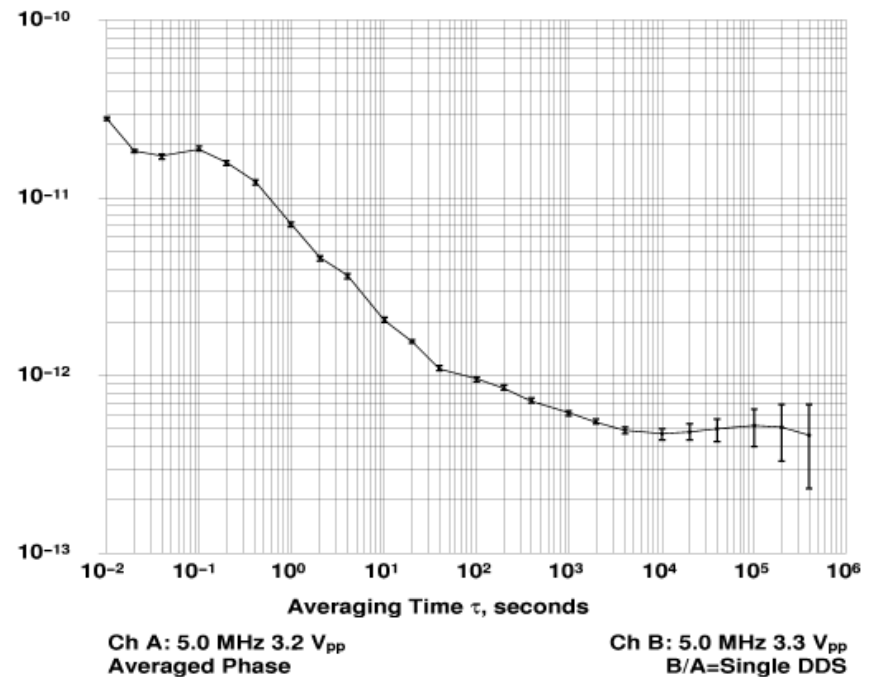
# $10^{-13}$ rubidium

- 8.64 ns/d ( $\sim 10$  ns/d)
- $\sim 10^{-13}$  mid-term
- $\sim 1 \times 10^{-11}/\text{m}$  drift



01 Dec 2006 23:05:04

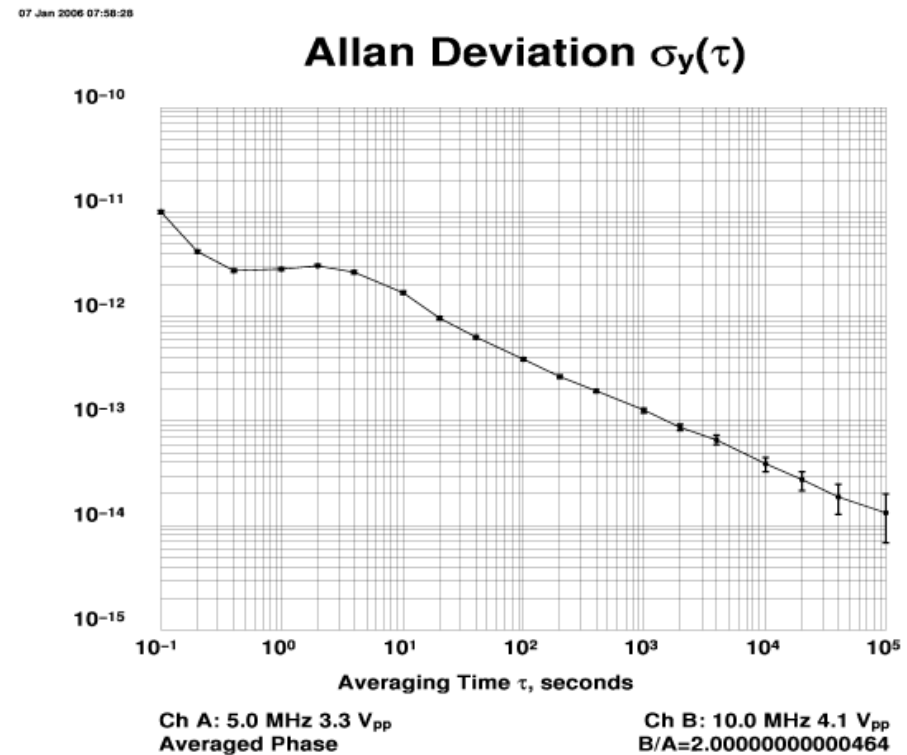
Allan Deviation  $\sigma_y(\tau)$



C:\tvb\Tscplot\Log1578.gif

# $10^{-14}$ cesium

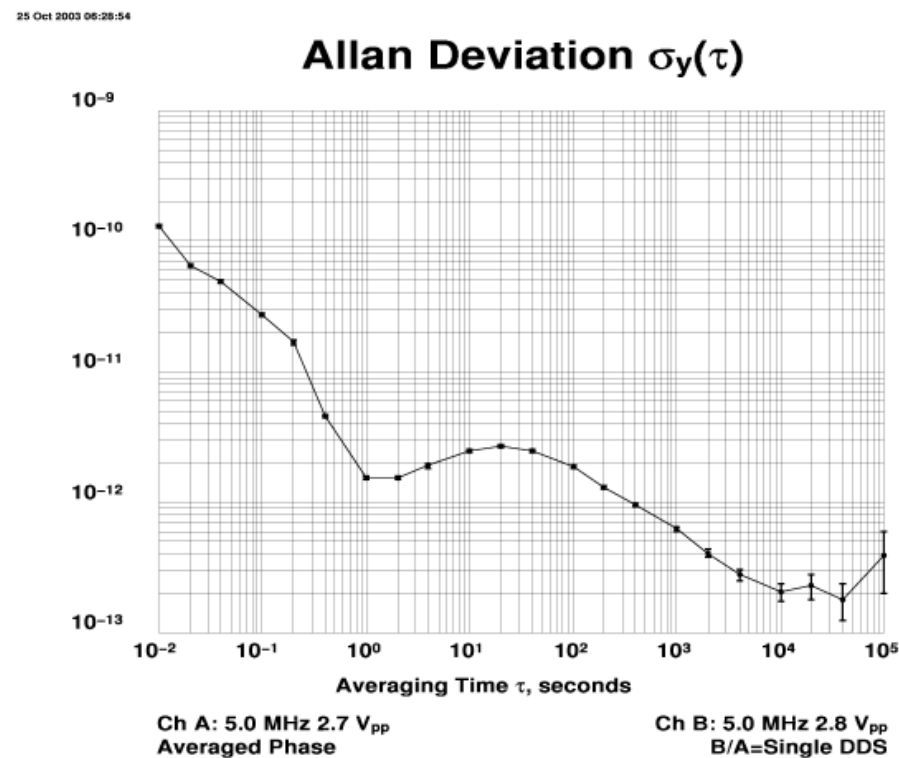
- 864 ps/d ( $\sim 1$  ns/d)
- $\sim 10^{-13}$  mid-term
- $\sim 1 \times 10^{-14}$  @ 1 day



C:\tvb\Tscplot\Log23362.gif

# $10^{-14}$ more cesium

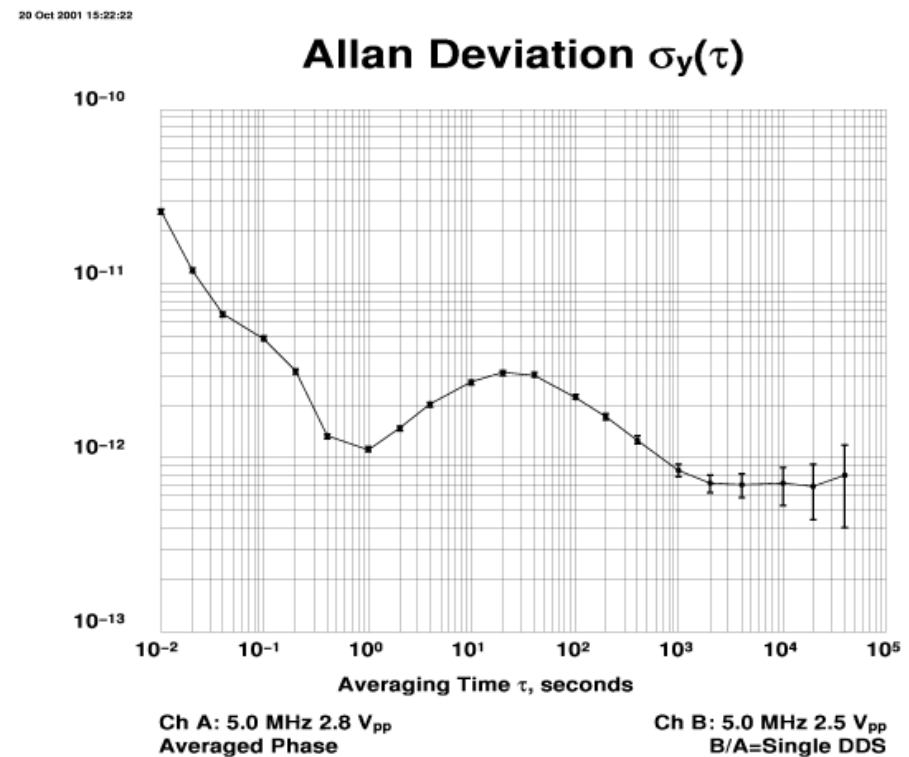
- $10^{-14}$  not!
- Cesium clocks differ by 2x - 50x
- E.g., old 5060A vs. new 5071A



C:\tvb\TSCPlot\Log4143.g1f

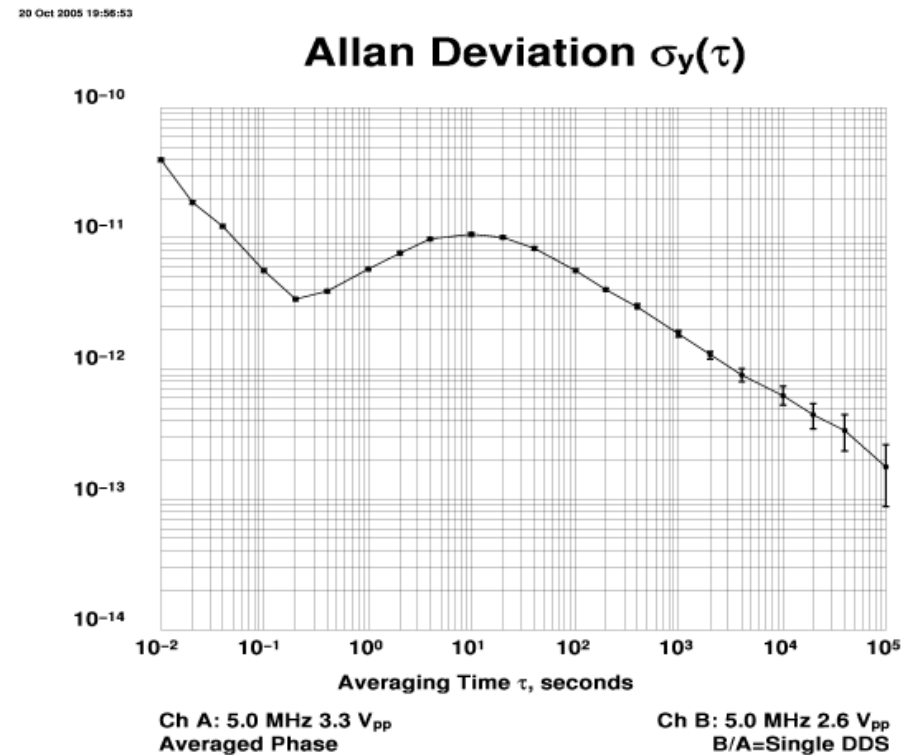
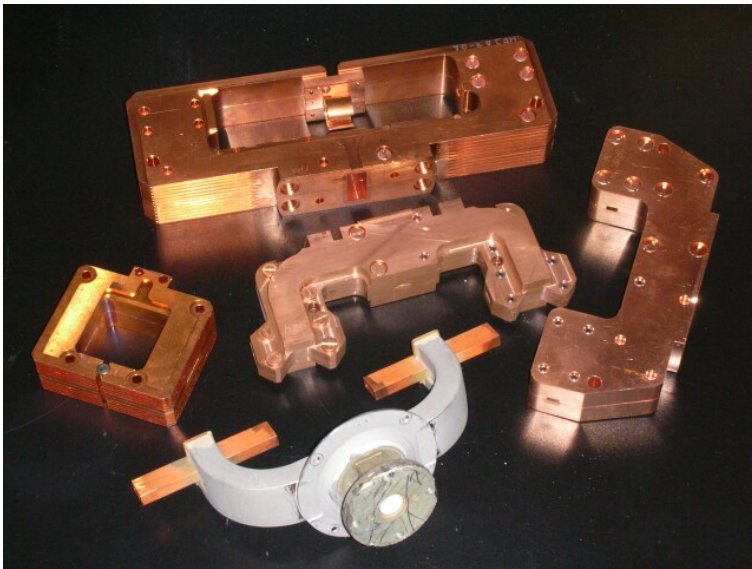
# $10^{-14}$ another cesium

- Not even close to  $10^{-14}$  @ 1 day
- FTS 4010
- Portable Clock
- Old, tired



# $10^{-14}$ one more cesium

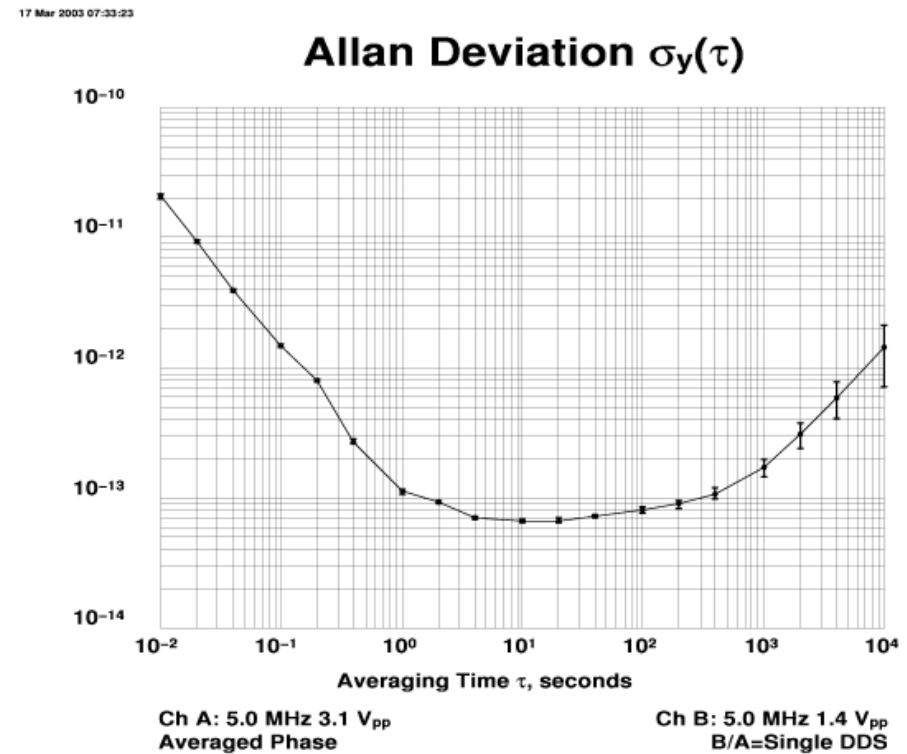
- About  $2 \times 10^{-13}$  @ 1 day
- FTS 4050
- See variety of Cs beam cavities



C:\tvb\Tscpl\ot\Log22421.gif

# $10^{-14}$ BVA quartz

- But can you get to high altitude and measure in 1 to 100 seconds?
- $10^{-13}$ ... $10^{-14}$  short
- $10^{-11}$ ... $10^{-12}$  drift

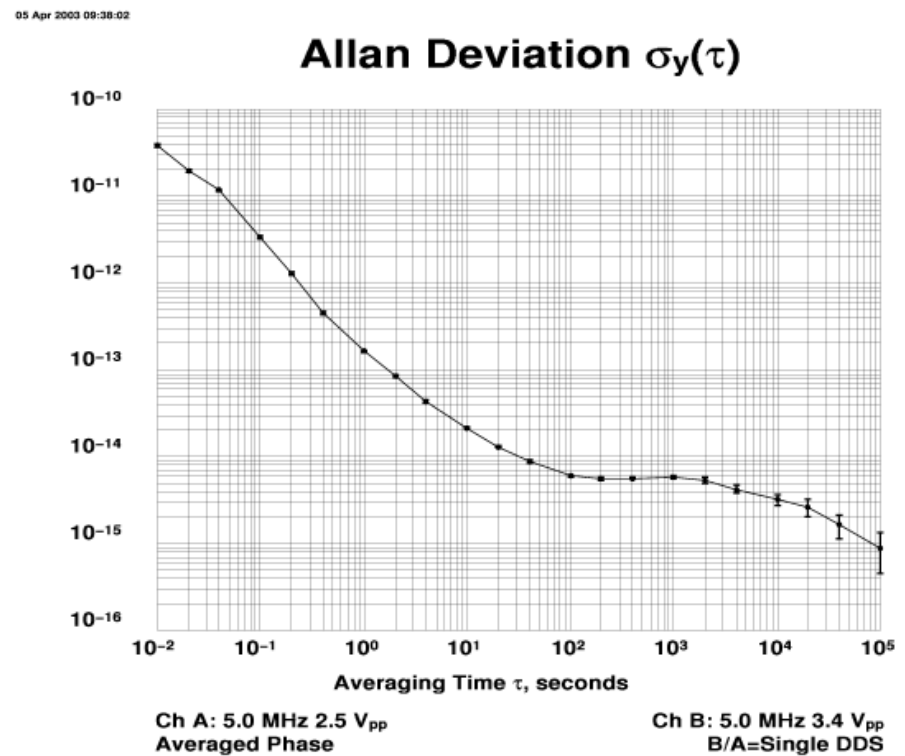


C:\tvb\Tscplot\Log1212.gif



# $10^{-15}$ active h-maser

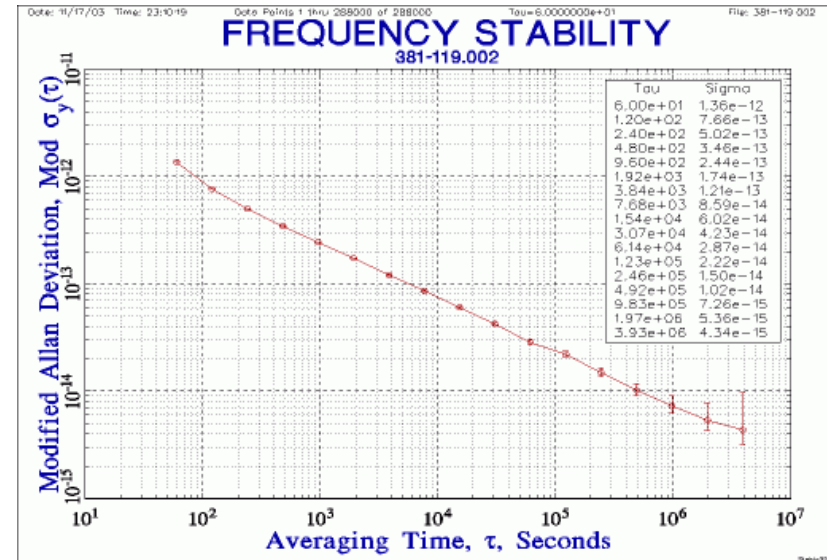
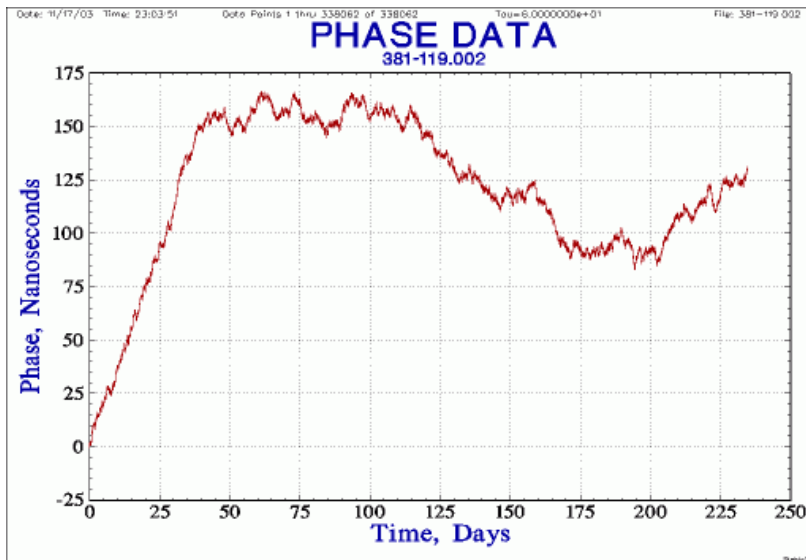
- 86.4 ps/d
- Near  $1 \times 10^{-15}$  @1d
- Cavity auto-tuned



C:\tvb\Tscplot\Log20148.gif

# $10^{-15}$ cesium, long-term

- High-perf units
- Pair near  $2 \times 10^{-14}$  at a day
- Floor near  $5 \times 10^{-15}$  in weeks



# Powers of Ten - summary

---

- 10% to  $10^{-15}$  - 15 orders of magnitude



# Chapter 6

- Experimental setup

# Key Parameters

---

- How high
- How long
- How stable
- How many
- How precise you measure



Cartoon by Dusan Petricic  
Scientific American column Wonders by Philip and Phyllis Morrison  
<http://www.sciam.com/1998/0298issue/0298wonders.html>

# Ingredients

---

- Portable clocks, *hp 5071A*, @3
  - Check against base clock (home)
  - Check against themselves (away)
- Base clock (passive H-maser)
  - Check against active H-maser)
  - Check against GPS @2
- Measurement system
  - *hp 53132A TIC* (~150 ps) @3
  - Laptop

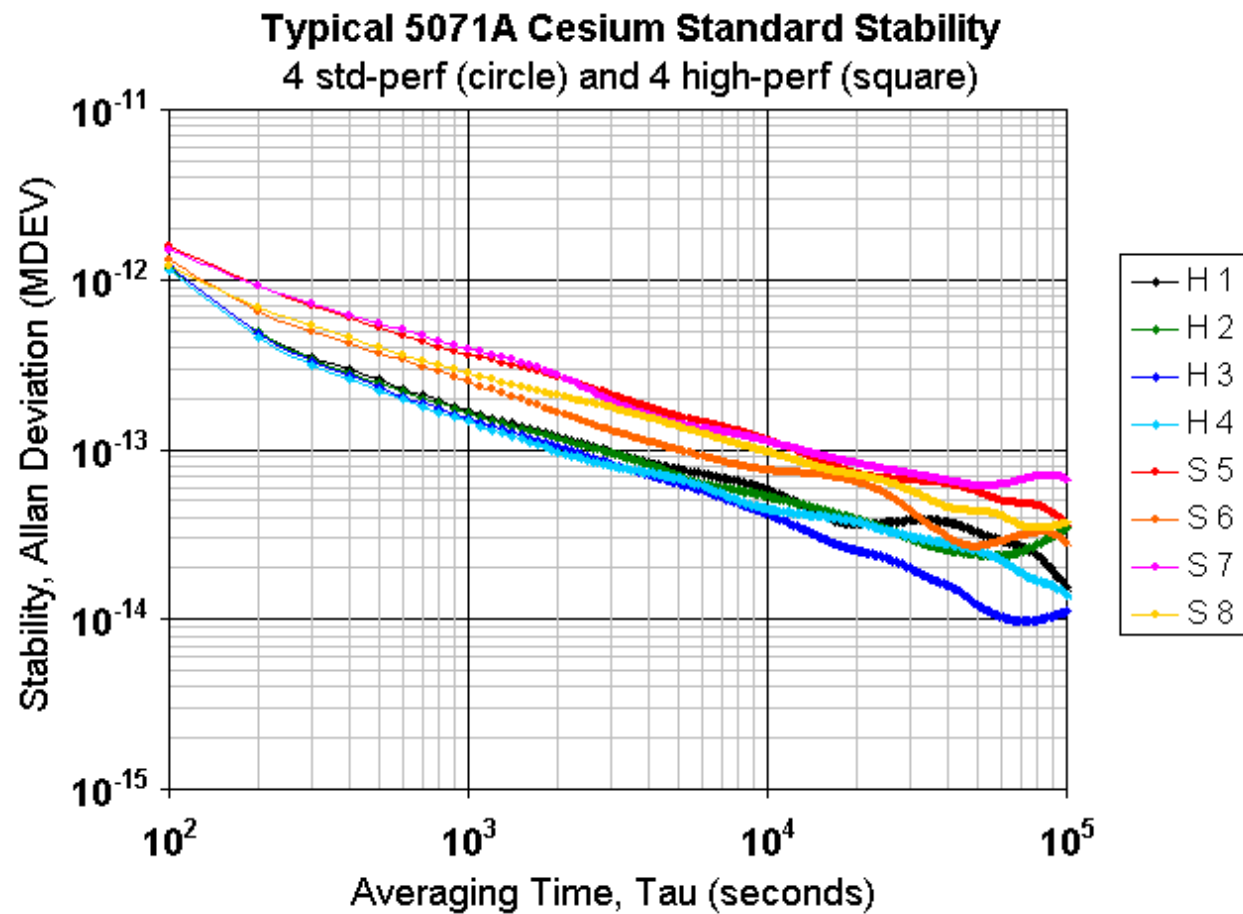
# Portable Clock(s)

---

- Many Cs tested (5060,5061,4050,4060)
- Three good 5071A/001 chosen
- Color coded clocks, cables, TIC, kids
- Deliberate phase offset of +1, +2, +4  $\mu\text{s}$
- 1 PPS cables kept with clocks
- HP 53132A TIC per clock
- Data logged at 1 Hz; 5 min averages

# 5071A

- Pick best ones...





# Data collection

- RS232 interface
- PC serial port logger
- MJD time-stamps
- 8 port serial-to-USB
- 53132A ti,mean,sdev
- 5071A stats
- GPS NMEA

```
53630.228030 5.775,8 us
53630.228067 5.775,8 us
53630.228067 N : 300
53630.228067 STD DEV: 0.000,390 us
53630.228067 MEAN : 5.775,600 us
53630.228067 MAX : 5.776,8 us
53630.228067 MIN : 5.774,3 us
53630.228079 5.775,8 us
53630.228090 5.775,8 us
53630.228102 5.775,3 us
53630.228113 5.775,8 us
53630.228125 5.776,3 us
```

```
scpi > syst:print?
```

```
MJD 53627 06:28:28
CBT ID: US31281148(H)
Status summary: operating normally
Power source: AC
Log status: 20 entries

Freq offset: 0e-15 Osc. control: -8.40 %
RF amplitude 1: 30.2 % RF amplitude 2: 28.6 %
Zeeman Freq: 39949 Hz C-field curr: 12.204 mA
E-multiplier: 1226 V Signal Gain: 14.4 %

CBT oven: 7.6 V CBT oven Err: 0.02 C
Osc. Oven: -9.0 V Ion Pump: 0.0 uA
Hw Ionizer: 1.0 V Mass spec: 12.8 V
SAW Tuning: 0.0 V DRO Tuning: 6.3 V
87MHz PLL: 0.9 V UP Clock PLL: 3.0 V
+12V supply: 12.3 V -12V supply: -12.3 V
+5V supply: 5.5 V Thermometer: 41.1 C
```

```
53630.940405 $GPGLL,4733.2630,N,12208.3683,W,223410,A,A*50
53630.940405 $GPBOD,,T,,M,,*47
53630.940405 $PGRME,10.6,M,13.2,M,17.0,M*1F
53630.940405 $PGRMZ,980,f,3*1A
53630.940405 $GPRTE,1,1,c,*37
53630.940428 $GPRMC,223412,A,4733.2630,N,12208.3683,W,0.0,0.0,170905,18.1,E,A*3C
53630.940428 $GPRMB,A,,,,,,,,,A,A*0B
53630.940428 $GPGGA,223412,4733.2630,N,12208.3683,W,1,04,2.9,298.4,M,-18.4,M,,*7F
53630.940428 $GPGSA,A,3,,08,,,,,19,,27,28,,,5.1,2.9,4.3*35
53630.940428 $GPGSV,3,1,11,07,21,191,36,08,76,089,49,10,07,249,00,11,14,099,00*7A
53630.940428 $GPGSV,3,2,11,13,00,161,00,18,00,347,00,19,23,044,42,26,35,309,00*72
53630.940428 $GPGSV,3,3,11,27,44,114,44,28,77,263,45,29,45,297,00*42
```

# Base Clock, 'House' standard

---

- Master 1 PPS, CH1-76 passive H-maser
- 1PPS distribution system (8x)
- 1PPS vs. HP 58503B GPSDO
- 1PPS vs. CNS-II (sawtooth-less M12+)
- 1PPS used as ref for 5071A (x3)
- Deliberate phase offset of  $-4 \mu\text{s}$
- 5 MHz vs. active maser

# AC / DC power

---

- Engine tap from minivan 12 VDC
- 2 batteries in parallel for 12 V
- 4 batteries in series/parallel for 24 V
- 12VDC/120VAC inverters
- AC power for clocks
- AC power for laptop(+batt) and TIC
- Triple backup for clocks (AC,DC,+batt)
- Power, voltage, and current monitors

# Comment on Clock Accuracy

---

- Need to predict time 2 days in future
- Not accuracy, but stability
  - ADEV ( $\tau=2d$ )
- 5071A/001 is  $\sim 1 \times 10^{-14}$
- Three clocks:
  - Redundancy (single point of failure)
  - Self-checking (one clock, two clocks...)
  - Lower uncertainty ( $\sqrt{3} = 1.7x$  better)

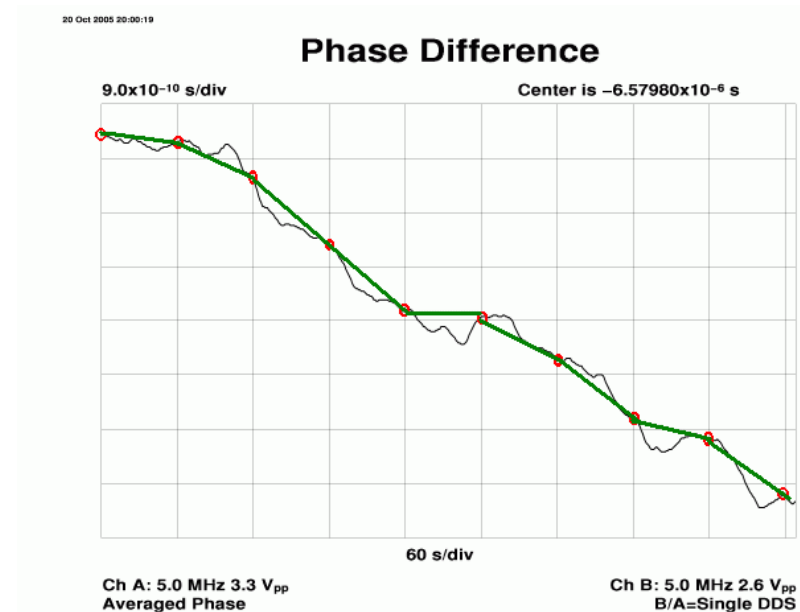
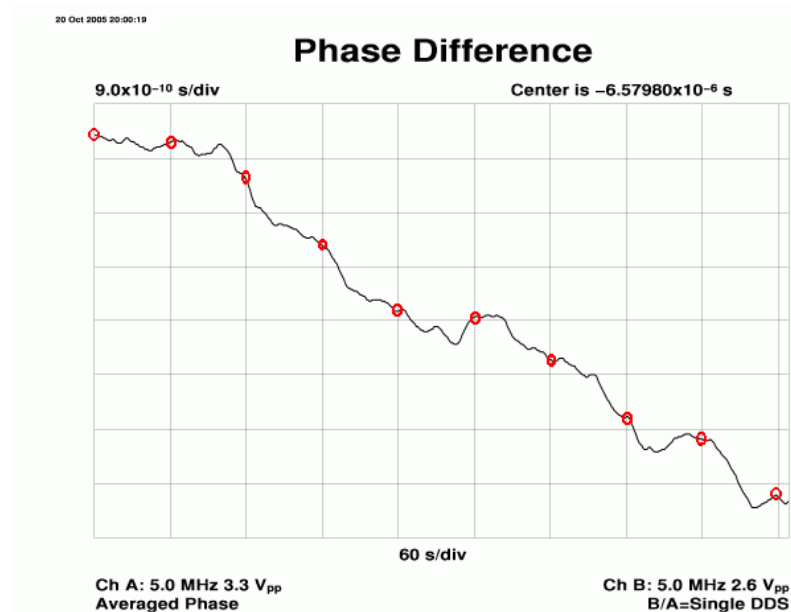
# Carrying the Time

---

- How to measure clocks when at home?
  - Compare with house reference
  - Compare amongst themselves
- How much to trust clocks when away?
  - What do clocks do when you're not looking?
  - Guess future behavior = known past
  - Past statistics give future predictions
  - 'Certainty' replaced with 'confidence'

# Stability: Measurements

- Phase measurements:  $p_0, p_1, p_2, \dots$
- Frequency *calculations* (tau T):  
 $f_1 = (p_1 - p_0)/T, f_2 = (p_2 - p_1)/T, \dots$



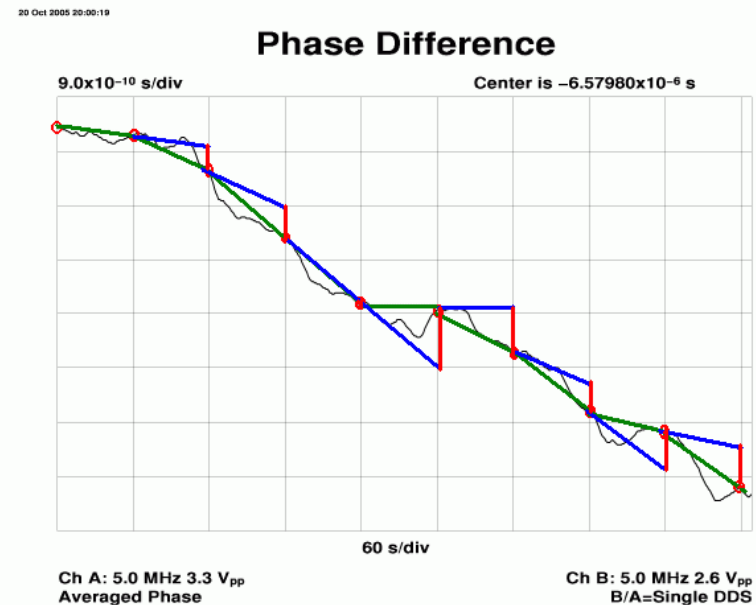
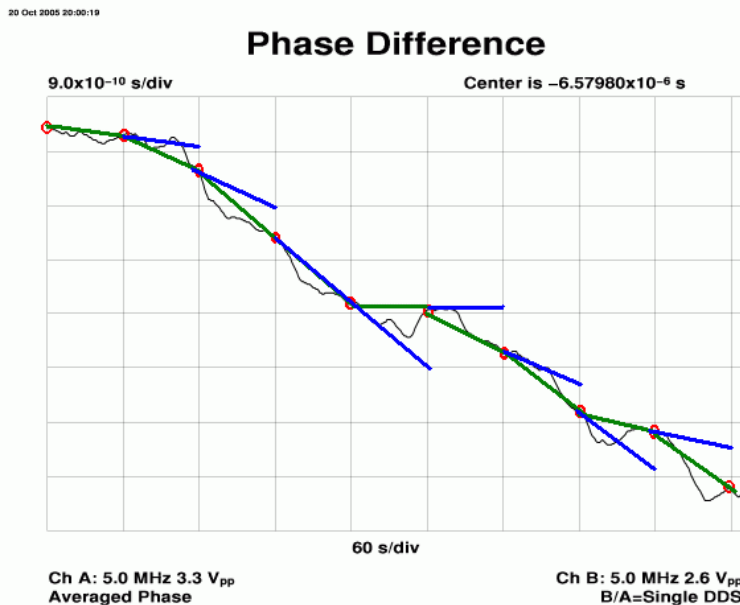
# Stability: Predictions

- Predict (extrapolate) future phase:

$$p2' = p1 + f1 \cdot T = p1 + (p1 - p0)$$

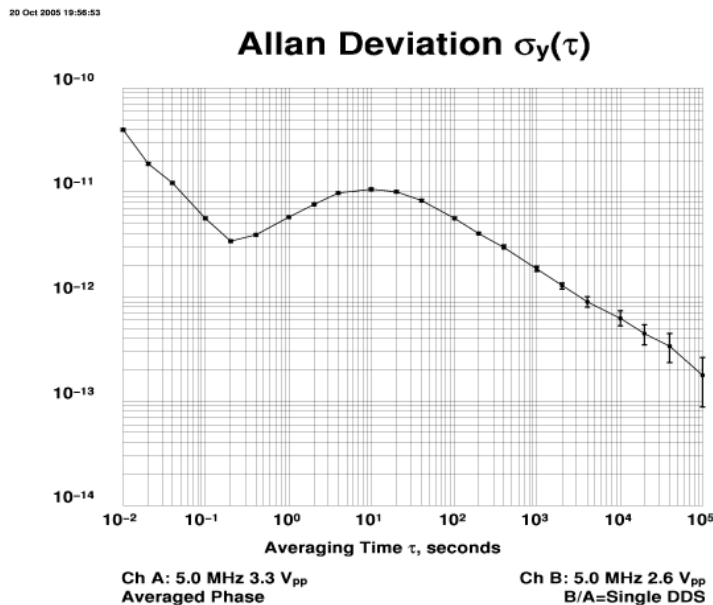
- Later, check prediction error:

$$e2 = p2 - p2' = p2 - 2p1 + p0$$



# Stability: Allan Deviation

- Stddev of prediction errors gives you estimate of future accuracy of clock
- This  $\Sigma[p2 - 2p1 + p0]$  thing is ADEV



C:\tvb\TSCp1ot\Log2421.gif

20 Oct 2005 19:56:12

**Allan Deviation Table**

Avg. Time (s)	Allan Deviation $\sigma_y(\tau)$	Avg. Time (s)	Allan Deviation $\sigma_y(\tau)$
0.01	3.99±.12x10 <sup>-11</sup>	400	3.00±.094x10 <sup>-12</sup>
0.02	1.86±.058x10 <sup>-11</sup>	1000	1.86±.092x10 <sup>-12</sup>
0.04	1.227±.038x10 <sup>-11</sup>	2000	1.28±.090x10 <sup>-12</sup>
0.1	5.63±.18x10 <sup>-12</sup>	4000	9.0±.89x10 <sup>-13</sup>
0.2	3.39±.11x10 <sup>-12</sup>	10000	6.3±.99x10 <sup>-13</sup>
0.4	3.93±.12x10 <sup>-12</sup>	20000	4.4±.97x10 <sup>-13</sup>
1	5.84±.18x10 <sup>-12</sup>	40000	3.4±1.1x10 <sup>-13</sup>
2	7.65±.24x10 <sup>-12</sup>	100000	1.7±.87x10 <sup>-13</sup>
4	9.82±.31x10 <sup>-12</sup>		
10	1.080±.034x10 <sup>-11</sup>		
20	1.017±.032x10 <sup>-11</sup>		
40	8.28±.26x10 <sup>-12</sup>		
100	5.69±.18x10 <sup>-12</sup>		
200	4.06±.13x10 <sup>-12</sup>		

Ch A: 5.0 MHz 3.3 V<sub>pp</sub>  
Averaged Phase

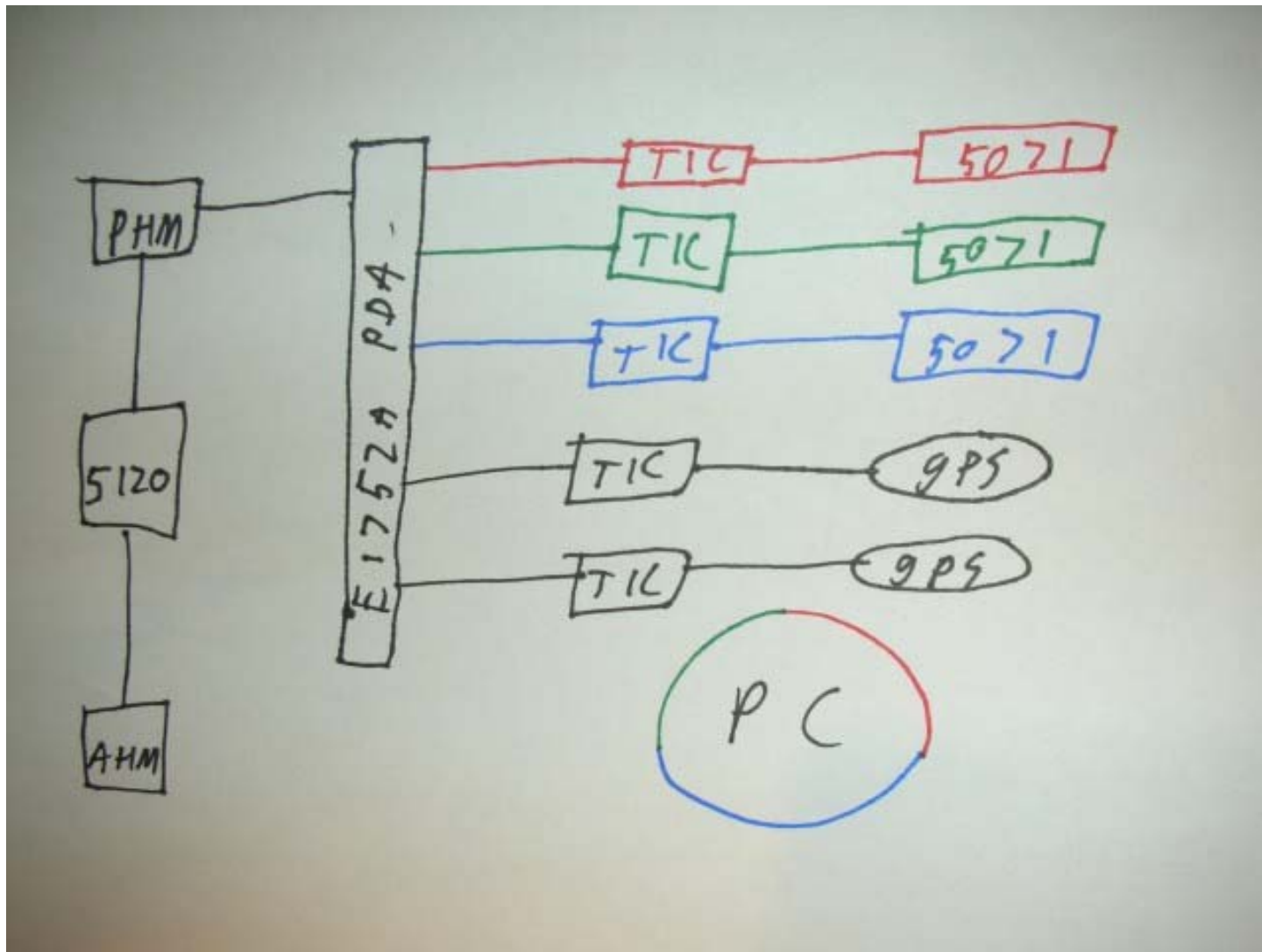
Ch B: 5.0 MHz 2.6 V<sub>pp</sub>  
B/A=Single DDS

C:\tvb\TSCp1ot\Log2422.gif



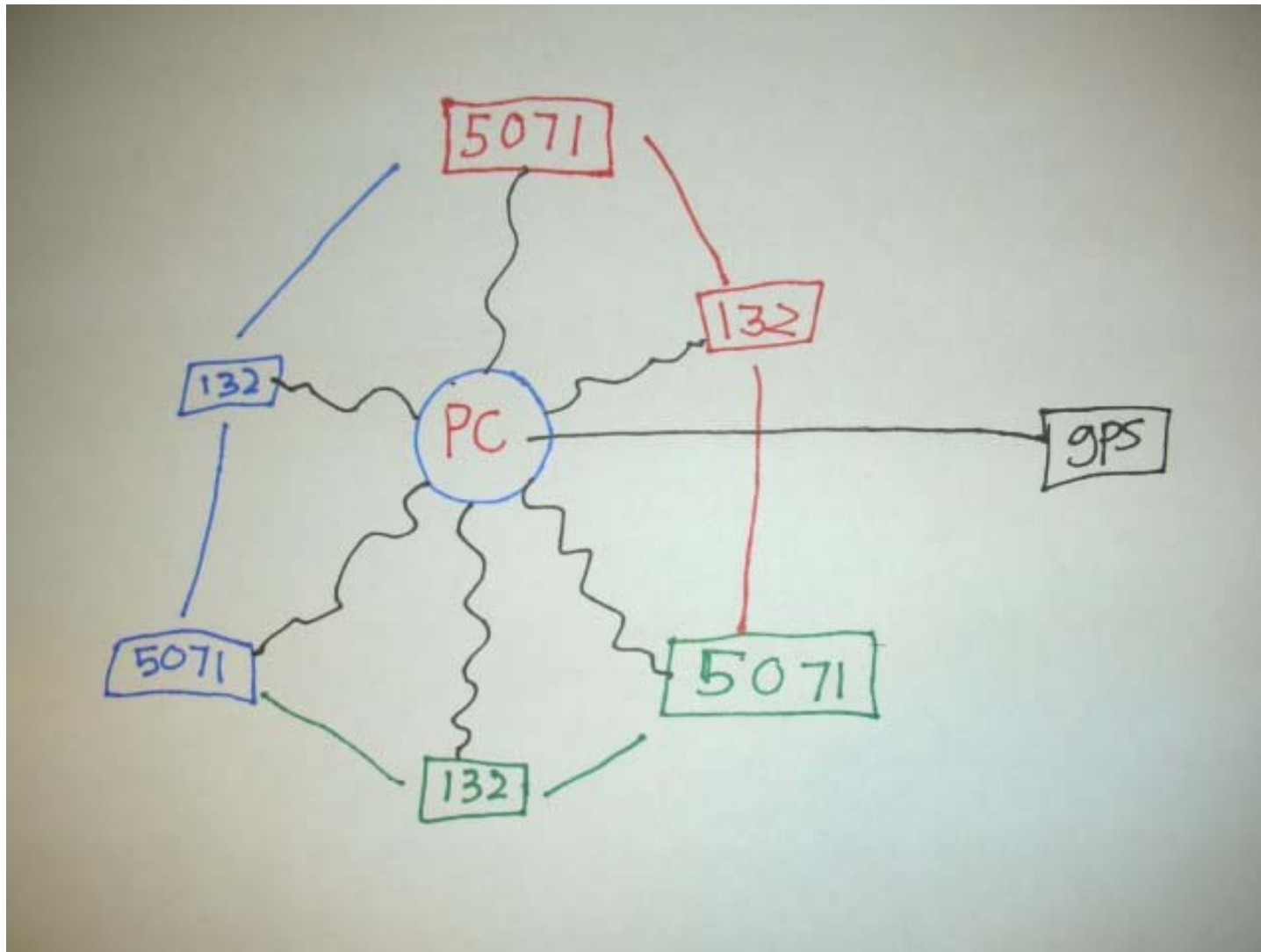
# Map - home clocks

---



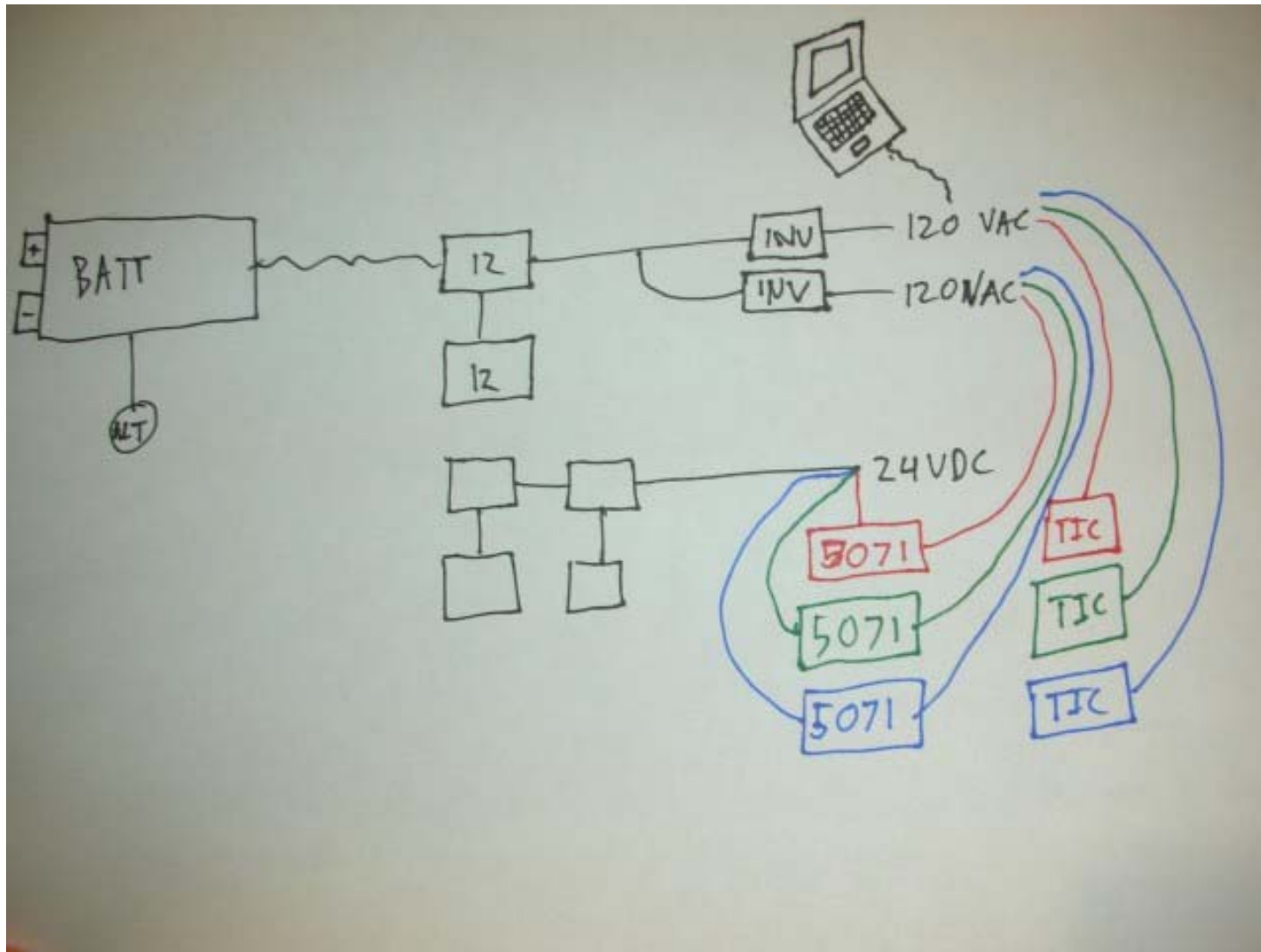
# Map - mobile clocks

---



# Map - mobile power

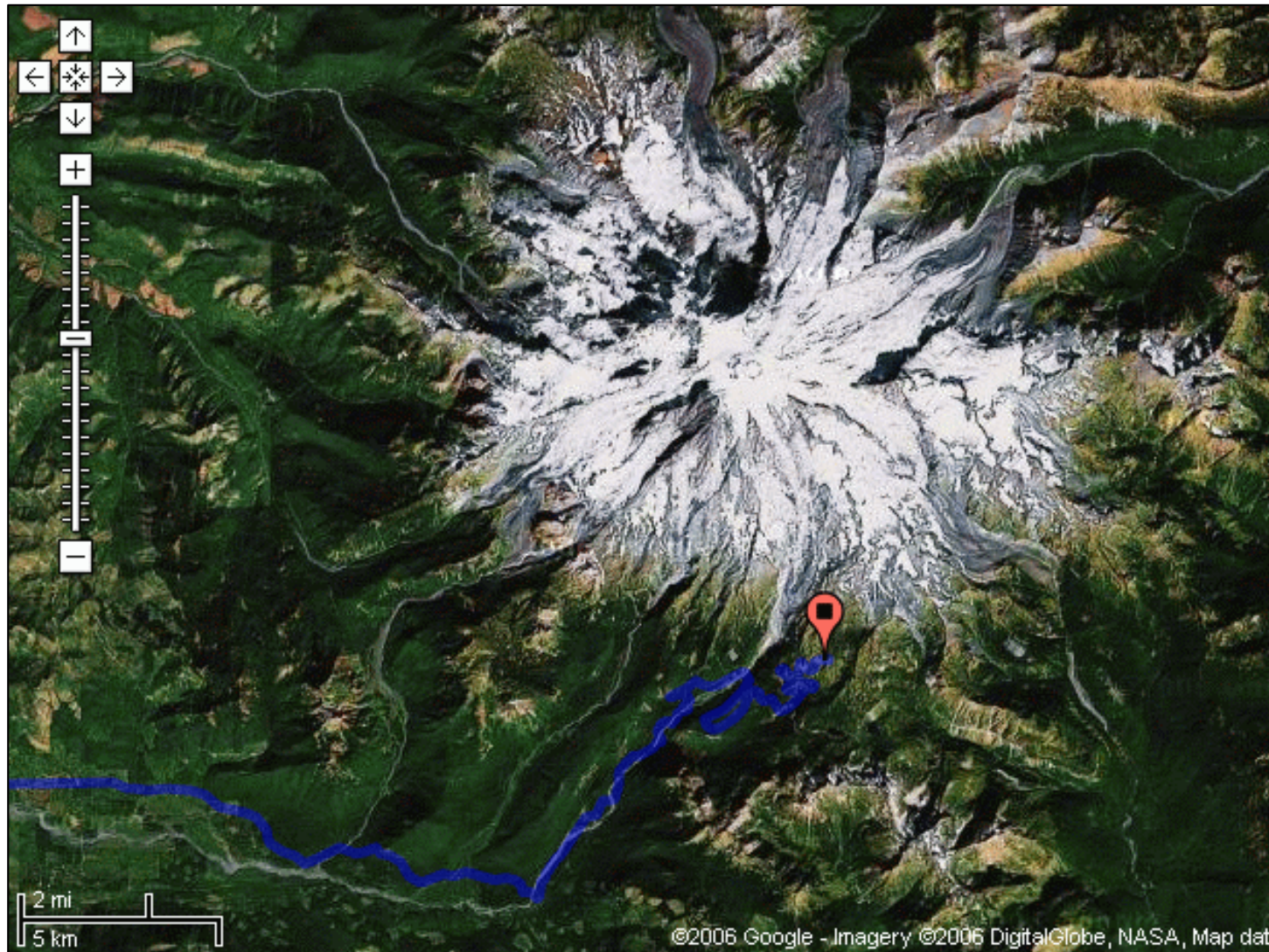
---



# Map - Paradise, Mt Rainier

---

• ~



# Chapter 7

- Photos of the trip

# The GREAT Trip, day 1

---

- Carrying clock downstairs. Limited time; car is a mess, but it works.



# The GREAT Trip, day 1

---

- Kids in the rear, clocks in the middle, and instrumentation in the front.



# The GREAT Trip, day 1

---

- Dad making final clock BNC connections to TIC; Mom says goodbye.





# The GREAT Trip, day 1

---

- Detail of TIC's and laptop in front seat and clocks in middle seat. 23:33:48 UTC



# The GREAT Trip, day 1

---

- Kids drink stop costs me \$8 and 125 ps ( $\frac{1}{4}$  hour  $\times$  500ps/h).



# The GREAT Trip, day 1

---

- Final gas stop and evening arrival in Rainier National Park.



# The GREAT Trip, day 2

---

- Paradise Inn is at 5400' elevation. Large parking lot to hide in.



# The GREAT Trip, day 2

---

- Classic old Northwest inn; you should visit sometime.



# The GREAT Trip, day 2

---

- Wonderful hiking trails and climbing.



# The GREAT Trip, day 2

---

- Good, the car is still there. Hike to Glacier Vista (6300')



# The GREAT Trip, day 2

---

- Oh no. The sun is really strong and the A/C isn't working as well as I hoped.





# The GREAT Trip, day 2

---

- Avoid a ticket and move the car again. Ouch, running low in fuel. Now what.



# The GREAT Trip, day 2

---

- Kids are fine. Trip is long. Looking for GPS location for next time. What! Valet shuts car off for an hour.



# The GREAT Trip, day 2

---

- Air is thin; little sleep; ponder Time; spend an hour; why are we doing this; Harrison; GPS. That's 500 ps/beer.



# The GREAT Trip, day 3

---

- Got gas at 6 AM. Used 15.78 gal in 34 h = 0.46 gph;  $\sim 2\text{h/gal}$ , so about 1 ns/gal. Cost me \$51 and 745 ps.



# The GREAT Trip, day 3

---

- More hiking, exploring, playing. It's a fun place for a while.



# The GREAT Trip, day 3

---

- 42 hours is up; time to leave. We're all tired. Can this really work? Go home.



# The GREAT Trip, day 3

---

- Carry clocks & TIC's back inside, reconnect same cables, resume phase comparison, unpack car. Sleep.



# Chapter 8

- Analysis of GPS data



# GPS Log

---

- Serial NMEA data stream (0.5 Hz)
- \$GPGGA (time/lat/lon/alt)
- \$GPRMC (time/date/lat/lon/speed)

53632.503380 \$GPRMC,120454,A,4644.1107,N,12151.8606,W,26.8,272.6,190905,17.8,E,A\*03

53632.503380 \$GPGGA,120454,4644.1107,N,12151.8606,W,1,03,2.2,727.7,M,-18.8,M,,\*77

- Software tool calculates time dilation

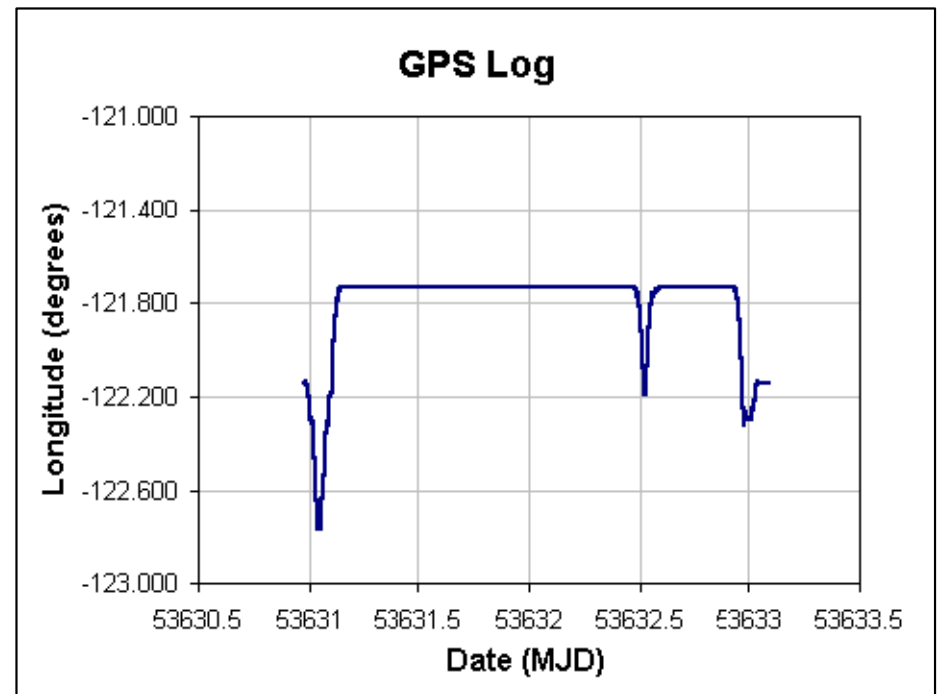
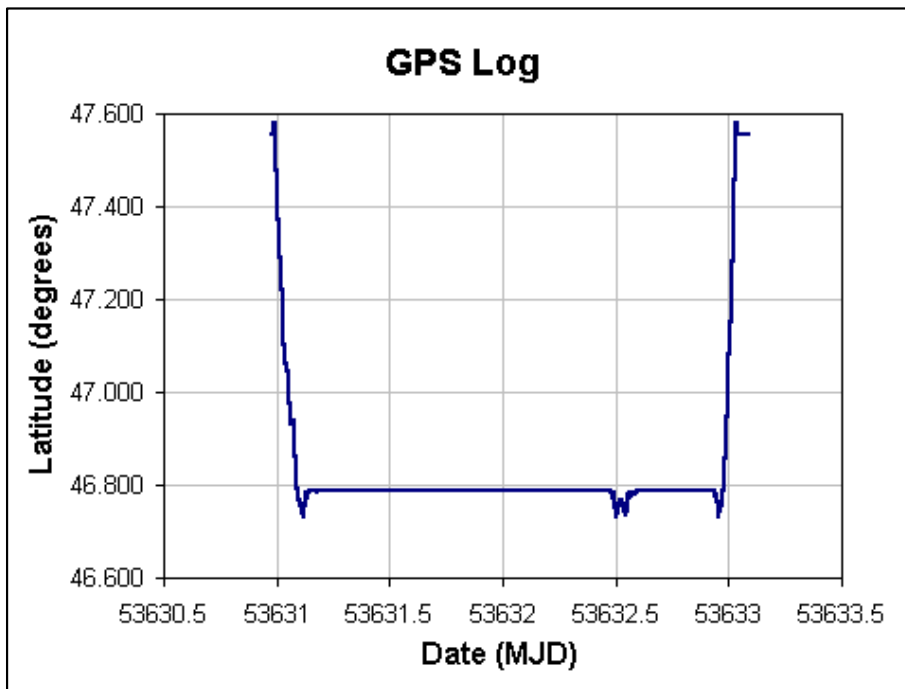
53632.503380 46.7352,-121.8640,728,14,0 17.325260 -0.027115 -0.076591 17.222

- Generated plots

# Plots from GPS Log

---

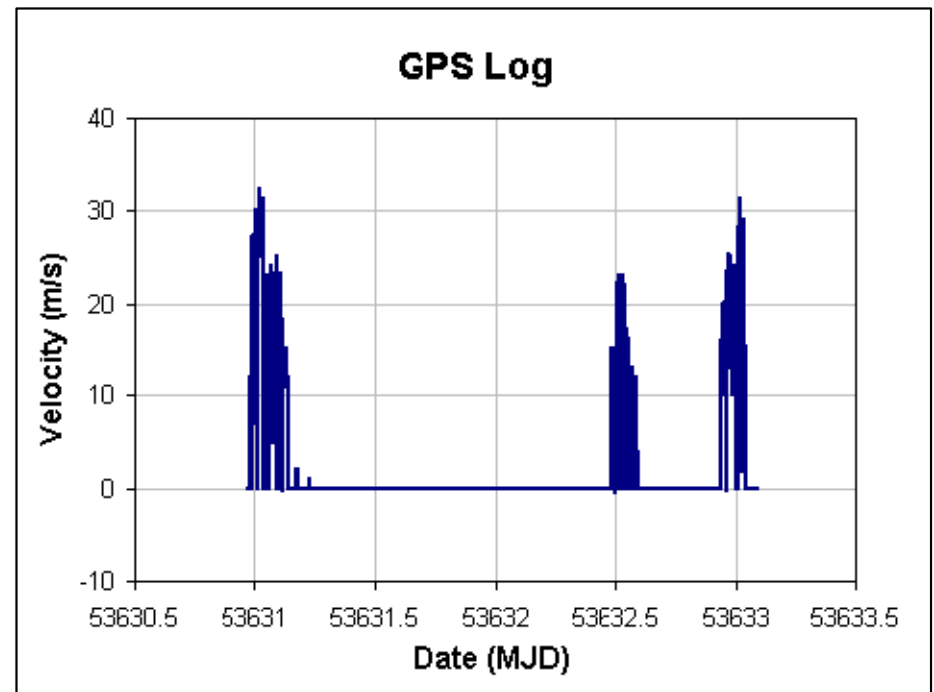
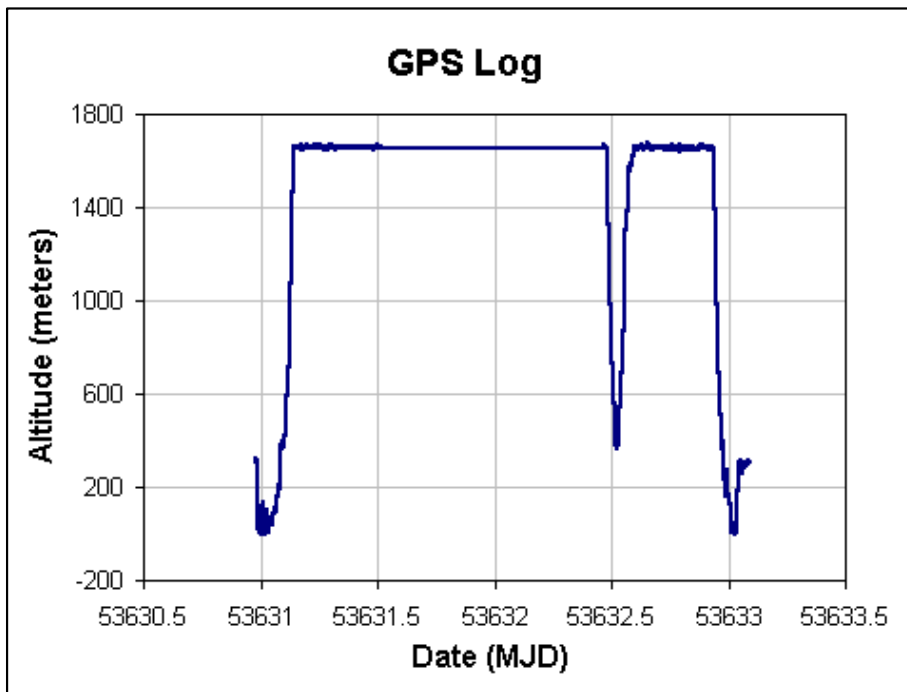
- Latitude, Longitude



# Plots from GPS Log

---

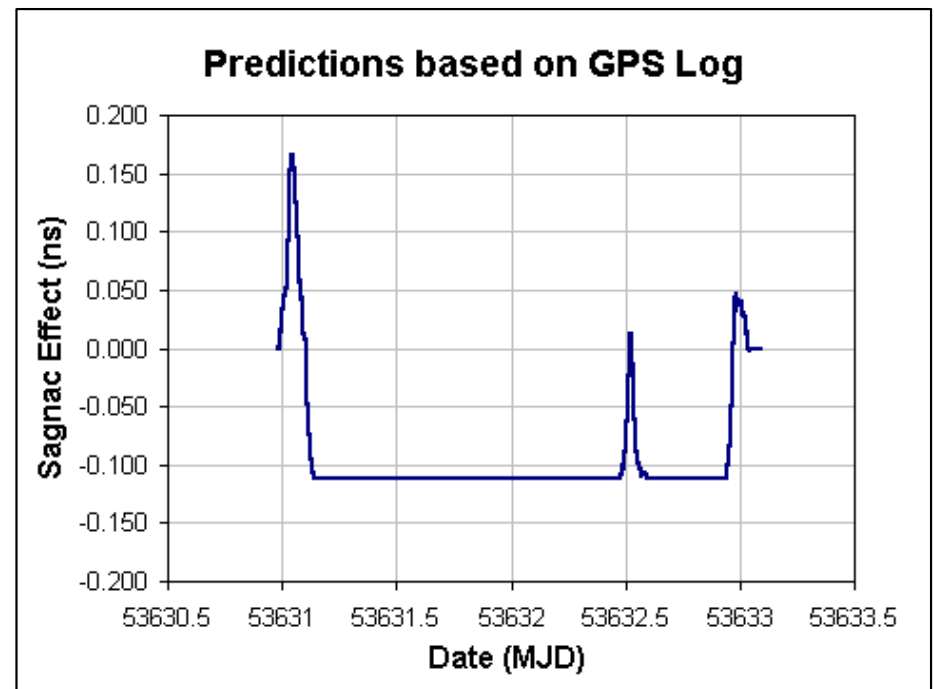
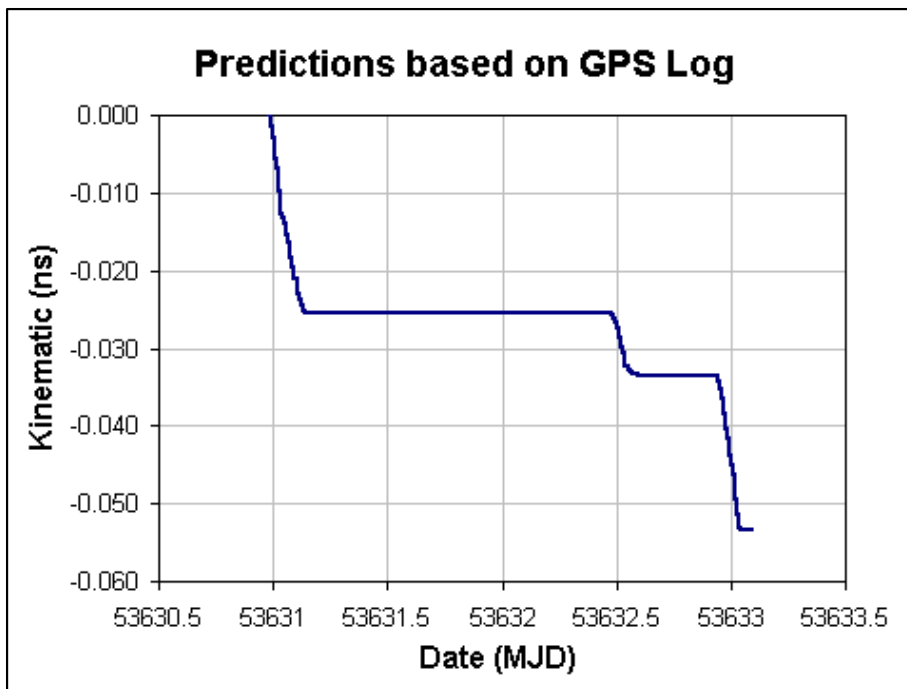
- Altitude, Velocity



# Predictions from GPS Log

---

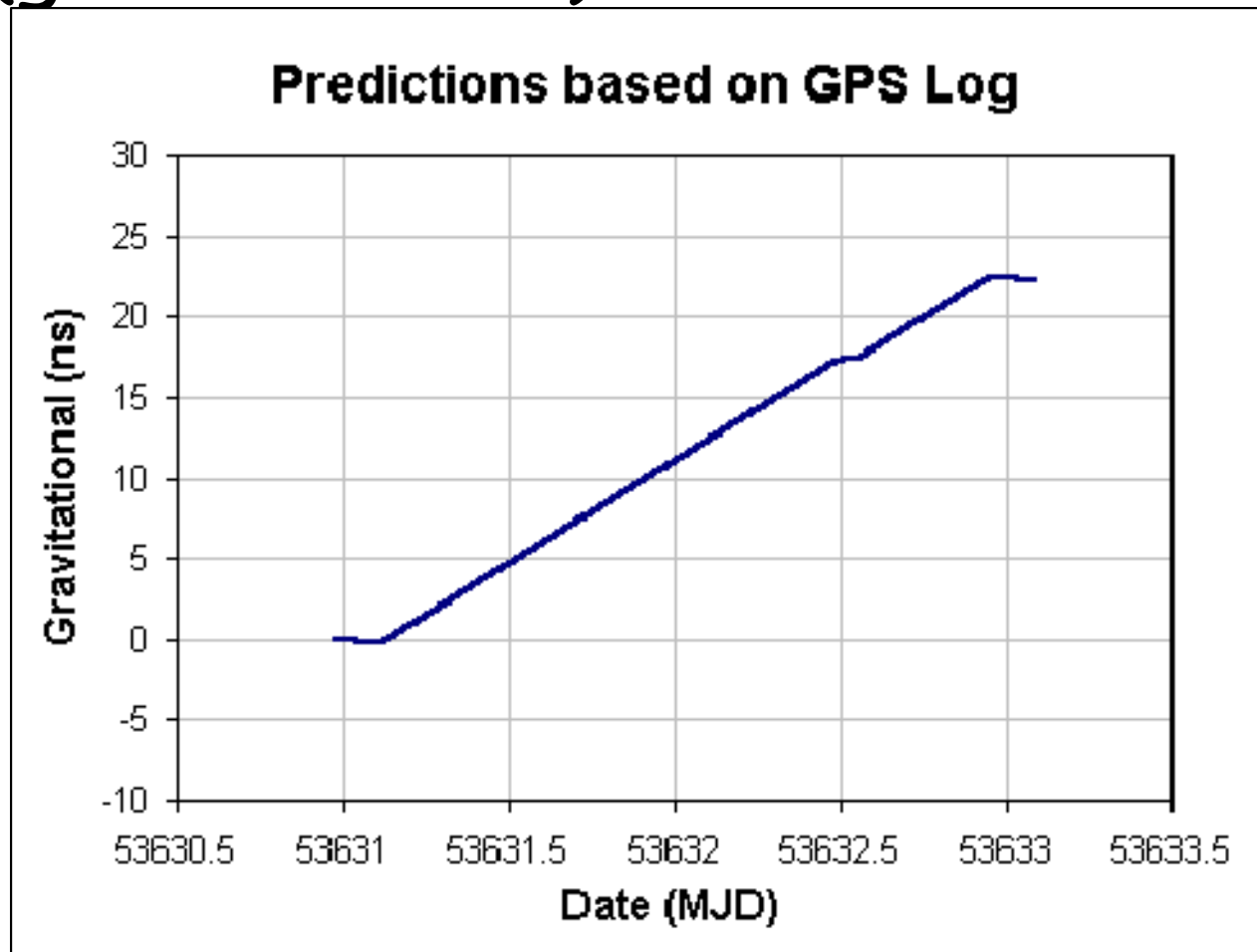
- SR (velocity): 50 ps
- Sagnac effect:  $\pm 150$  ps (net 1 ps)



# Predictions from GPS Log

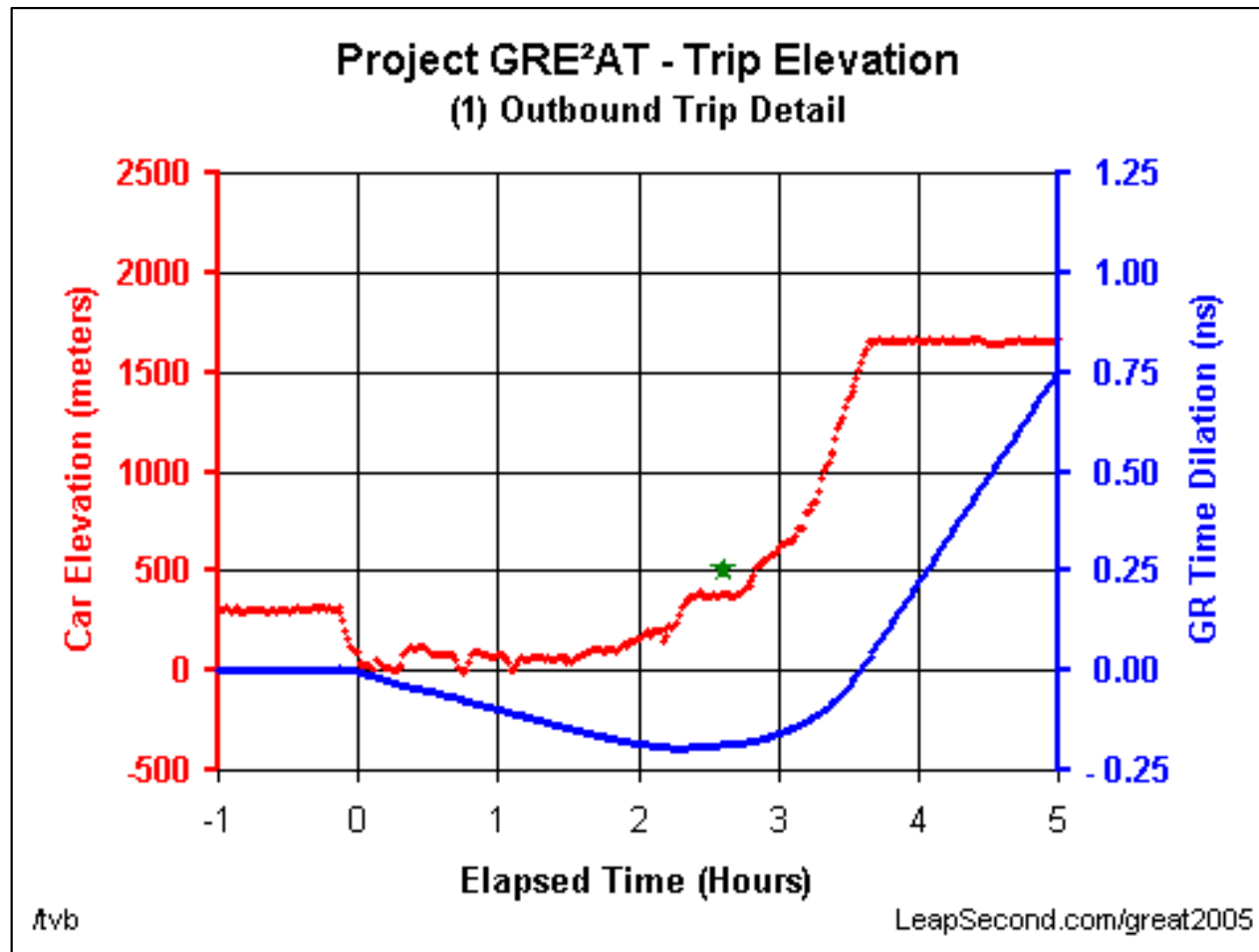
---

- GR (gravitational): 22.37 ns



# Composite plot - beginning

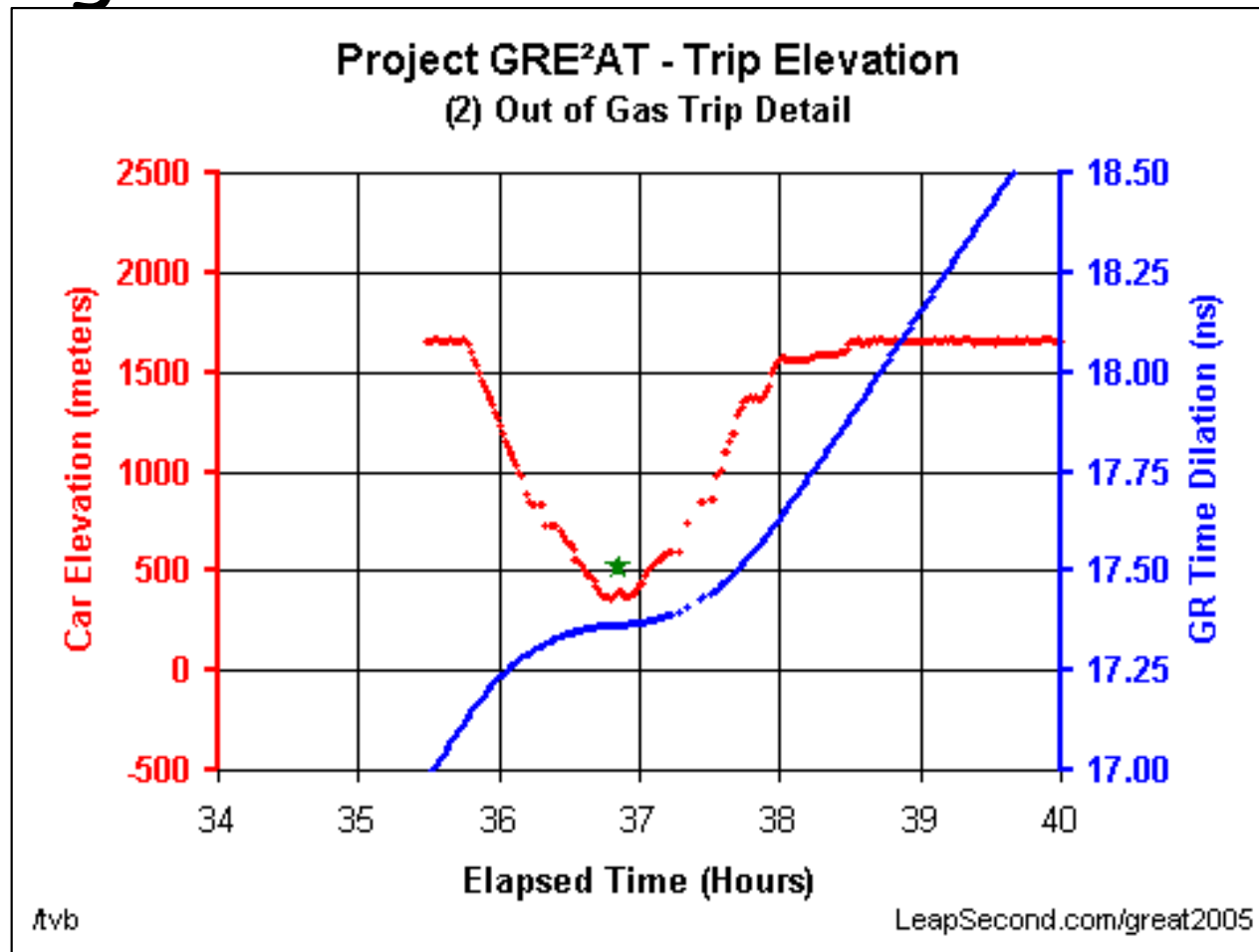
- Trip start



# Composite plot - middle

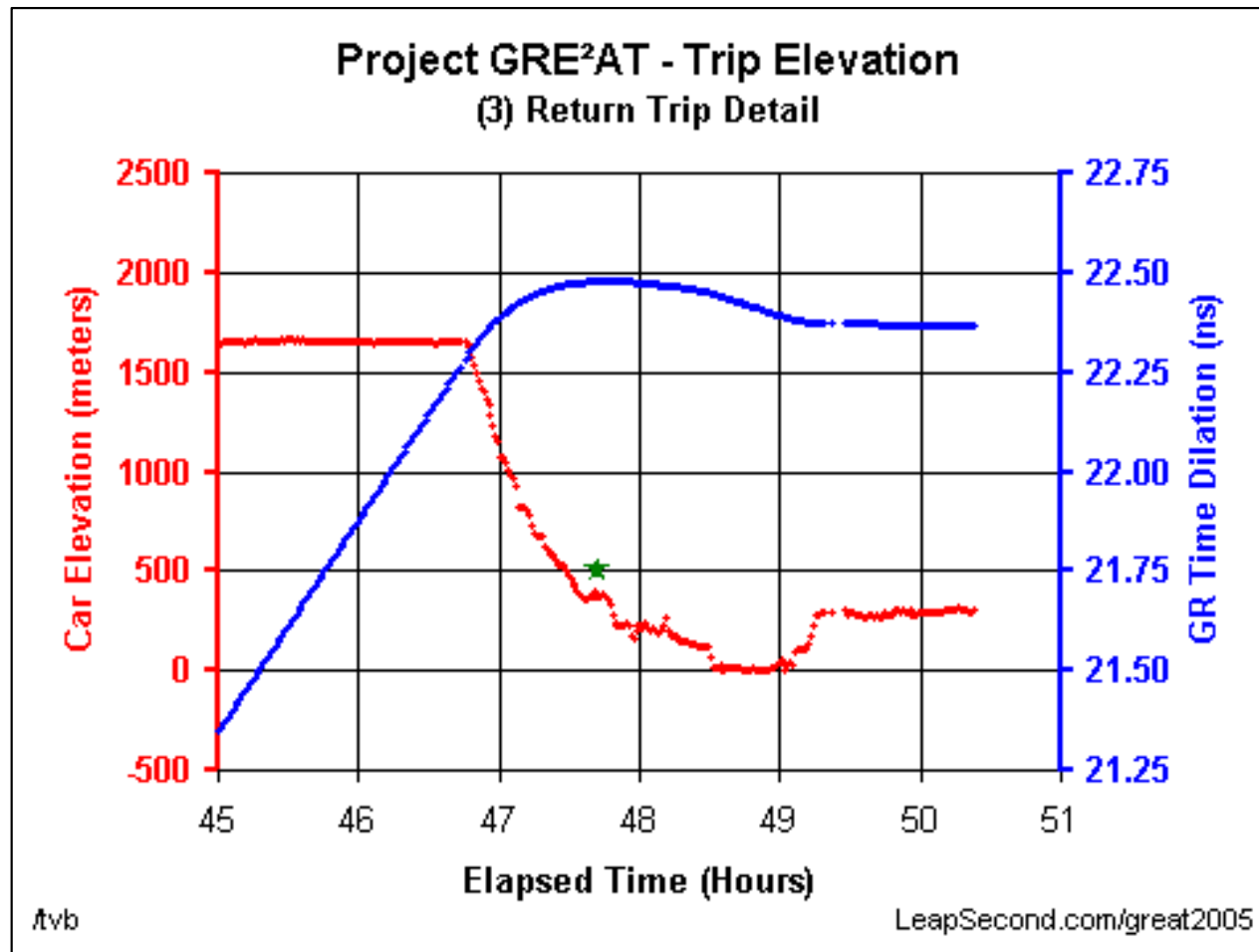
---

- More gas



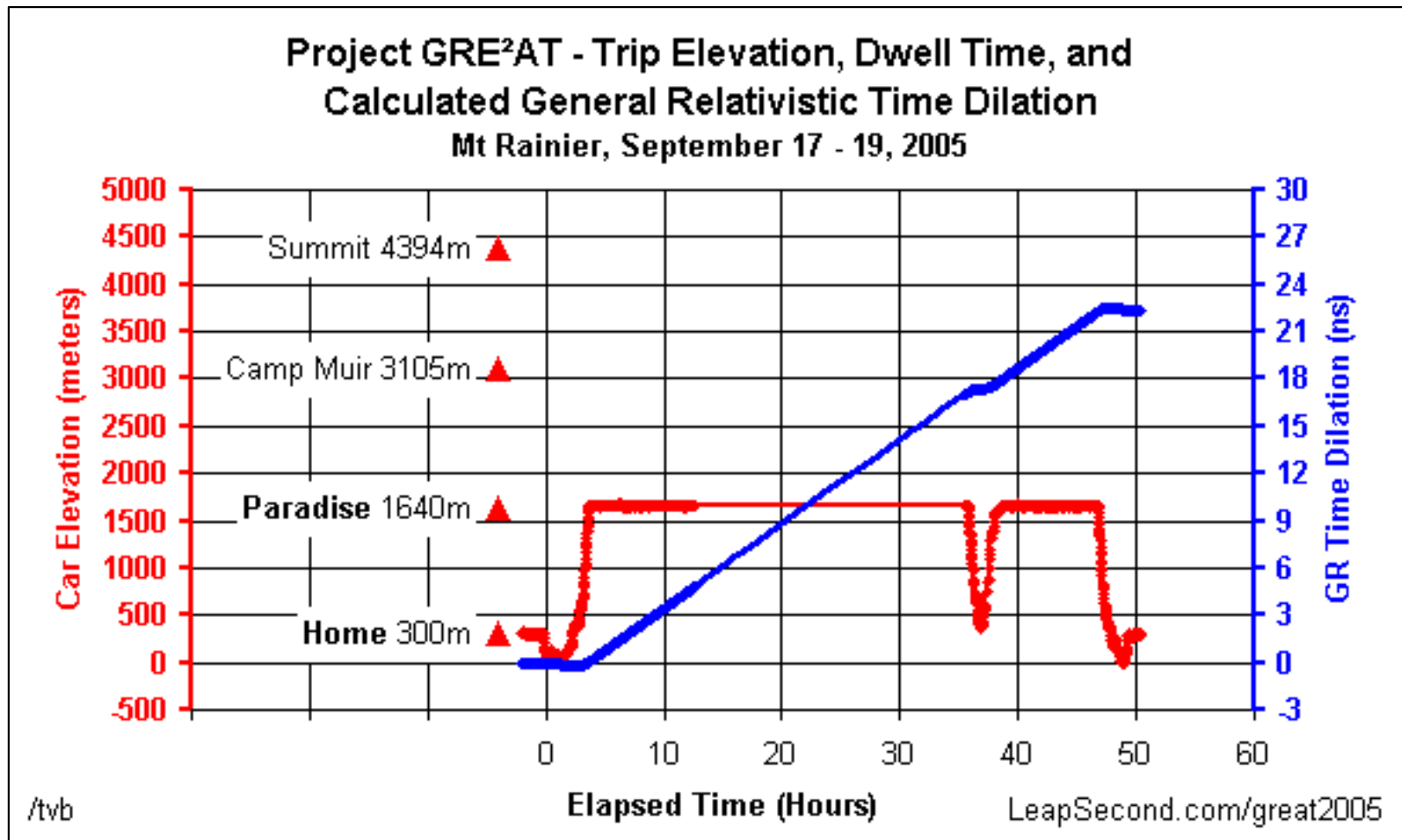
# Composite plot - end

- Trip end





# Composite plot (net 22.32 ns)



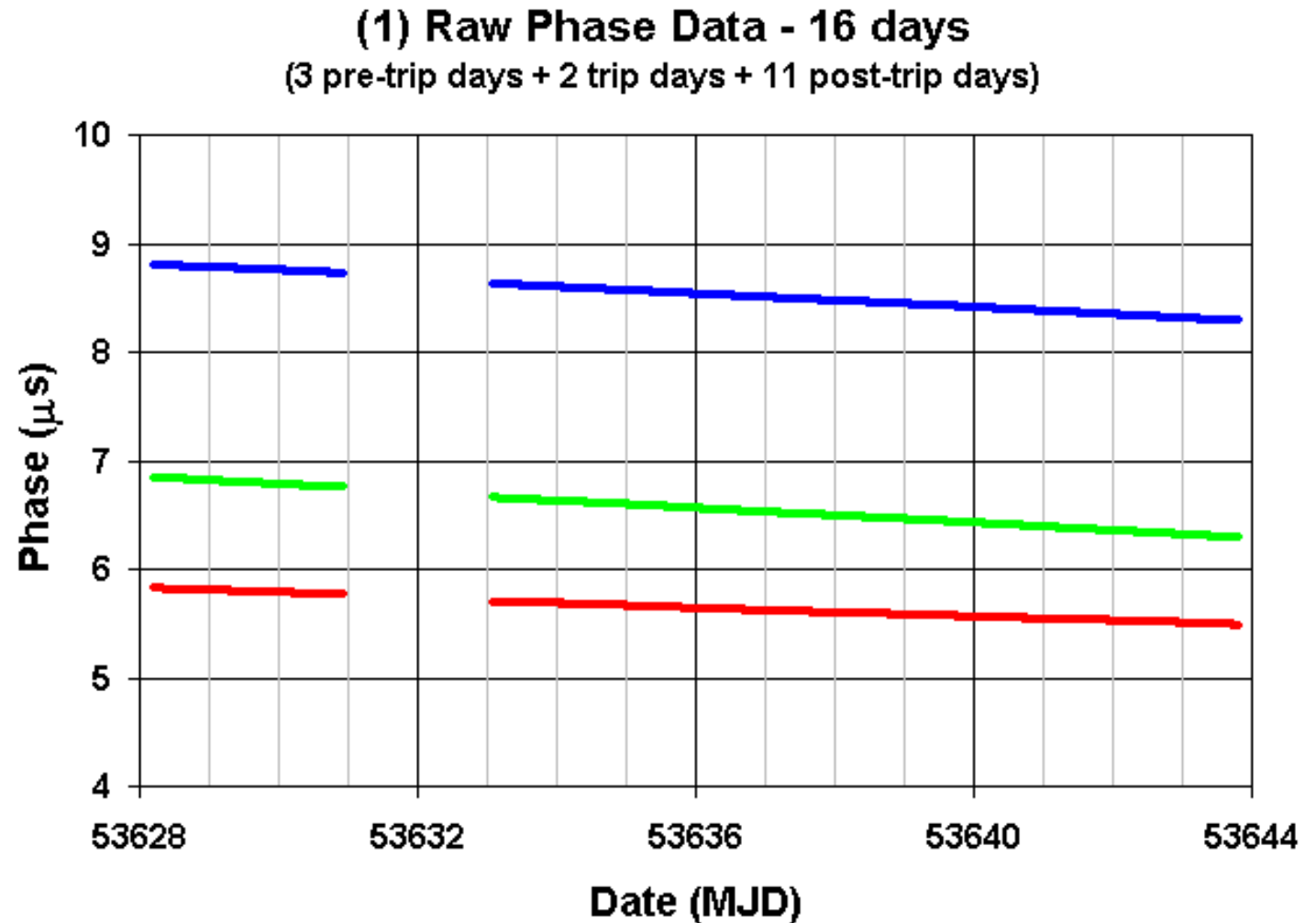
# Chapter 9

- Analysis of clock data

# Worked example

---

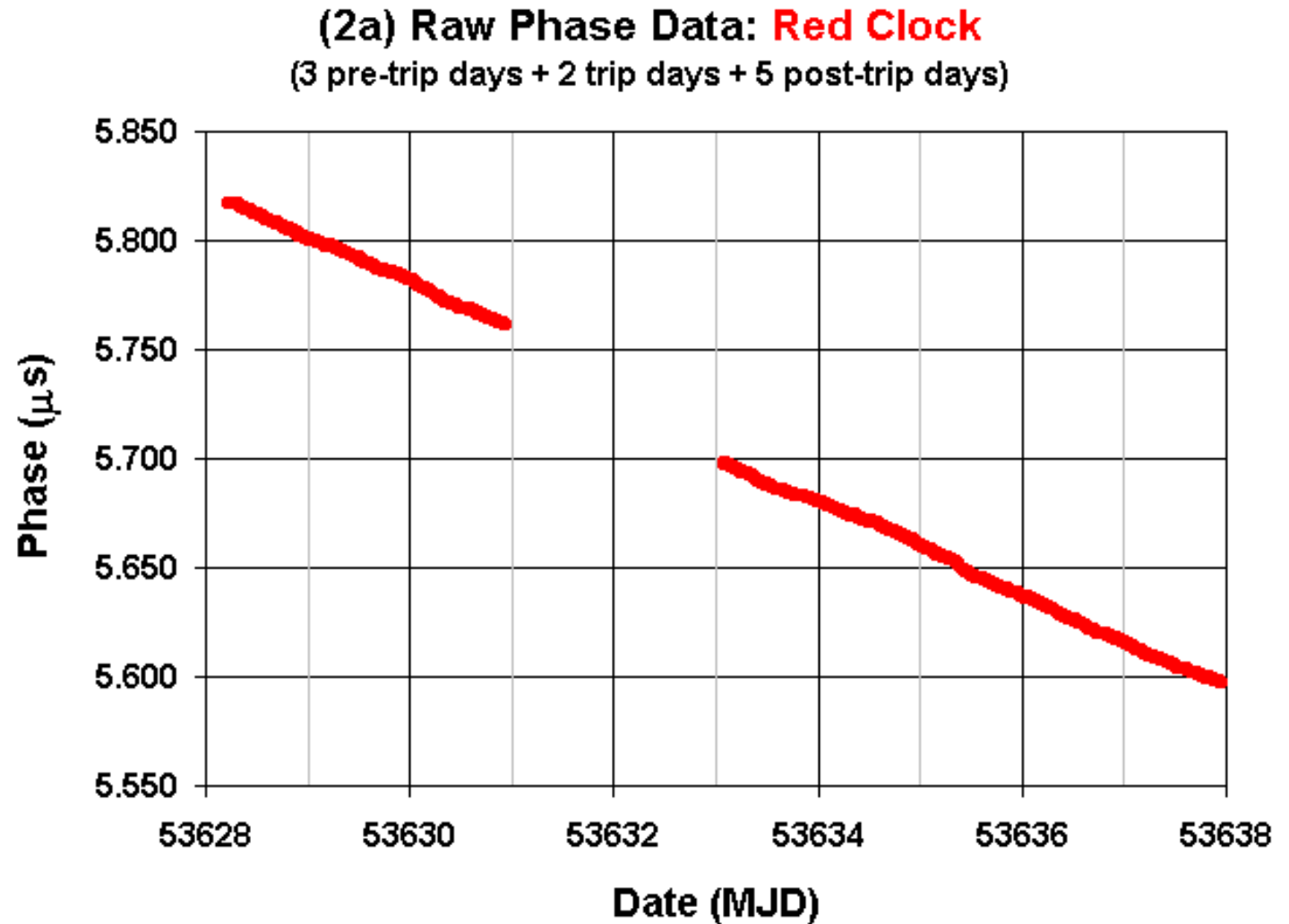
- Raw data
- 3 clocks



# Worked example

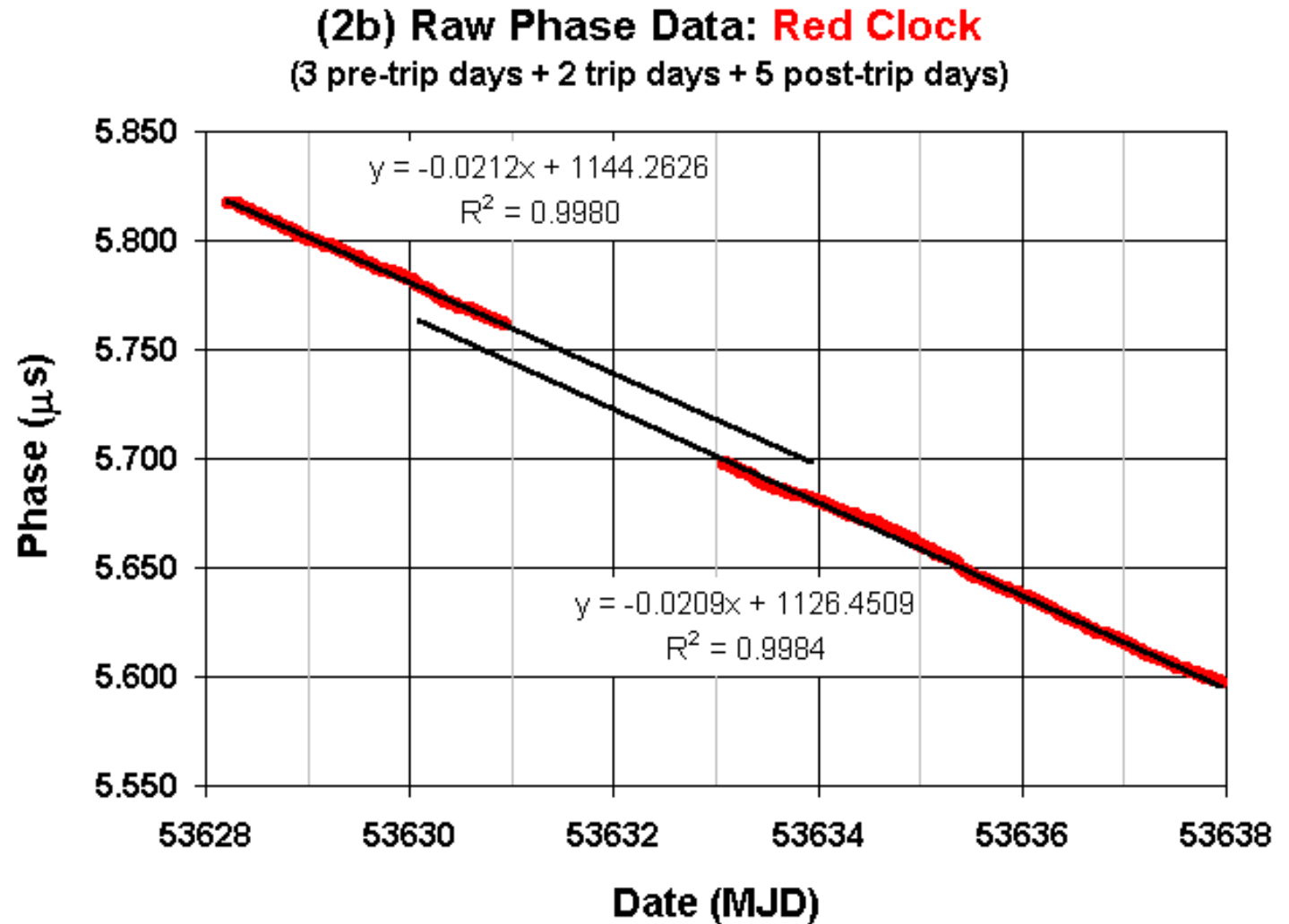
---

- Red only
- $5.85 \mu\text{s}$
- $5.55 \mu\text{s}$
- $-220 \text{ ns}$
- 10 days



# Worked example

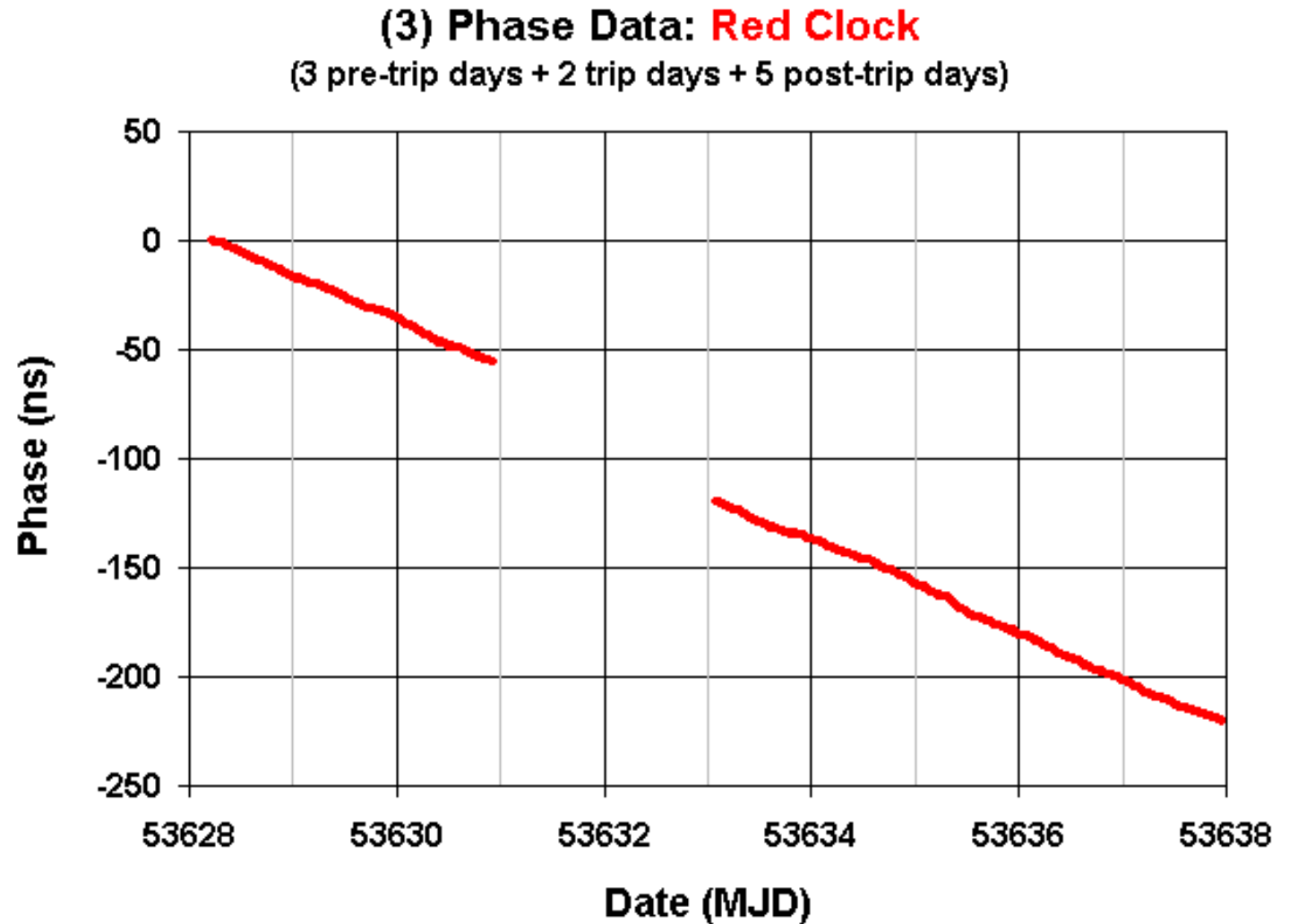
- Slope (freq)
- Pre/post
- -21.2  
-20.9  
ns/d
- 2.454  
2.419  
 $\times 10^{-13}$



# Worked example

---

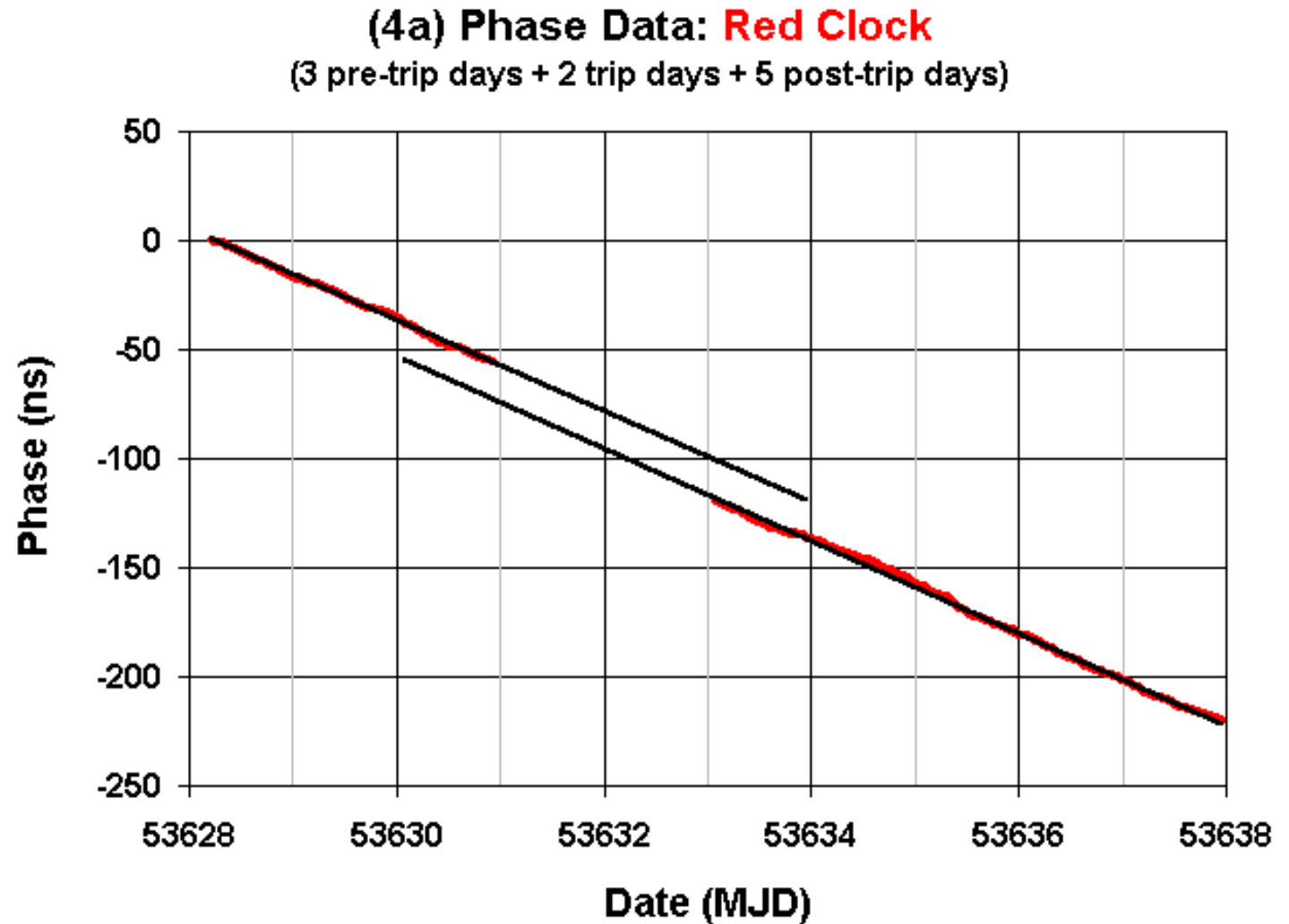
- Remove fixed  $\sim 5.8\mu\text{s}$  offset



# Worked example

---

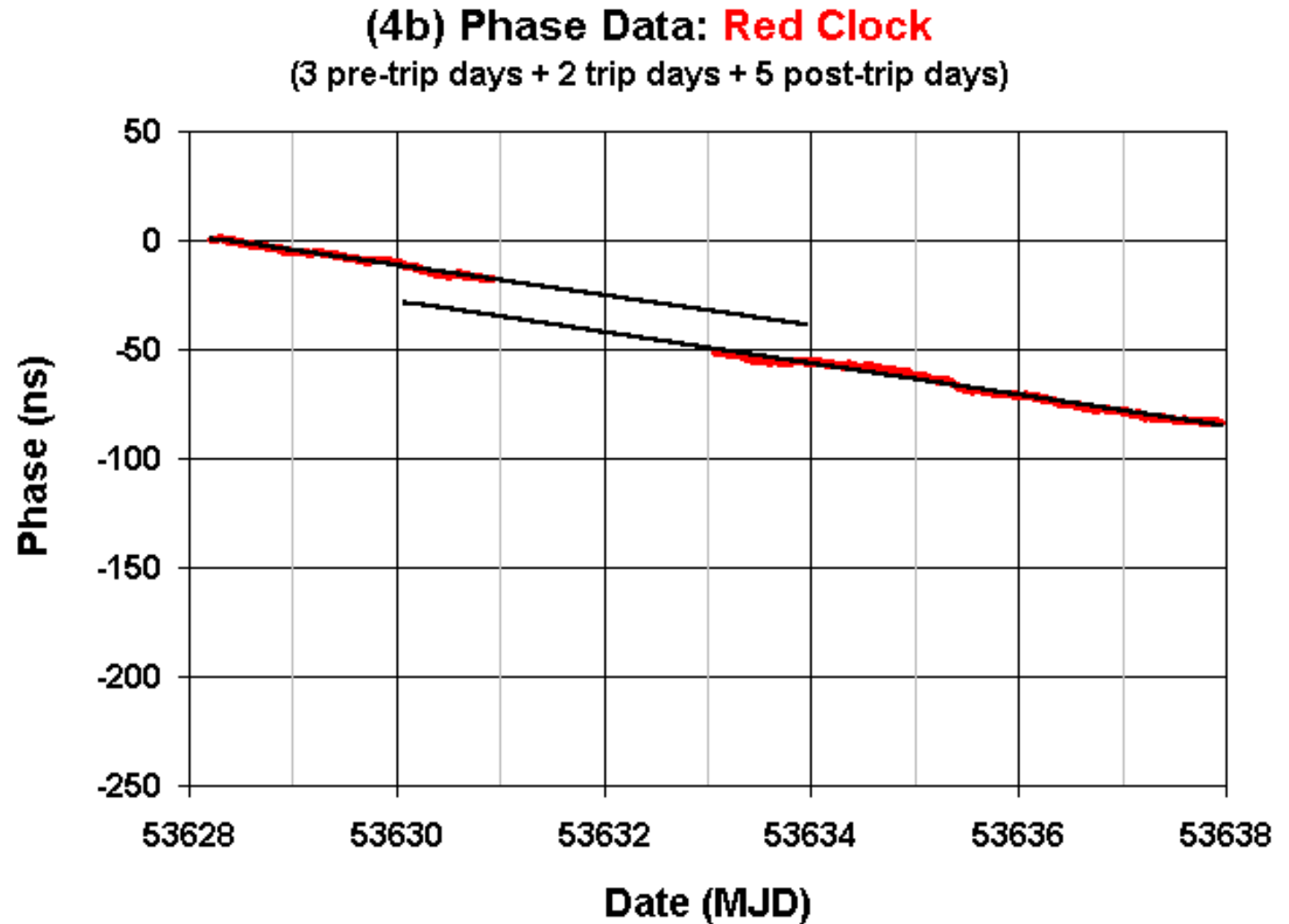
- Line fit
- $0 \times 10^{-13}$
- Phase offset
- No freq diff



# Worked example

---

- More fit
- $1.62 \times 10^{-13}$

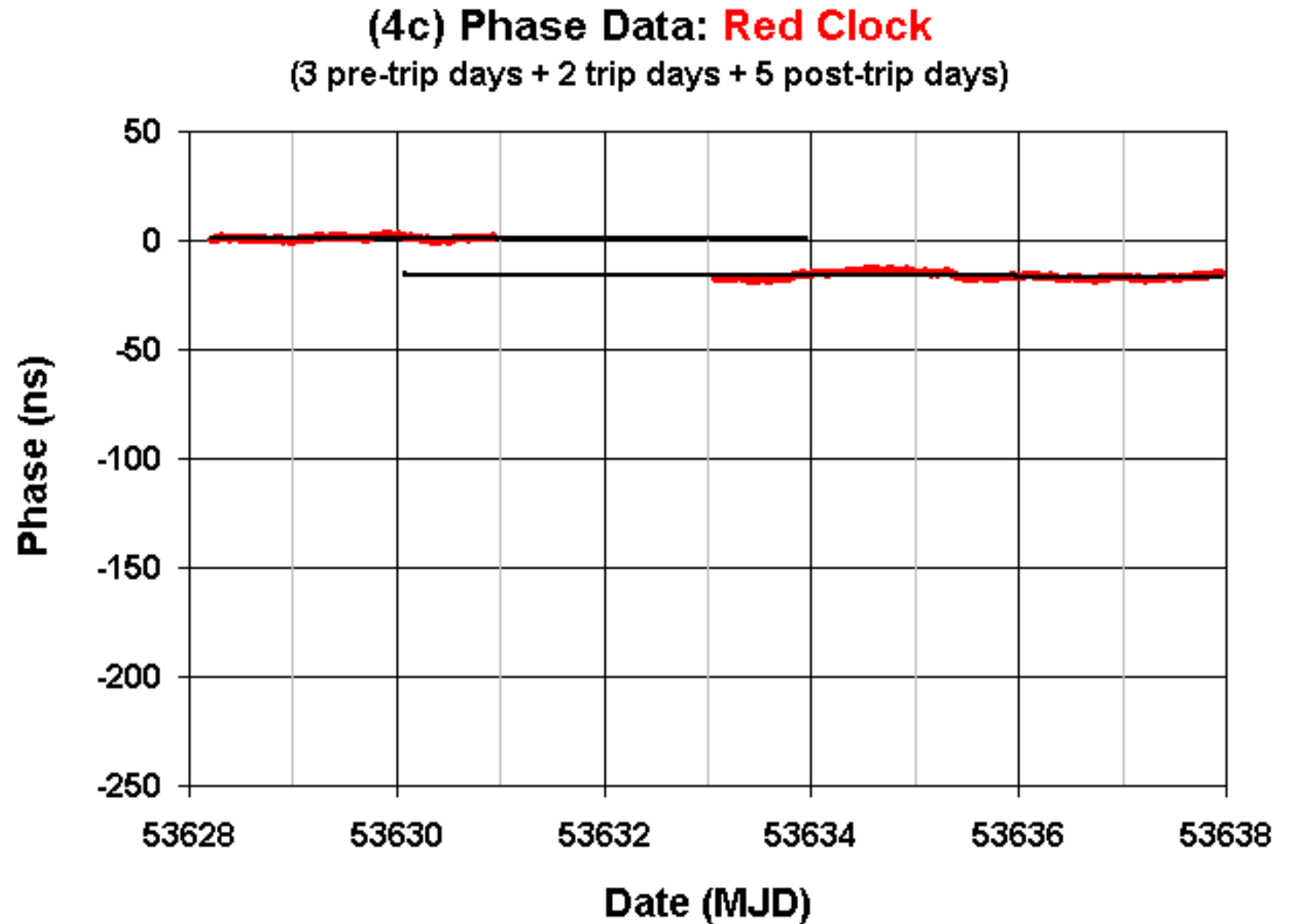




# Worked example

---

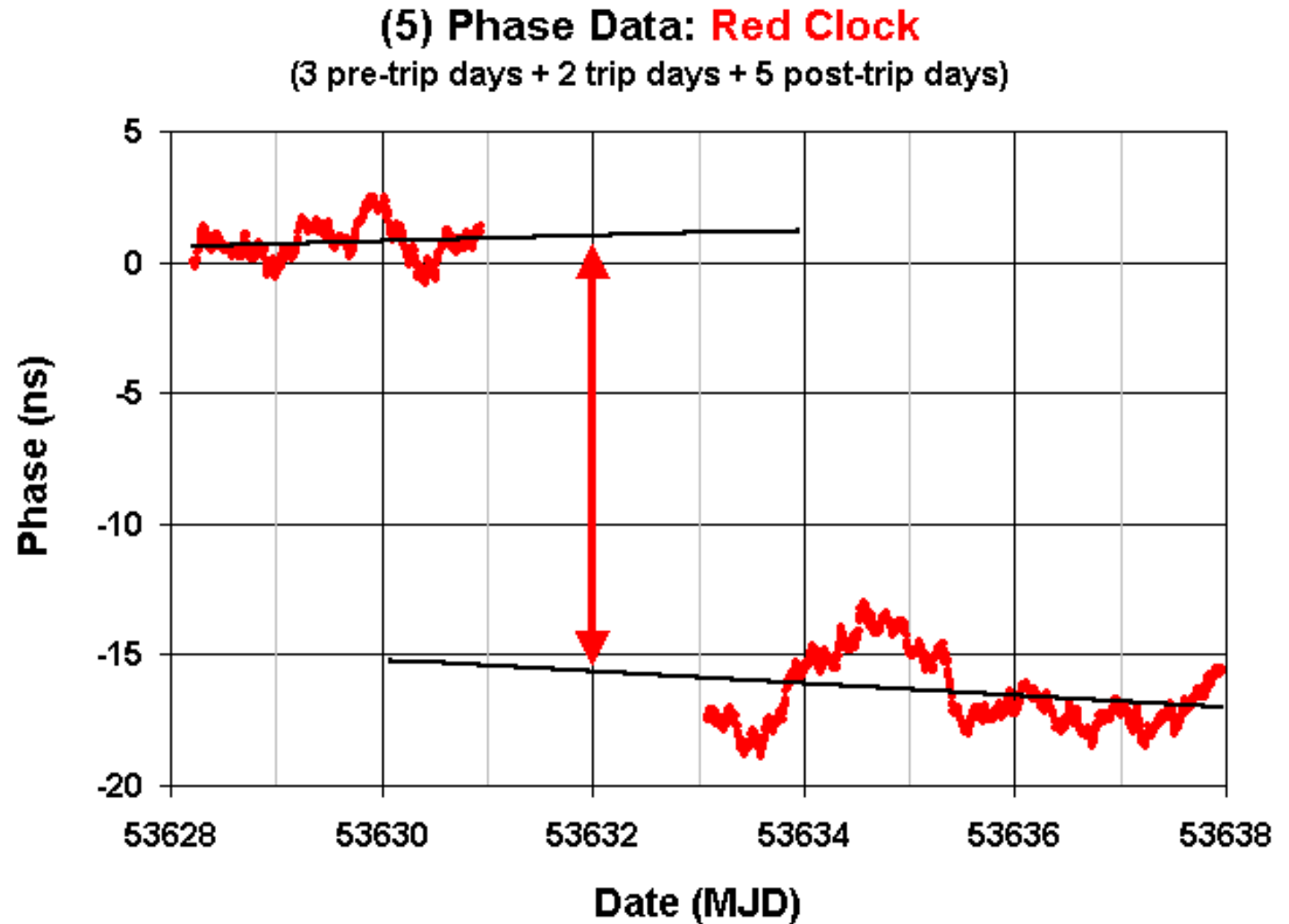
- Best fit
- $2.43 \times 10^{-13}$



# Worked example

---

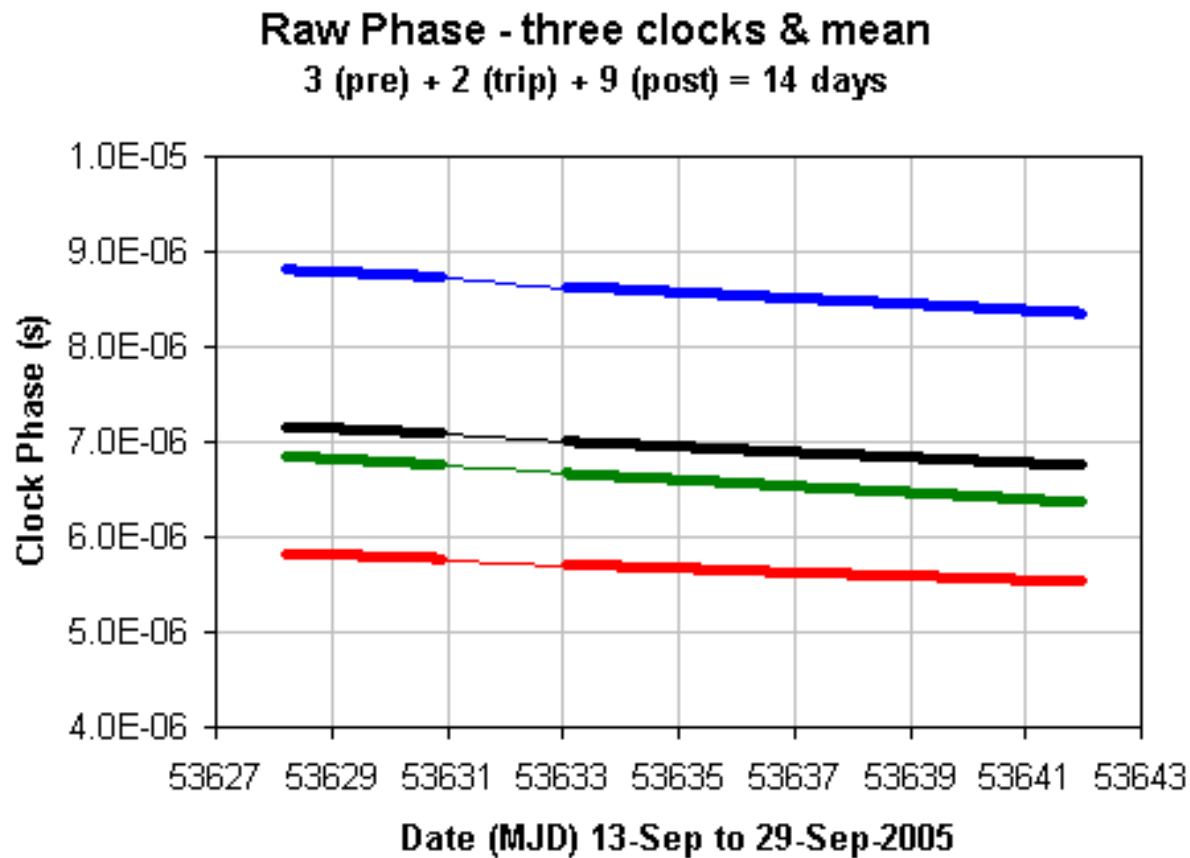
- Expand scale
- $\sim 1$  ns/d match
- Huge time jump!



# Results

---

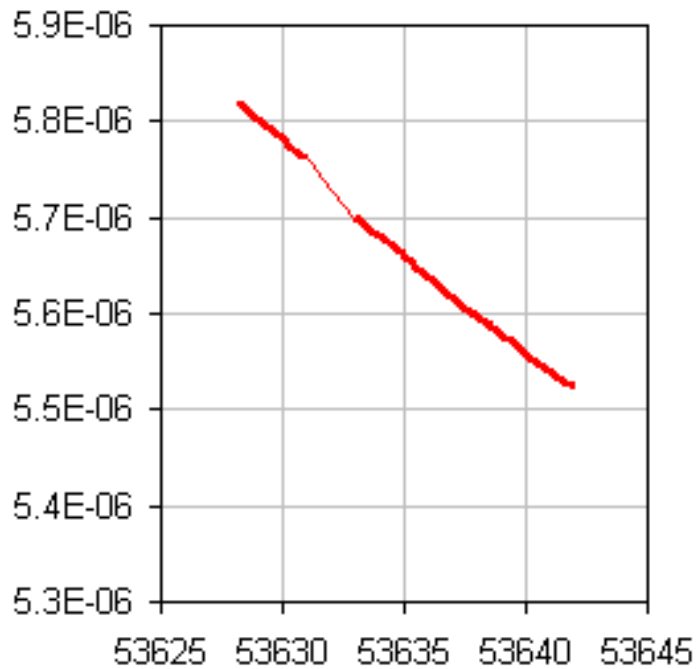
- Raw clock phase, with mean



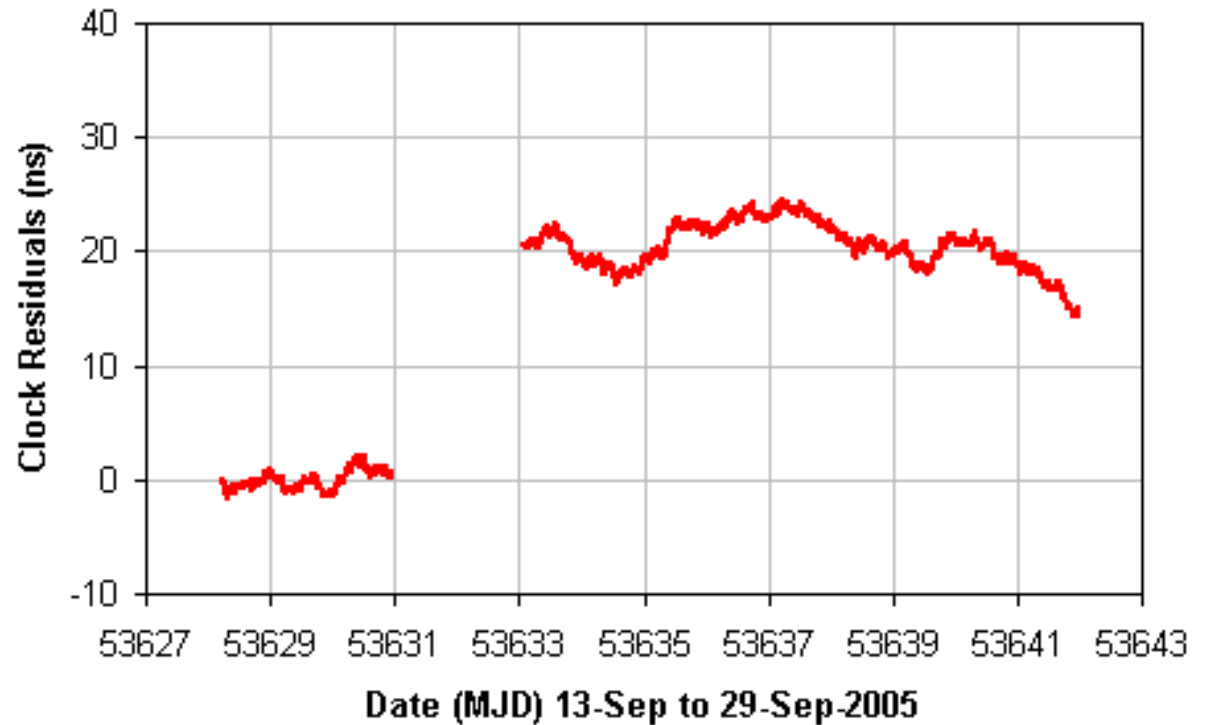
# Results

---

- Red
- 20.3 ns



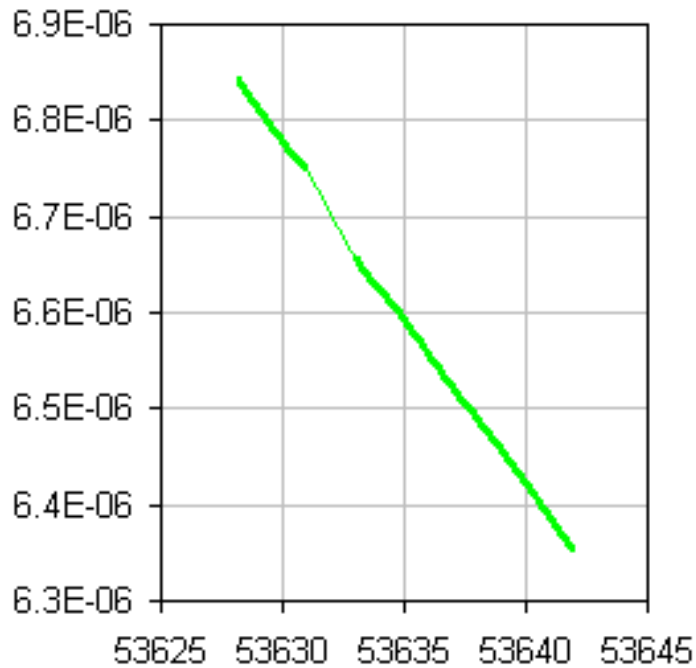
Project GREAT - Single Clock - **Red**  
3 (pre) + 2 (trip) + 9 (post) = 14 days



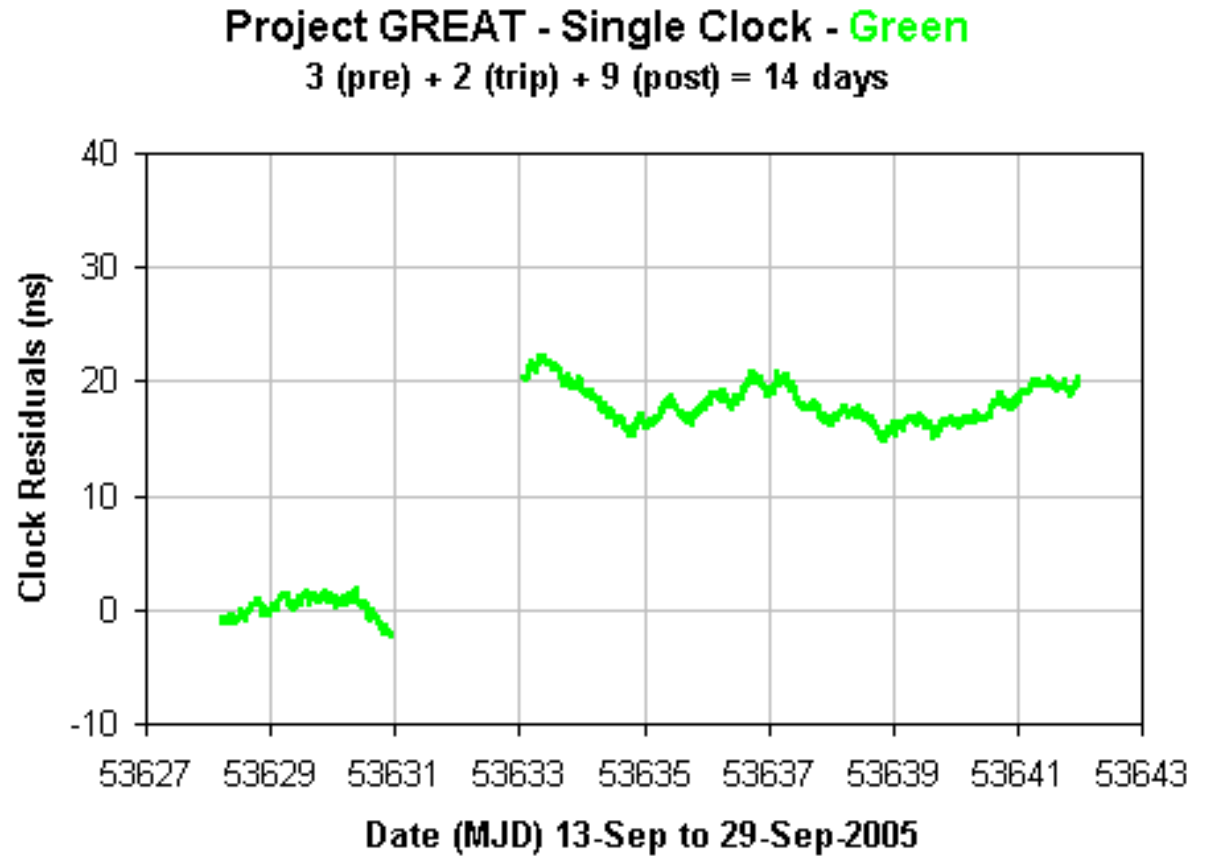
# Results

---

- Green
- 17.5 ns



06-Dec-2006

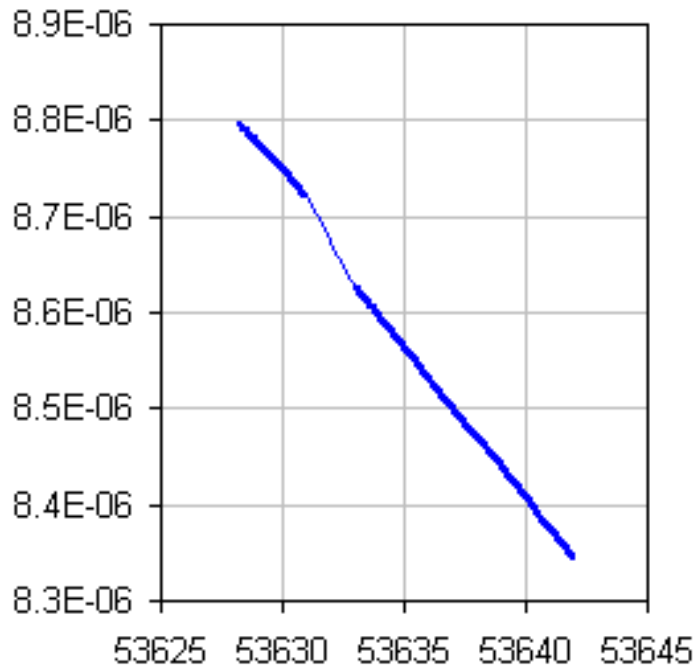


Project GREAT

157

# Results

- Blue
- 26.3 ns
- 29.7 ns



06-Dec-2006

Project GREAT - Single Clock - Blue  
3 (pre) + 2 (trip) + 9 (post) = 14 days



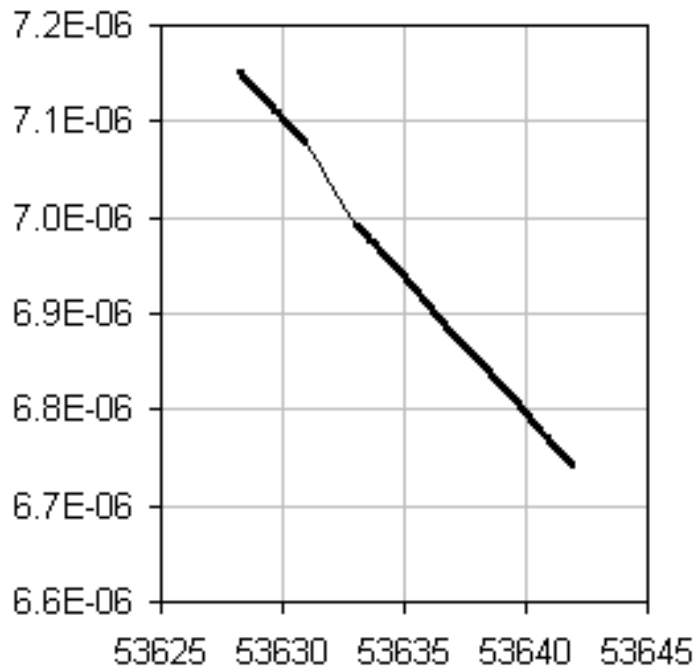
Project GREAT

158

# Results

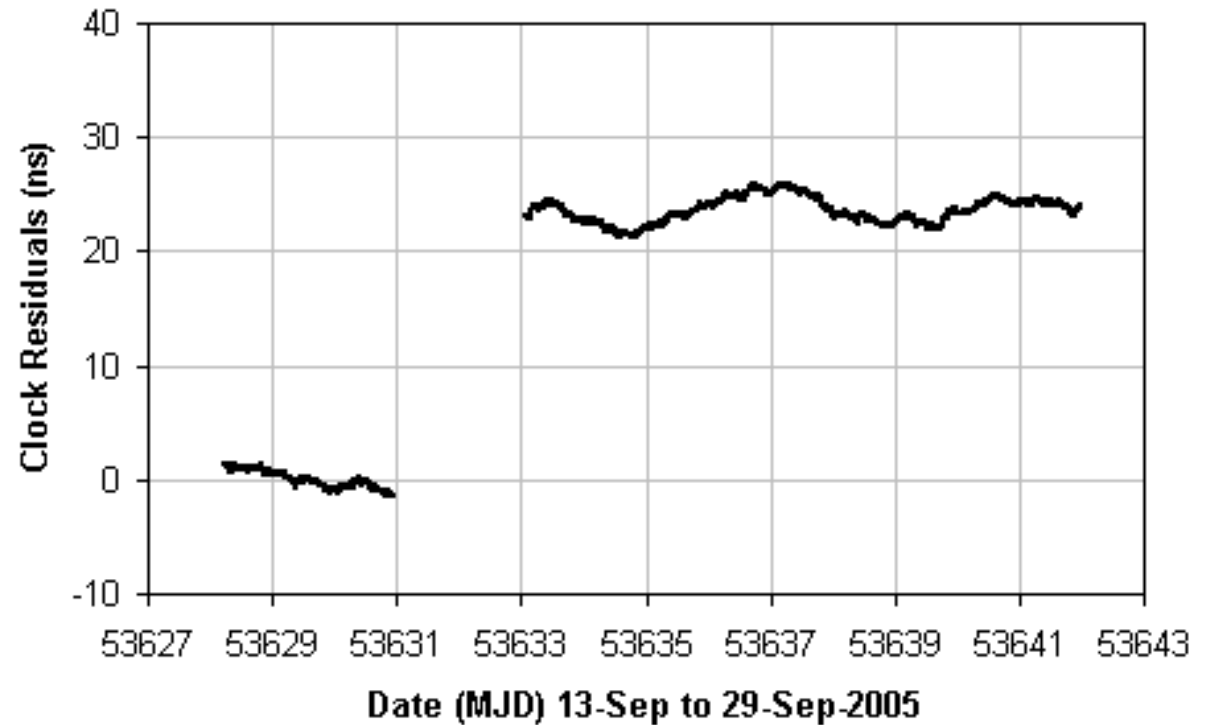
---

- Mean
- 23.2 ns



06-Dec-2006

Project GREAT - 3x Composite Clock  
3 (pre) + 2 (trip) + 9 (post) = 14 days



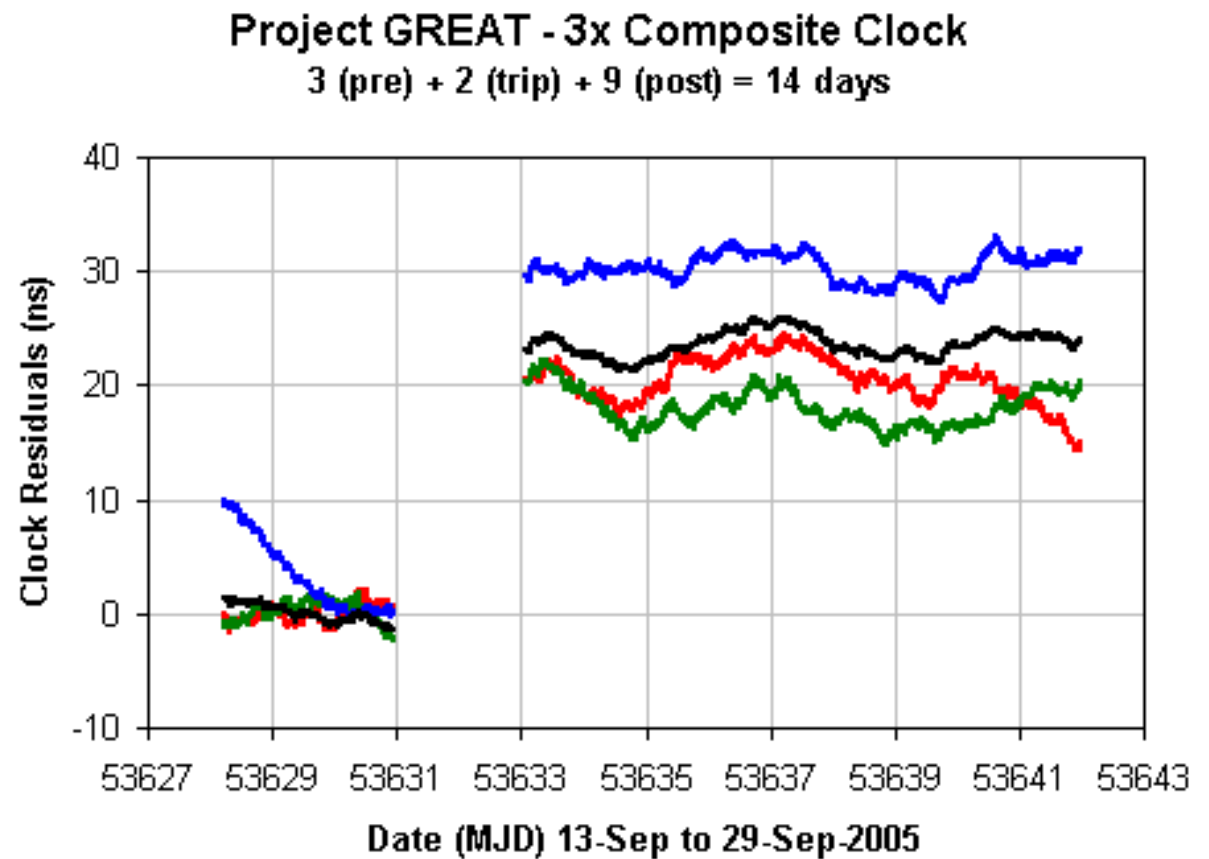
Project GREAT

159

# Results

---

- Composite
- $\pm 4$  ns(?)



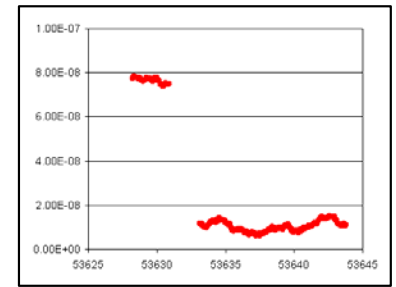


# Analysis Methods

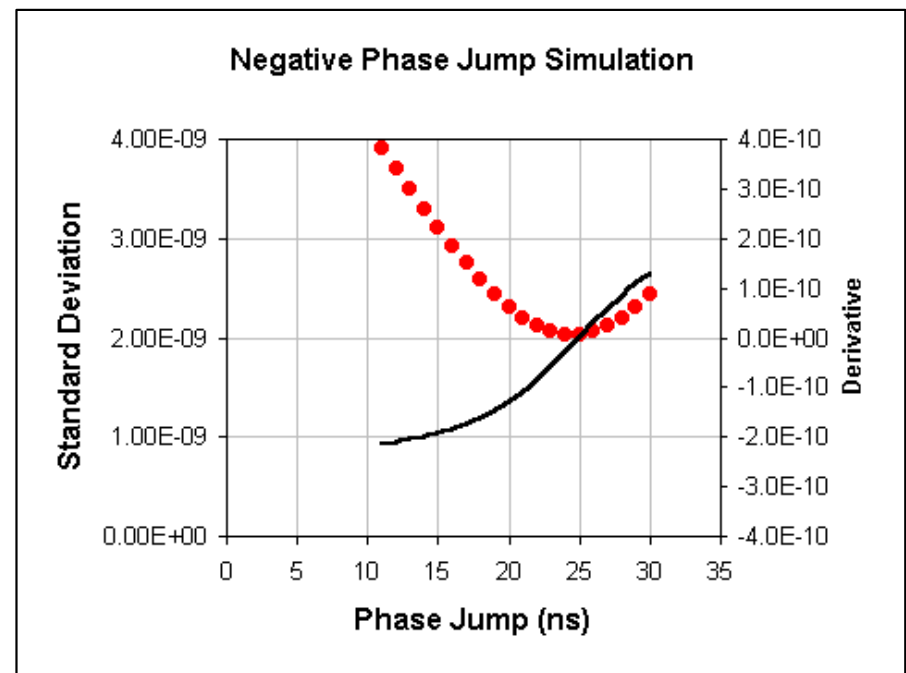
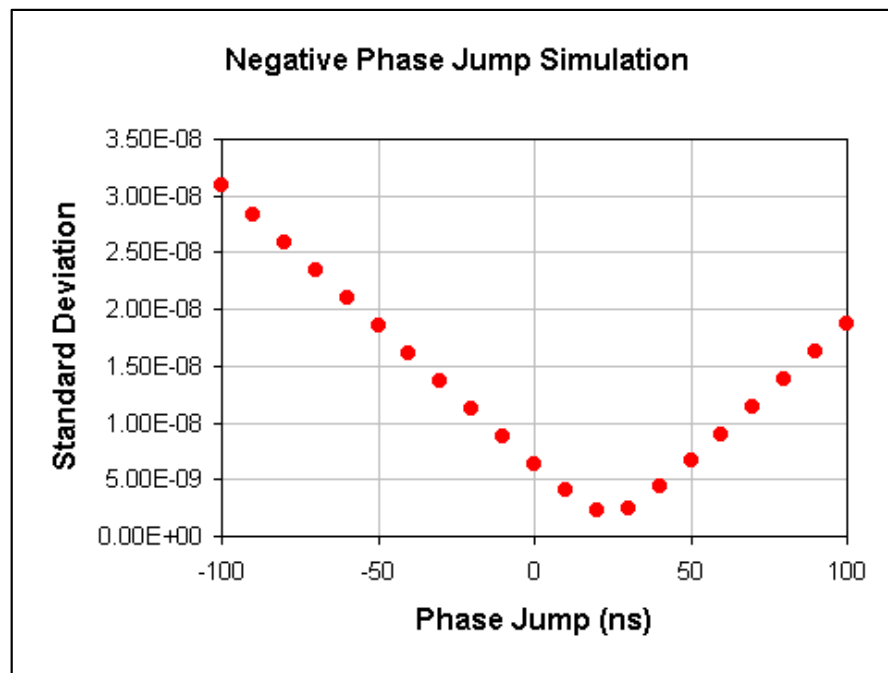
---

- Frequency before extrapolated forward
- Frequency after extrapolated backward
- Both before and after; mean frequency
- Continuous or hourly/daily averages?
- One day; or  $\pm 3$  days;  $-n + m$  days?
- Mean phase or last/first phase?
- Calculated removal of phase jump until optimal least squares fit?

# Phase Jump Simulation



- Artificially remove time dilation
- Stddev improves to a point



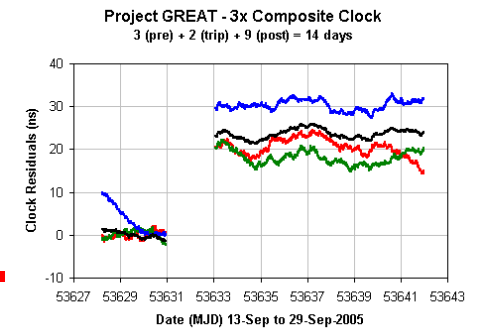
# Ambiguity

---

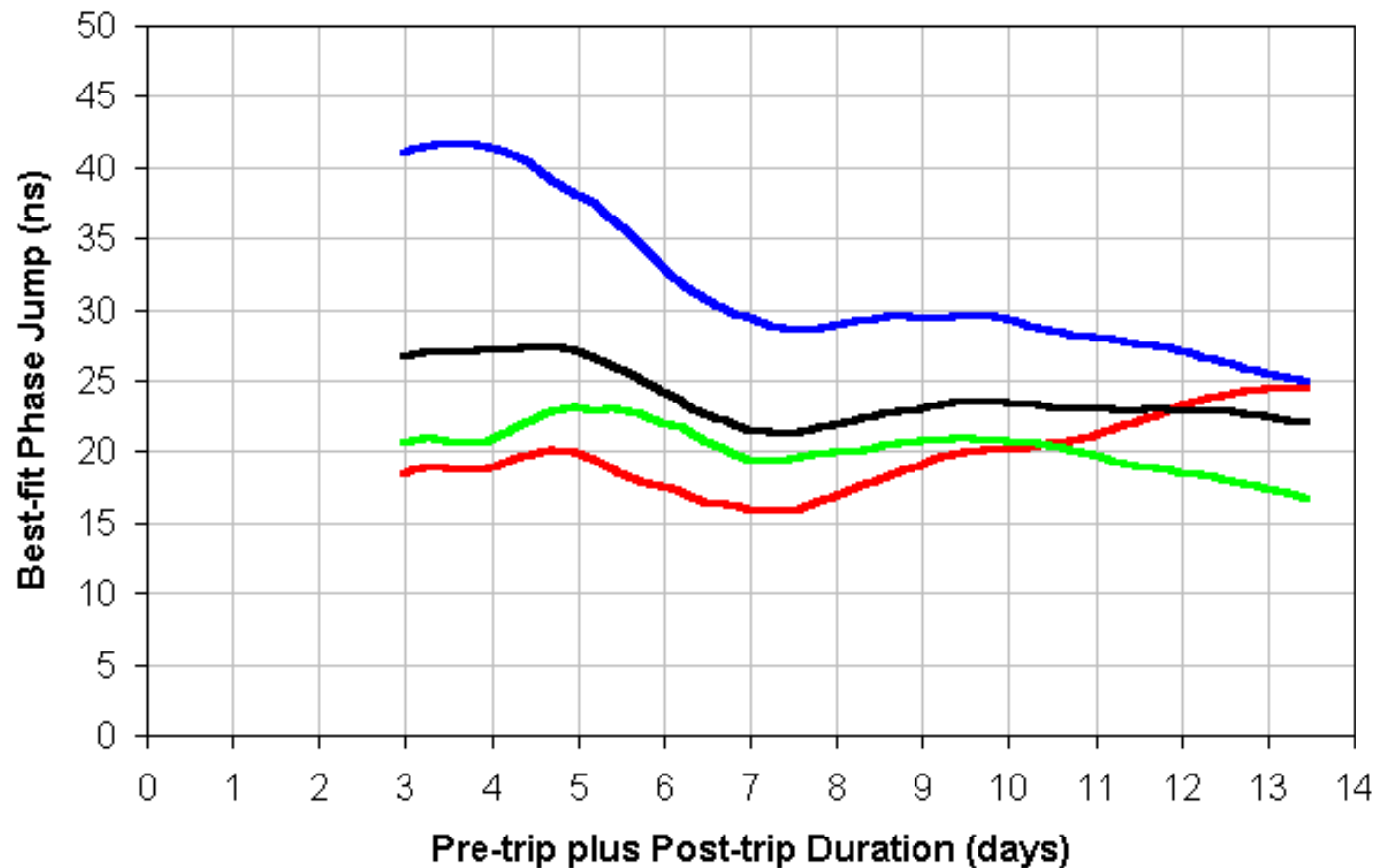
- Gap in time is clear, but
- Precise magnitude depends on both pre- post-trip rate precision, which is
- Influenced by frequency averaging time
  - 1 hour? 1 day? 2 days? 7 days?
- Might be a bit subjective, but
- All methods seem to agree to a few ns

# Ambiguity

- 3+3?
- 3+5?
- 3+10?
- 1+1?
- 3+3?



Effect of post-trip duration



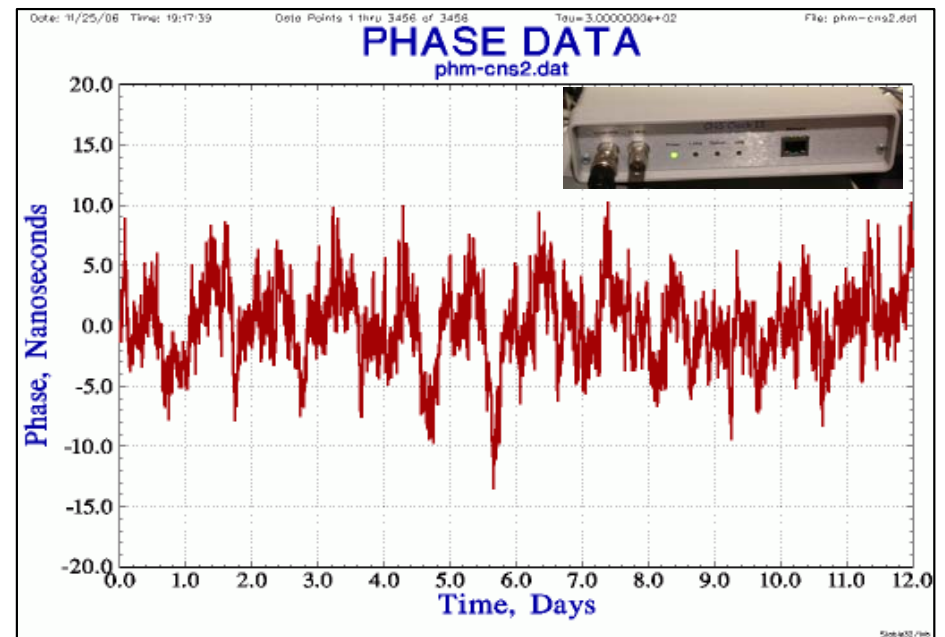
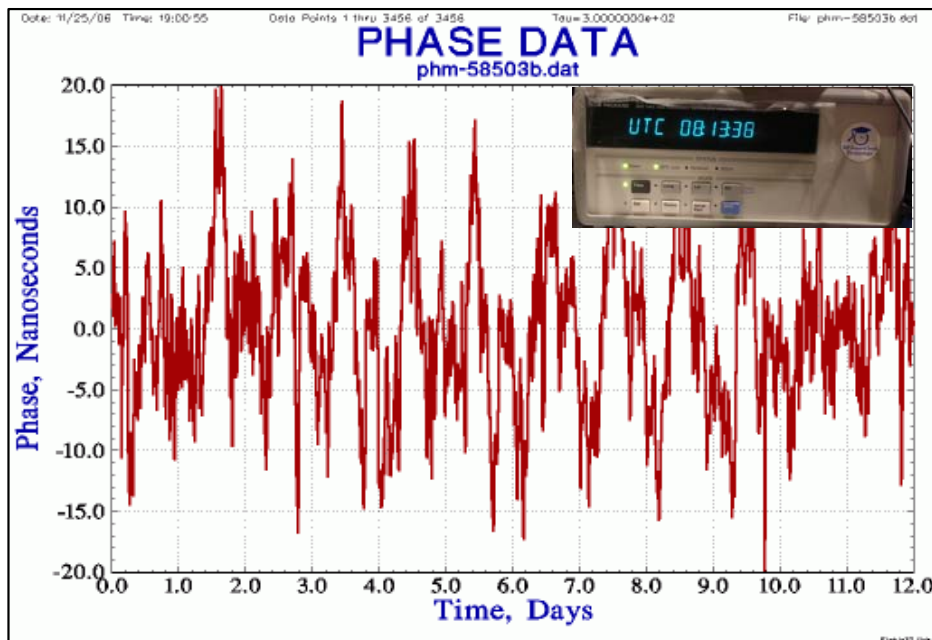
# Chapter 10

- Base & portable clock performance

# Base Clock

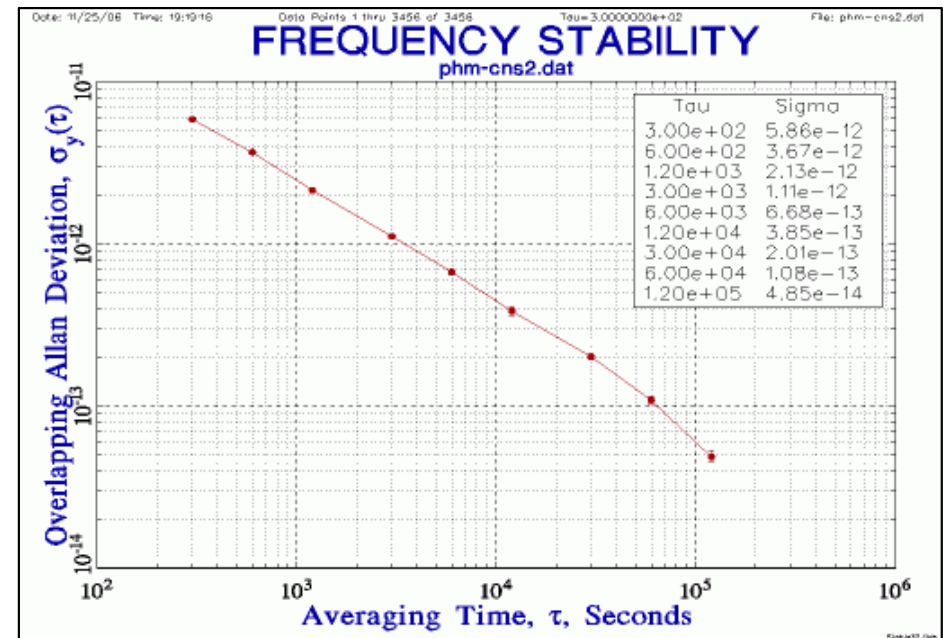
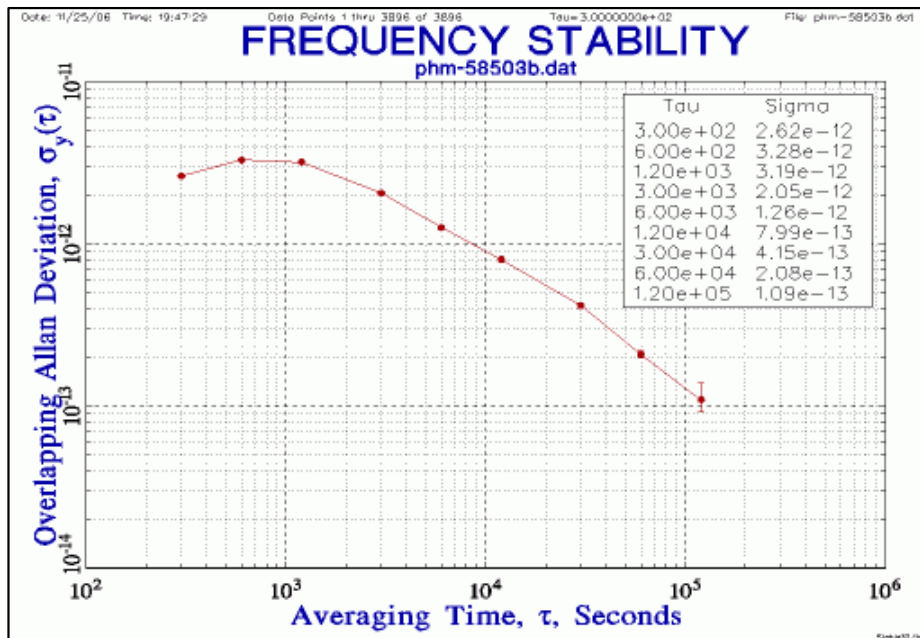
---

- House ref is passive H-maser
- Ref vs. GPS; phase (12-days)



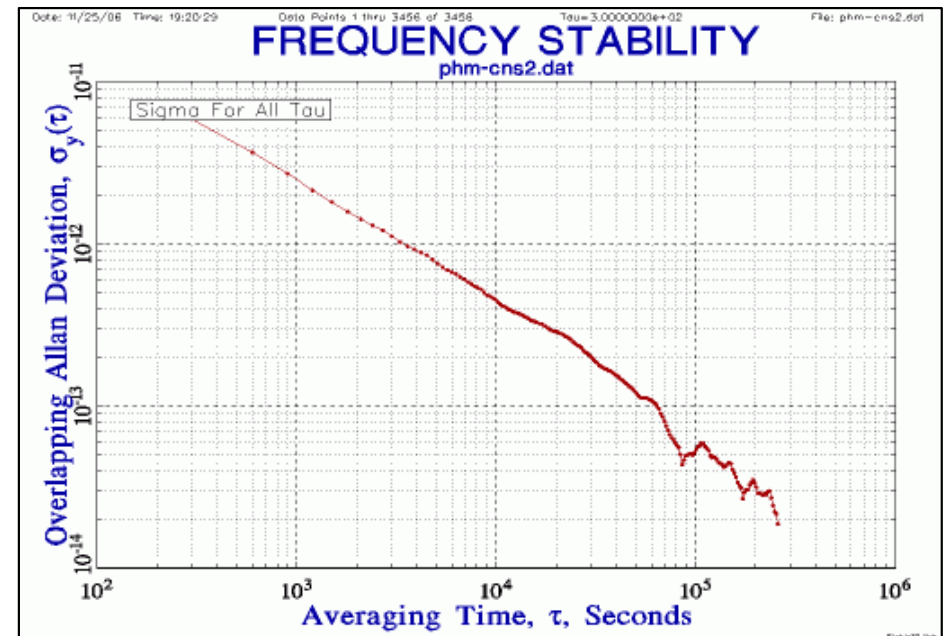
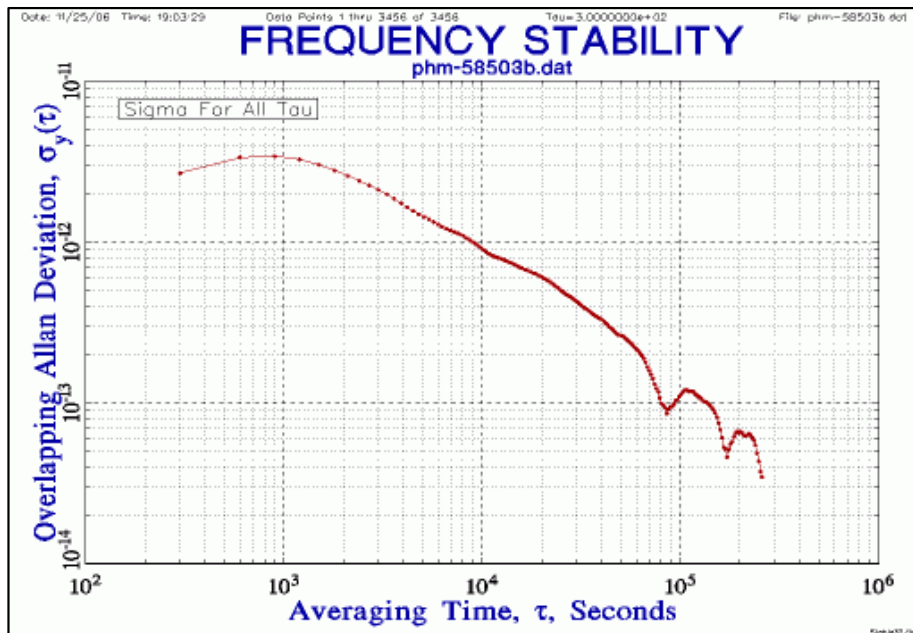
# Base Clock

- Ref vs. GPS, ADEV (decade)
- Near/below  $10^{-13}$  at 1 d



# Base Clock

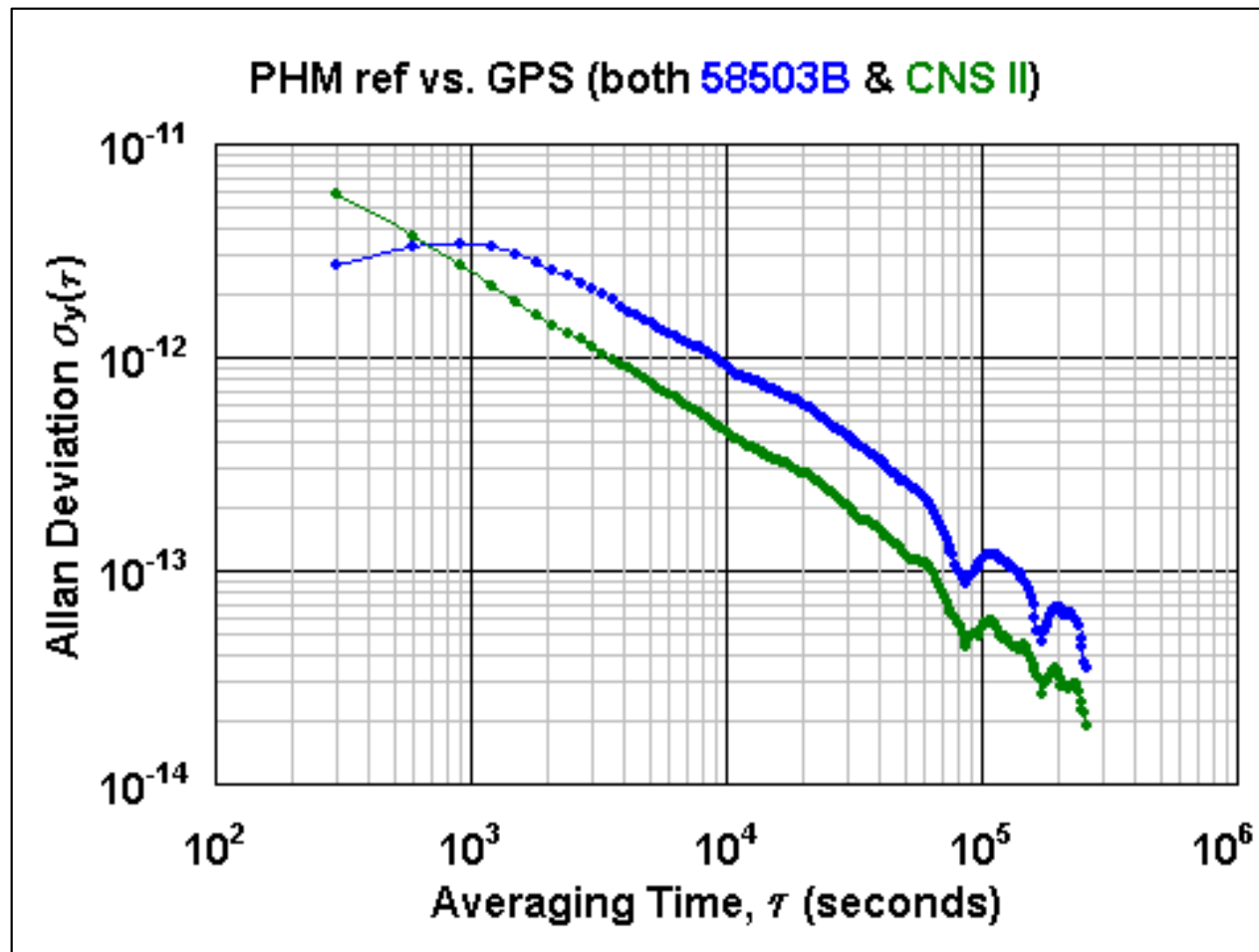
- Ref vs. GPS, ADEV (*many tau*)
- Note 1 d, 2 d better than 1.5 d





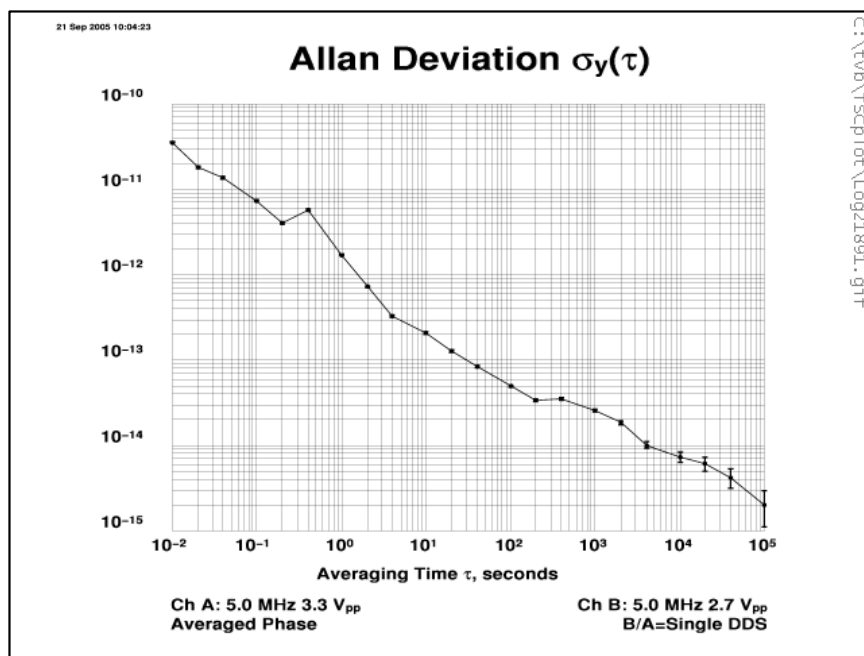
# Base Clock

- Composite ADEV



# Base Clock

- Passive H-maser ref vs. active H-maser
- $2 \times 10^{-15}$  at 1 day means no worries



21 Sep 2005 10:08:02

**Allan Deviation Table**

Avg. Time (s)	Allan Deviation $\sigma_y(\tau)$	Avg. Time (s)	Allan Deviation $\sigma_y(\tau)$
0.01	$3.57 \pm .11 \times 10^{-11}$	400	$3.54 \pm .11 \times 10^{-14}$
0.02	$1.83 \pm .057 \times 10^{-11}$	1000	$2.56 \pm .11 \times 10^{-14}$
0.04	$1.371 \pm .043 \times 10^{-11}$	2000	$1.85 \pm .11 \times 10^{-14}$
0.1	$7.42 \pm .23 \times 10^{-12}$	4000	$1.01 \pm .084 \times 10^{-14}$
0.2	$4.07 \pm .13 \times 10^{-12}$	10000	$7.3 \pm .97 \times 10^{-15}$
0.4	$5.71 \pm .18 \times 10^{-12}$	20000	$6.1 \pm 1.1 \times 10^{-15}$
1	$1.71 \pm .054 \times 10^{-12}$	40000	$4.2 \pm 1.1 \times 10^{-15}$
2	$7.18 \pm .22 \times 10^{-13}$	100000	$2.0 \pm .90 \times 10^{-15}$
4	$3.26 \pm .10 \times 10^{-13}$		
10	$2.08 \pm .065 \times 10^{-13}$		
20	$1.274 \pm .040 \times 10^{-13}$		
40	$8.34 \pm .26 \times 10^{-14}$		
100	$4.91 \pm .15 \times 10^{-14}$		
200	$3.41 \pm .11 \times 10^{-14}$		

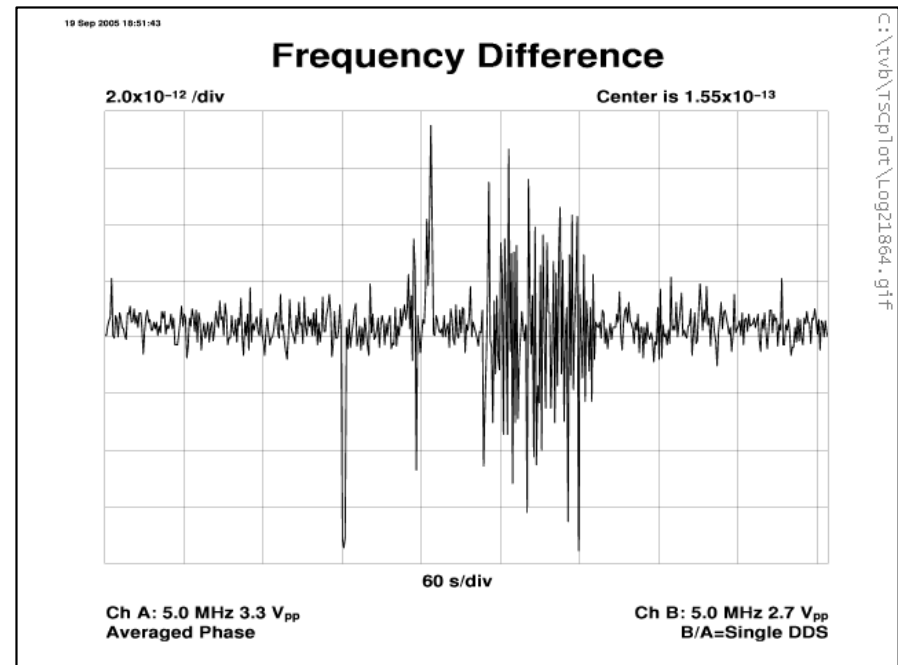
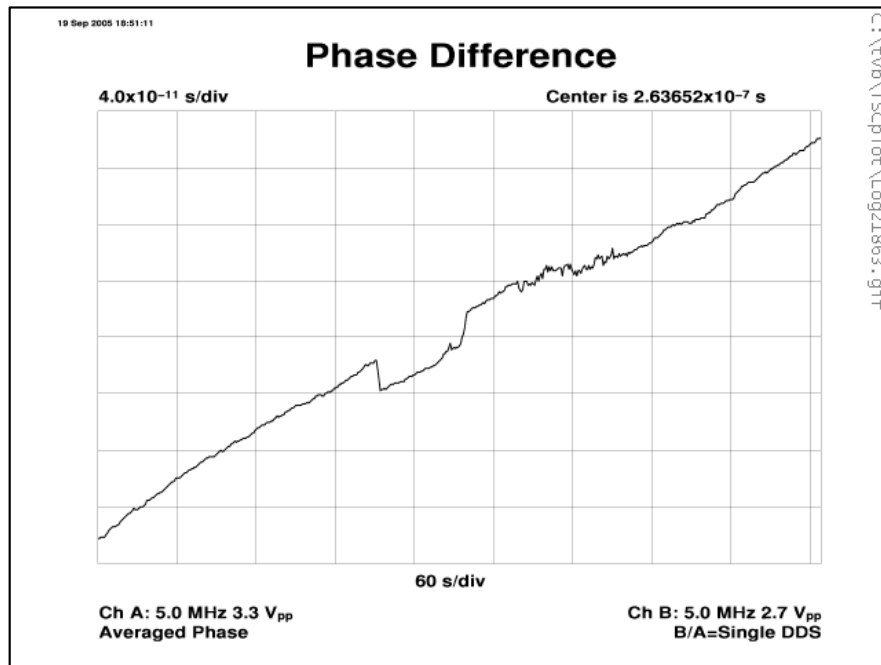
Ch A: 5.0 MHz 3.3 V<sub>pp</sub>  
Averaged Phase

Ch B: 5.0 MHz 2.7 V<sub>pp</sub>  
B/A=Single DDS

c:\tvb\Tscpl\of\Log21892.g1f

# Base Clock

- But weird *short-term* stability
- Probably OK (20 ps jumps, 10 ps noise)

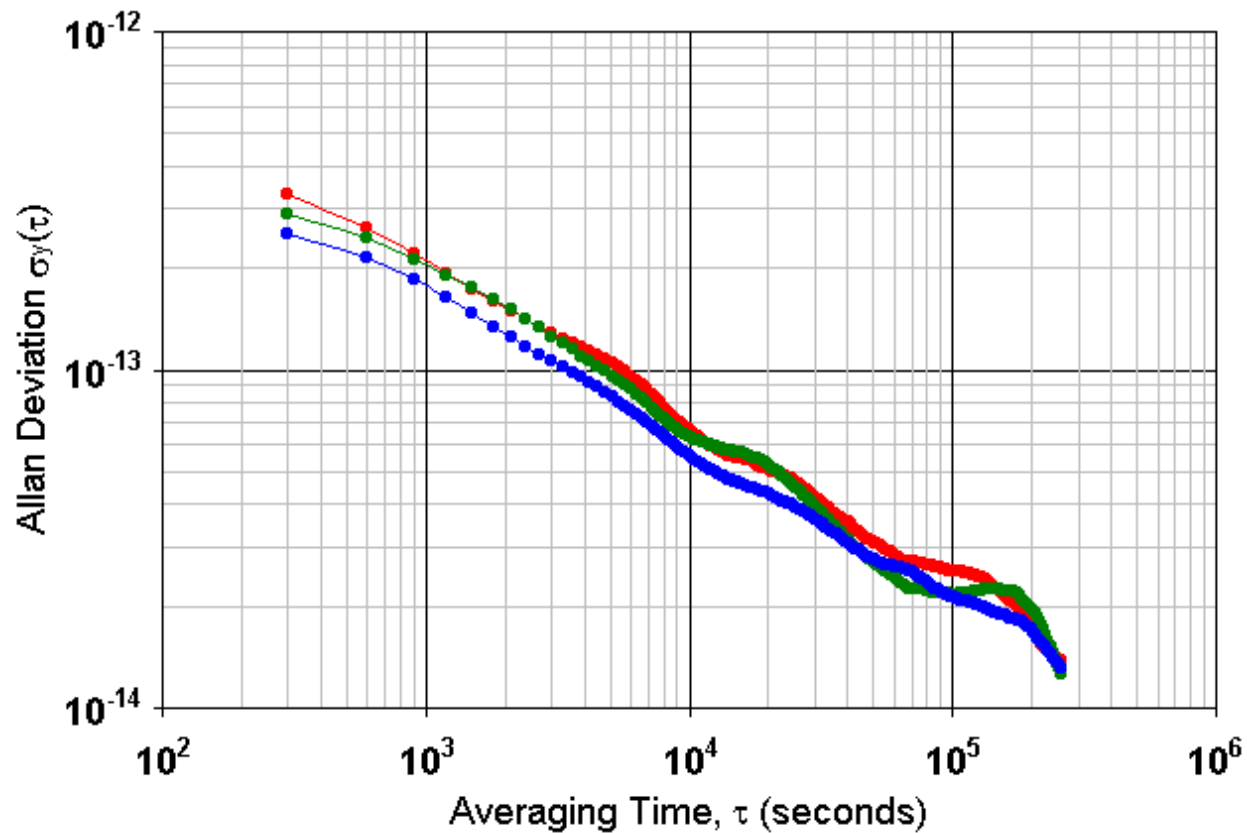


# Portable Clock(s)

---

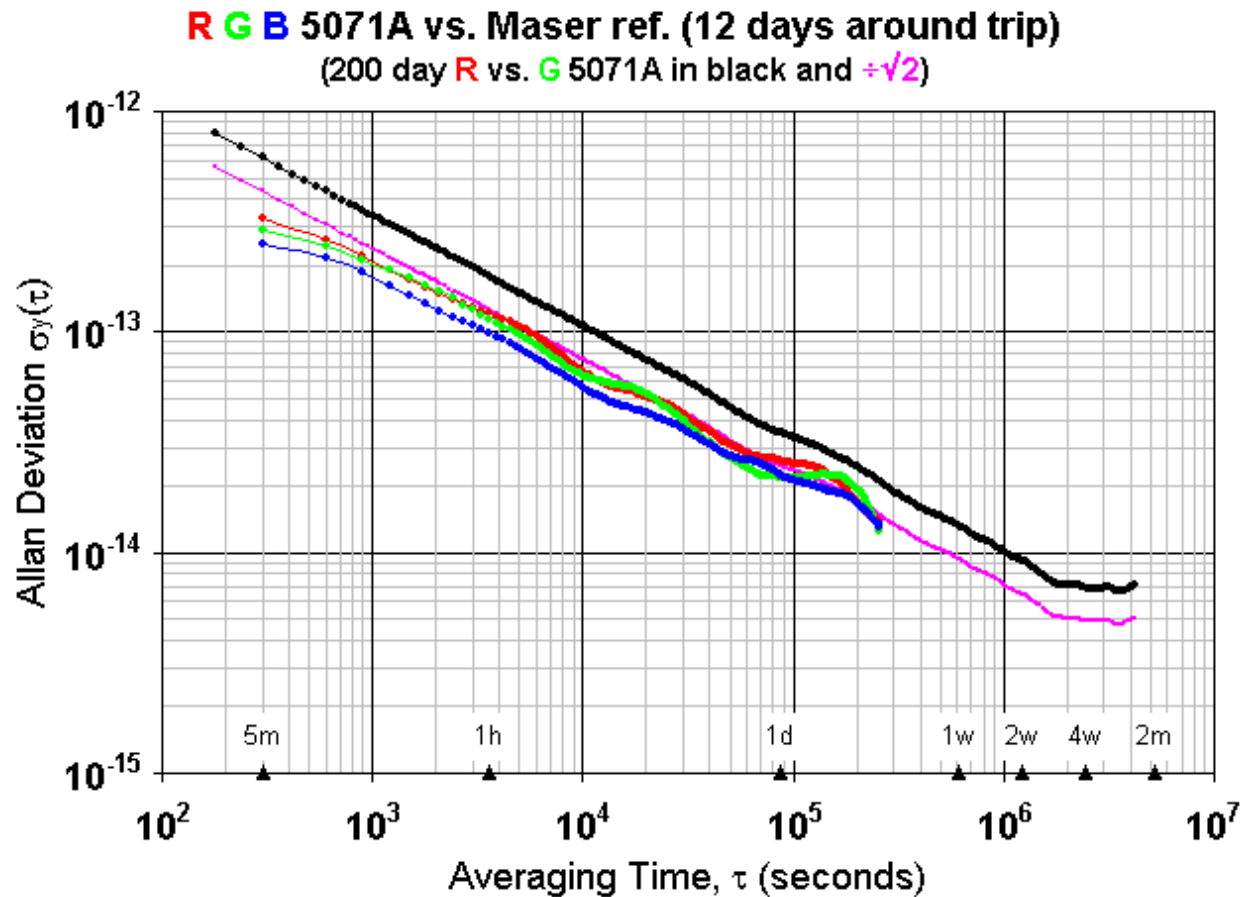
- ~2 days before trip + ~10 days after tip

5071A Performance (12 days)



# Portable Clock(s)

- ~3 week trip would work even better



# Confidence Summary

---

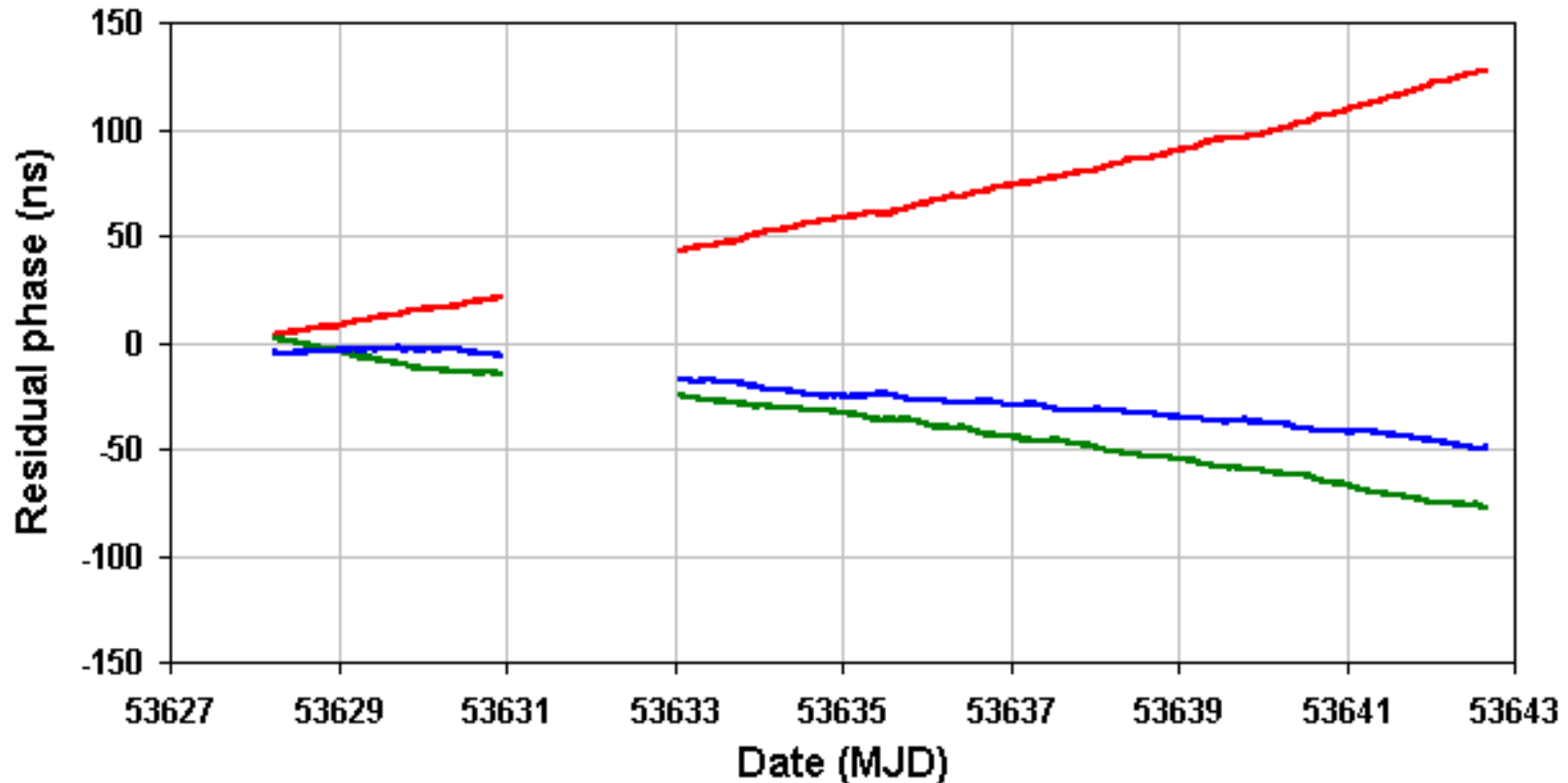
- Base clock is good to  $\sim 2 \times 10^{-15}$
- Portable clocks are good to  $\sim 2 \times 10^{-14}$
- Relativistic effect is  $\sim 1.5 \times 10^{-13}$
- GPS log is much better than 1%
- No show-stopper glitches
- So experiment accuracy is  $\sim 15\%$
- 15% of 22 ns is  $\sim 3$  ns

# 3-Hat, phase (home)

---

- $Cs_i - Cs_j$  via lab reference

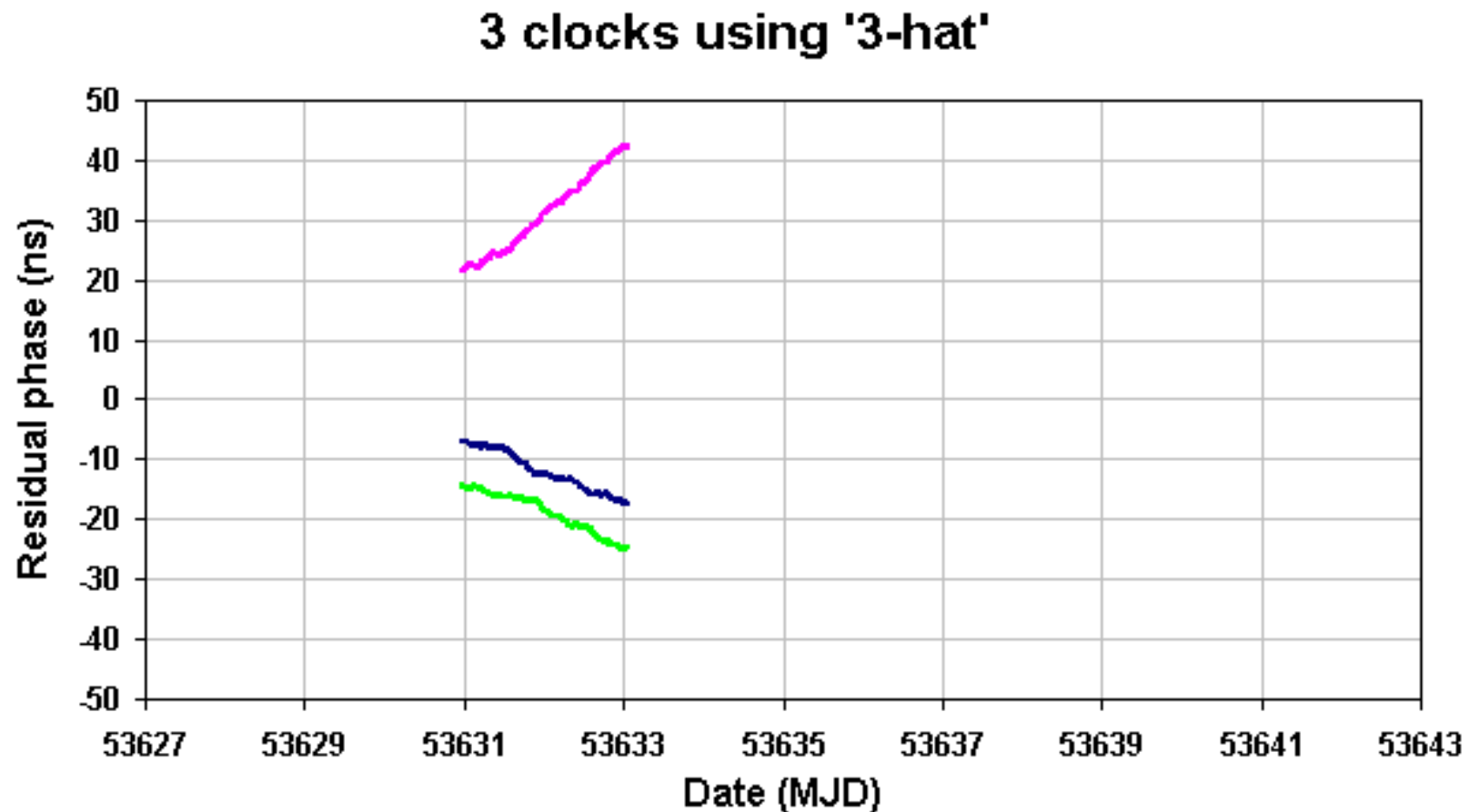
3 clocks using '3-hat'



# 3-Hat, phase (away)

---

- $Cs_i - Cs_j$  via mutual-comparisons

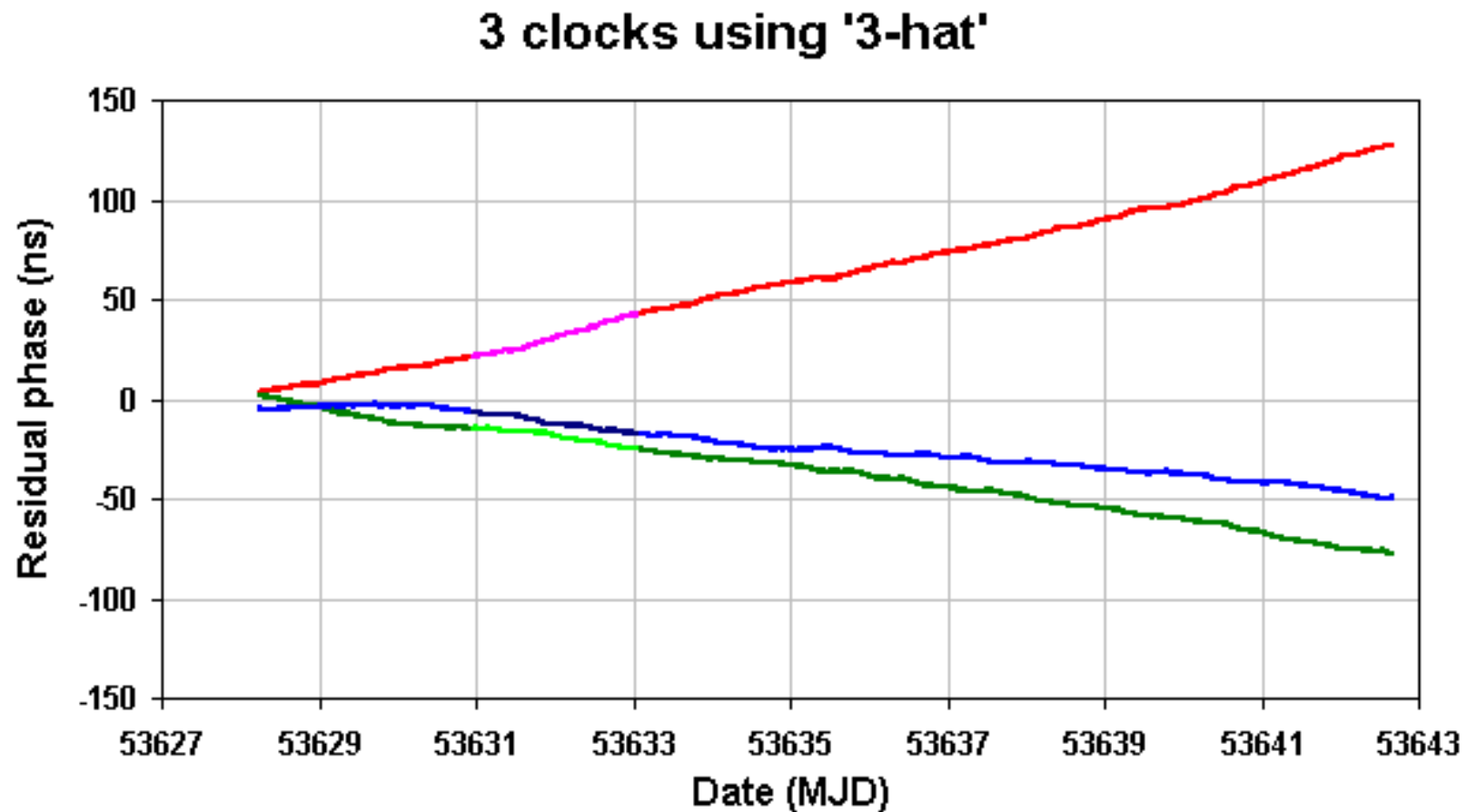




# 3-Hat, phase (combined)

---

- $Cs_i - Cs_j$  continuous

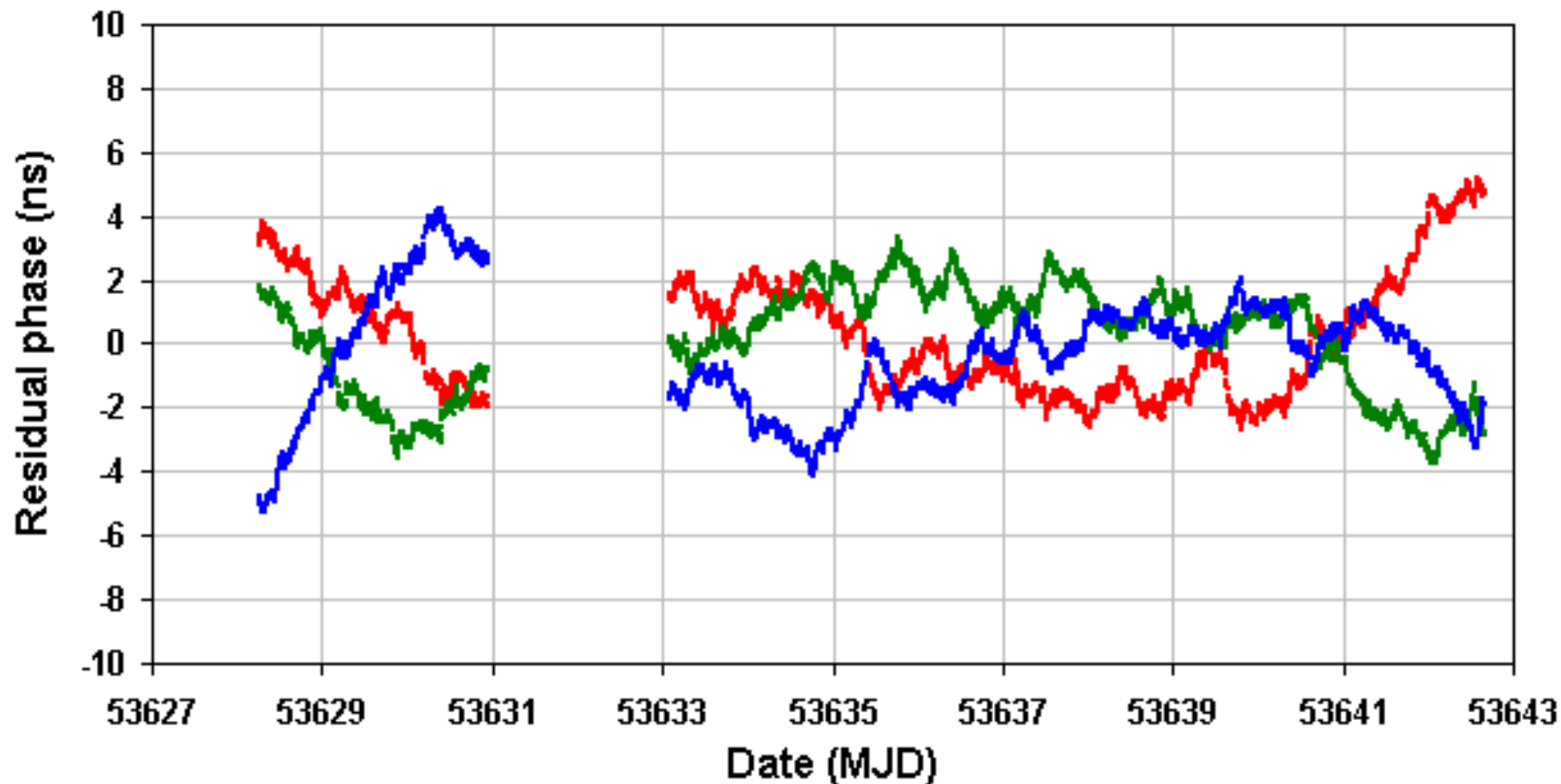


# 3-Hat, resid (home)

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- $Cs_i - Cs_j$  via lab reference

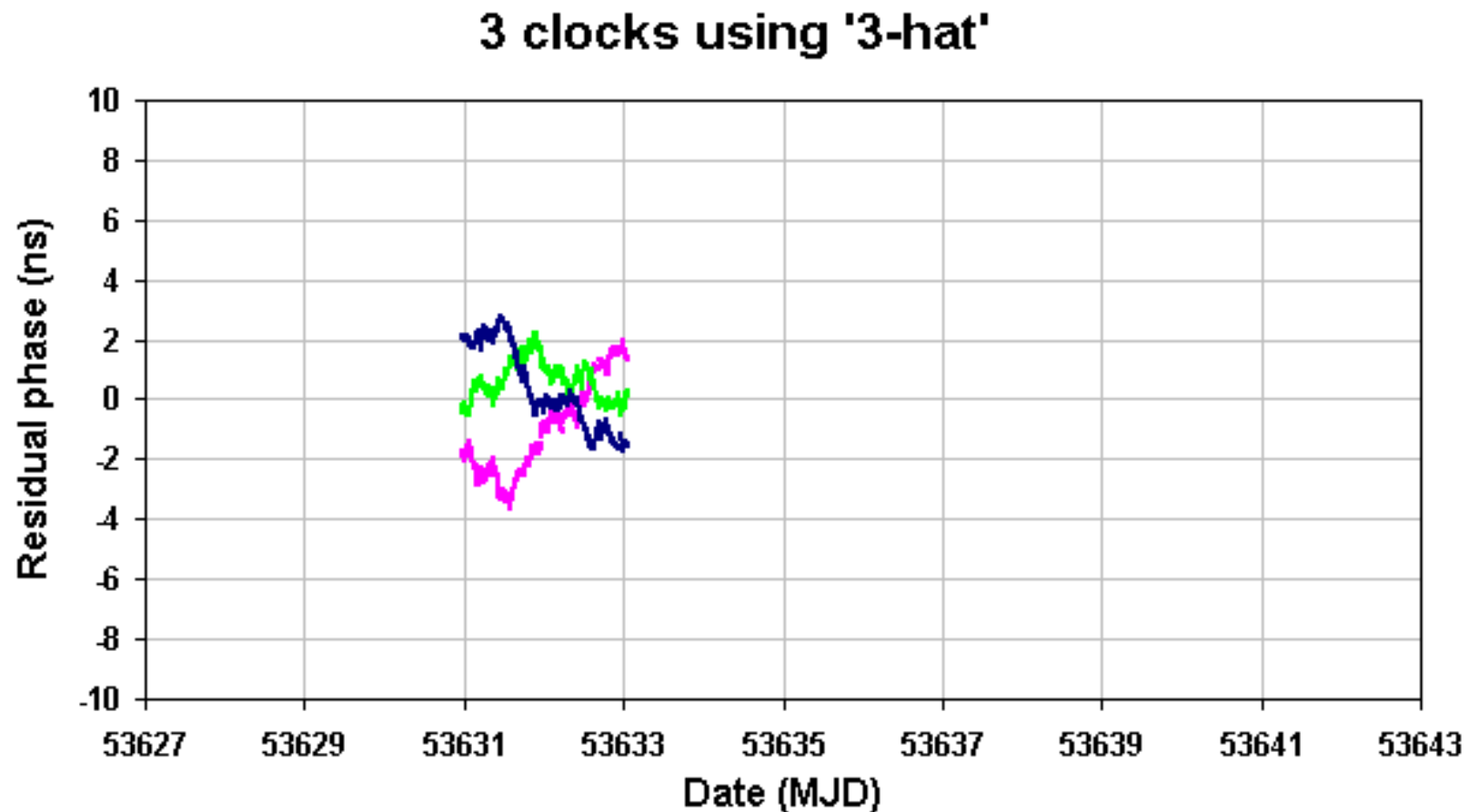
3 clocks using '3-hat'



# 3-Hat, resid (away)

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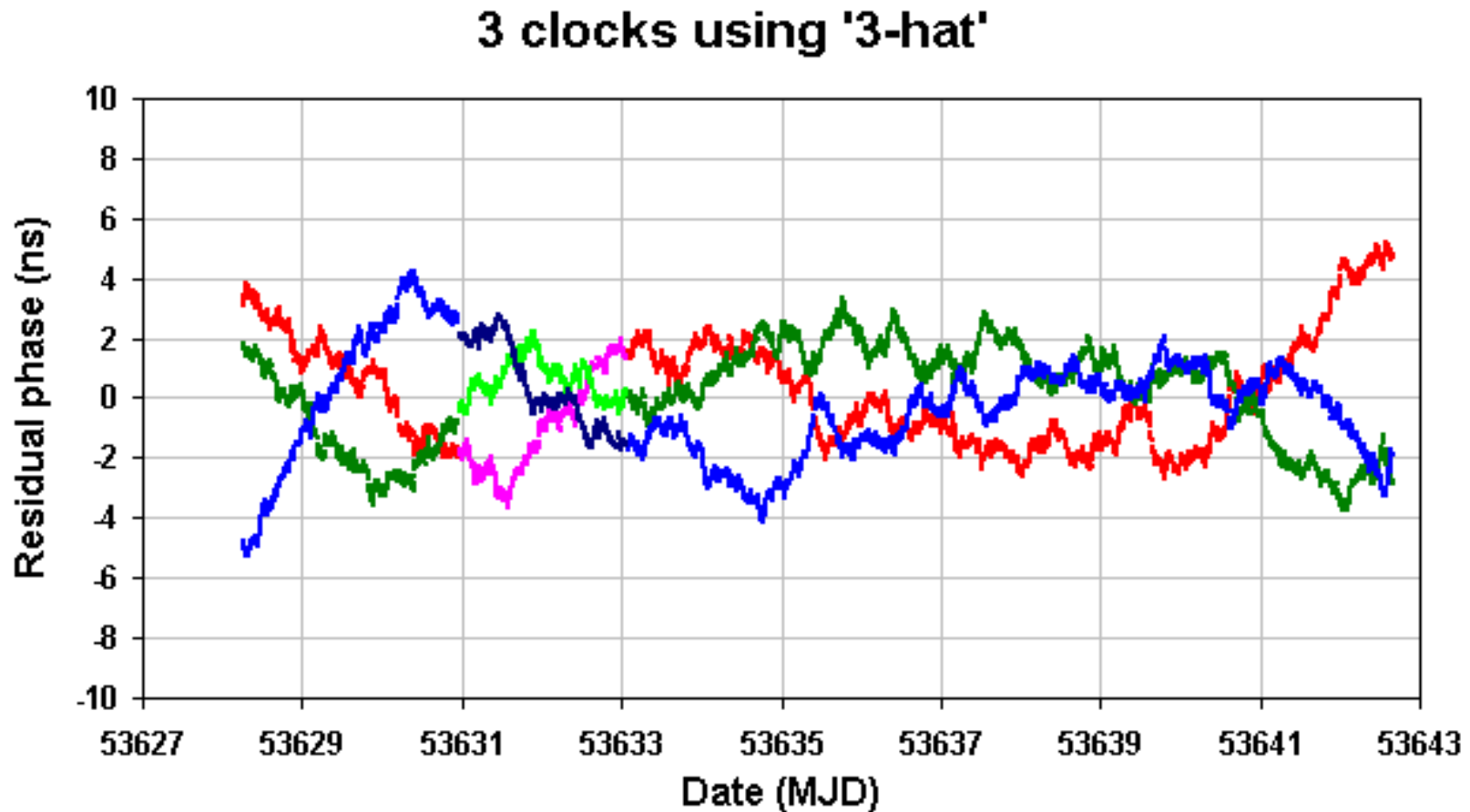
- $Cs_i - Cs_j$  via mutual-comparisons



# 3-Hat, resid (combined)

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- $Cs_i - Cs_j$

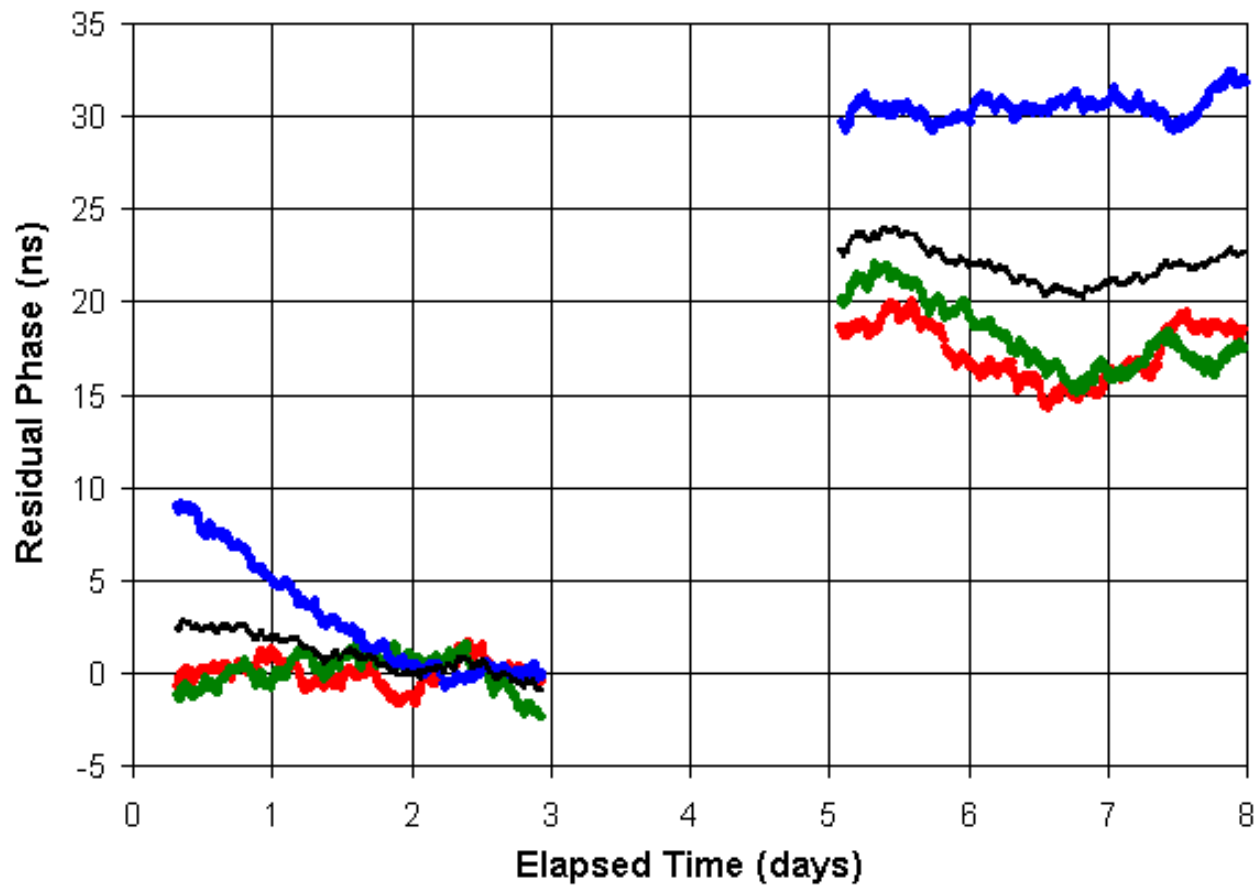


# Final Graph; 3+2+3 days

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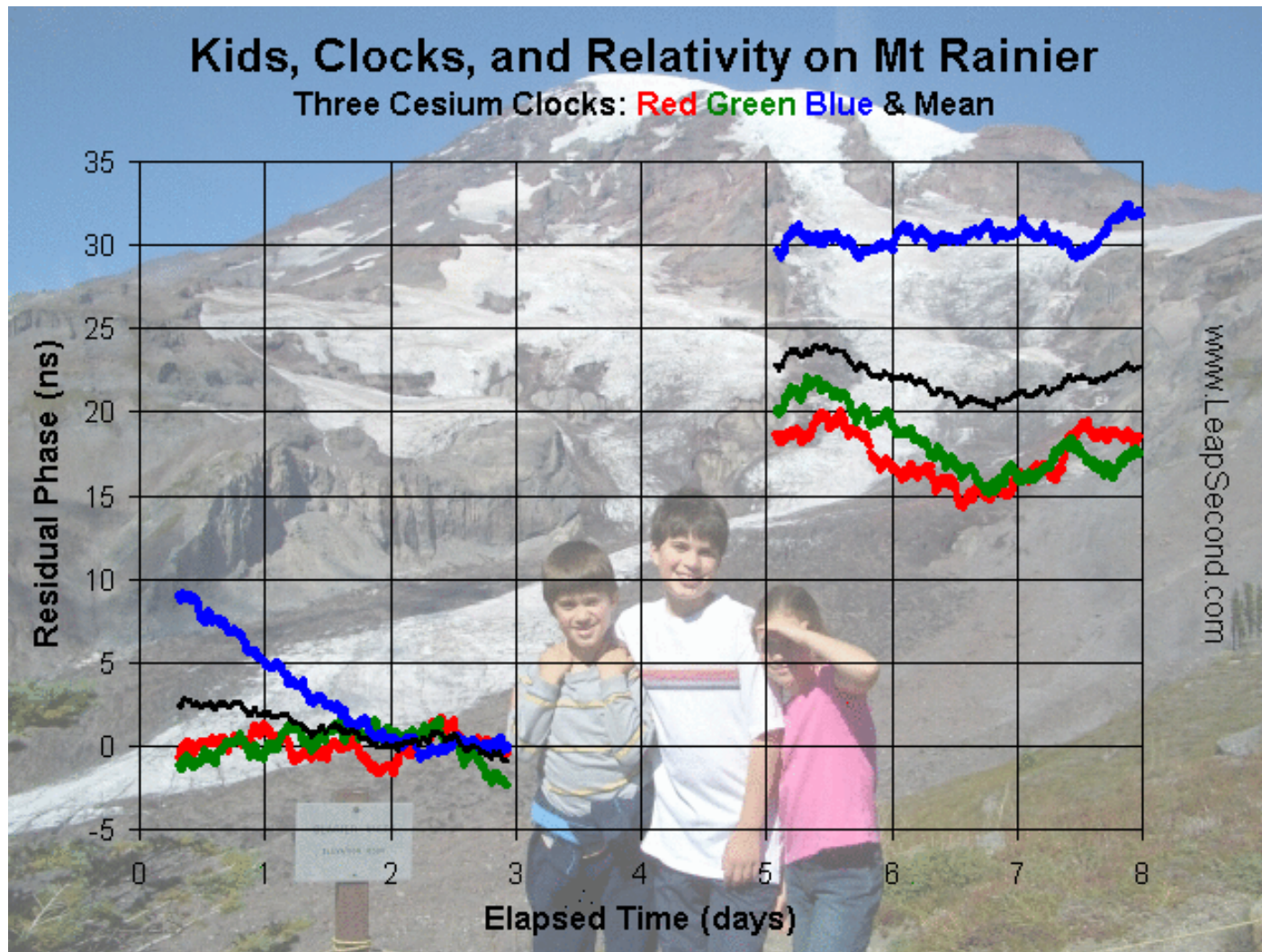
## Kids, Clocks, and Relativity on Mt Rainier

Three Cesium Clocks: Red Green Blue & Mean



www.LeapSecond.com

# Final Graph; +kids +mountain



# Chapter 11

- Conclusion

# What went wrong

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- Difficult physical clock transfers
- Direct morning sunlight temperature
- Unexpected out-of-gas event, OK
- Hotel turned minivan off, OK
- GPS battery ran out, OK
- One TIC was 53131A (500 ps vs. 150 ps)
- Minivan A/C has poor algorithm
- Parking lot hassles, OK
- More exhausting than expected



# What went right

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- No loss of clock
- No loss of any data
- Relativity effects obvious and stunning
- Three clocks was good idea
- Mean closer than hoped for
- Standard deviation wider than expected
- Good input for another run
- Not bad for a first try
- Kids had a great time!

# Conclusions

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- Experiment worked rather well
- We now believe what we know
- Fun technical challenge
- Echo of historical experiments
- Useful precise time teaching example
- A fitting 2005 PTTI celebration
- Came back much\* older and wiser
- Relativity is now "child's play"
- Best 22 ns of my life!

# Thank you

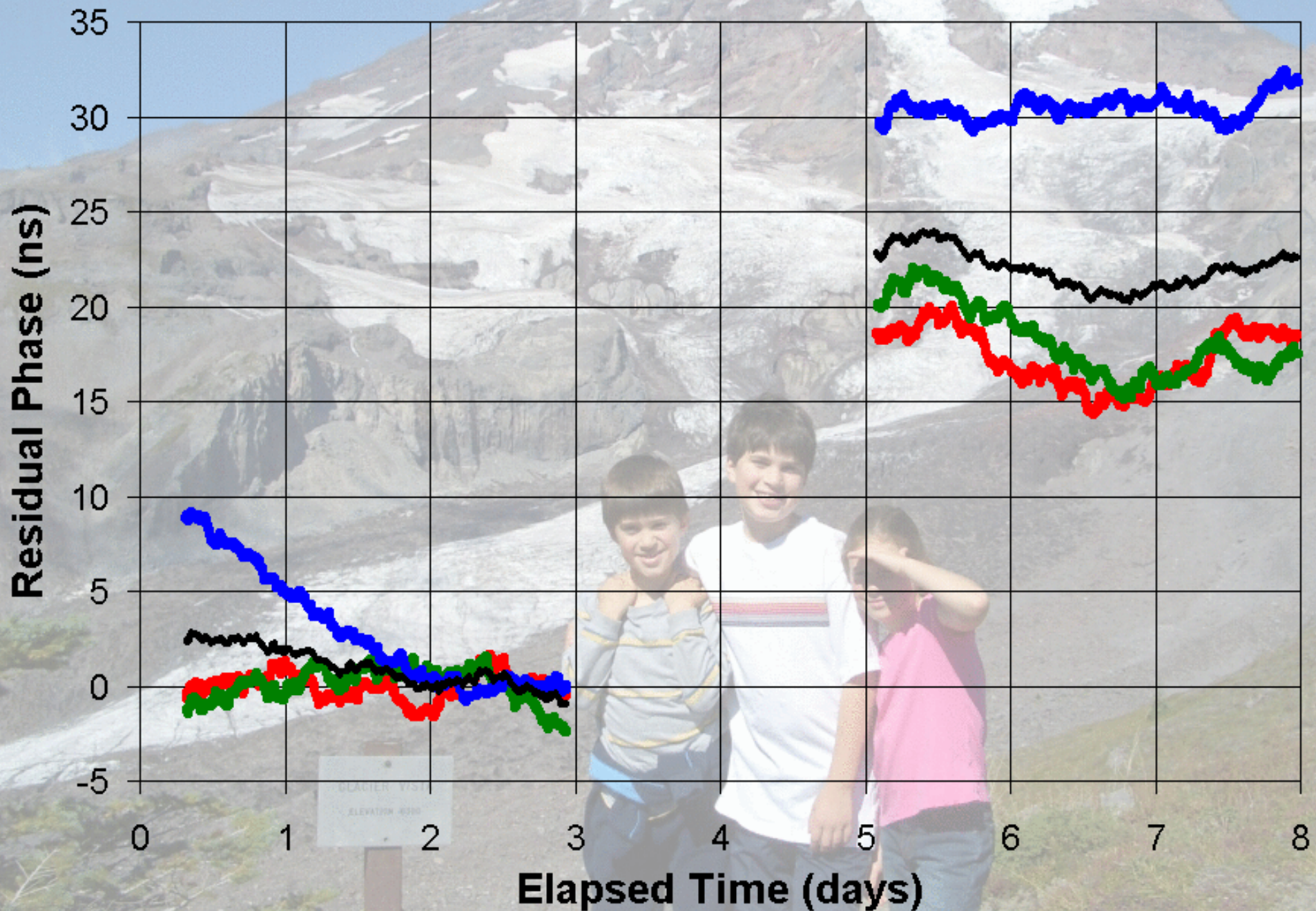
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- For years of inspiration and support
- More info: [www.LeanSecond.com](http://www.LeanSecond.com)
- Email: [TVB@leapsecond.com](mailto:TVB@leapsecond.com)
- Patience from wife & kids
- Time for questions...

**G**RE<sup>2</sup>**A**T    **G**eneral **R**elativity  
                         **E**instein / **E**ssen  
                         **A**nniversary **T**est

# Kids, Clocks, and Relativity on Mt Rainier

Three Cesium Clocks: **Red** **Green** **Blue** & Mean



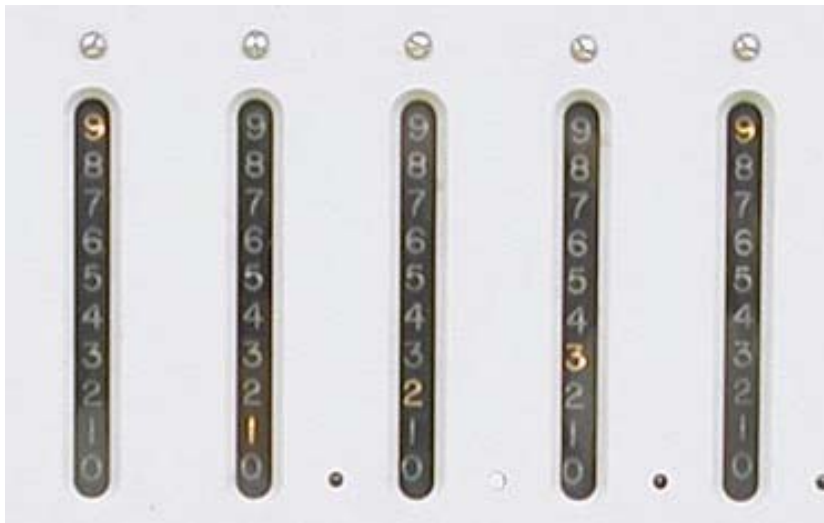
# Chapter

- Extra material

# Einstein & Atomic Clocks

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- Verifying GR with atomic clocks
- Did Einstein know? (he died in 1955)
- NBS Cs 1953, Essen 1955, ...
- Naumann & Stroke article



# Project GREAT 2007 ?

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- Make minivan a lab not just a transport
- 2+ week pre-trip, 1+ week post-trip
- Single switch: ext Maser vs. int Rb ref
- Careful solar and thermal insulation
- Use park/Inn power instead of car engine
- Proper air con solution in vehicle
- Real-time plots; wireless status & alerts!
- More kids; more clocks (5?)
- Test 1970's H&K-era 5061A's for contrast
- Try direct GPS frequency measurement

# Humor - cesium wristwatch

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- Bill's watch...



“Atomic Bill” – first true atomic wrist watch  
<http://www.leapsecond.com/pages/atomic-bill/>



# Humor - portable cesium clock

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- Tom's backpack (Project GREAT, ver 1)



"Atomic Tom" – climbing with atomic clocks  
<http://www.leapsecond.com/pages/atomic-tom/>

# Humor - 'Glimmer Twins'

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- GR says high clocks run faster
- 1965: Keith gets 'high' (for 40 years)
- 2005: looks much older...



# Humor - relativity

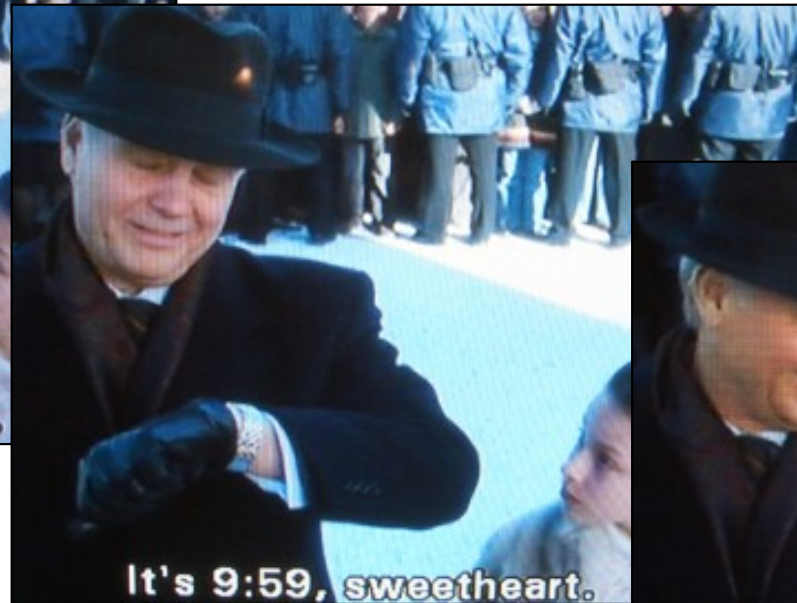
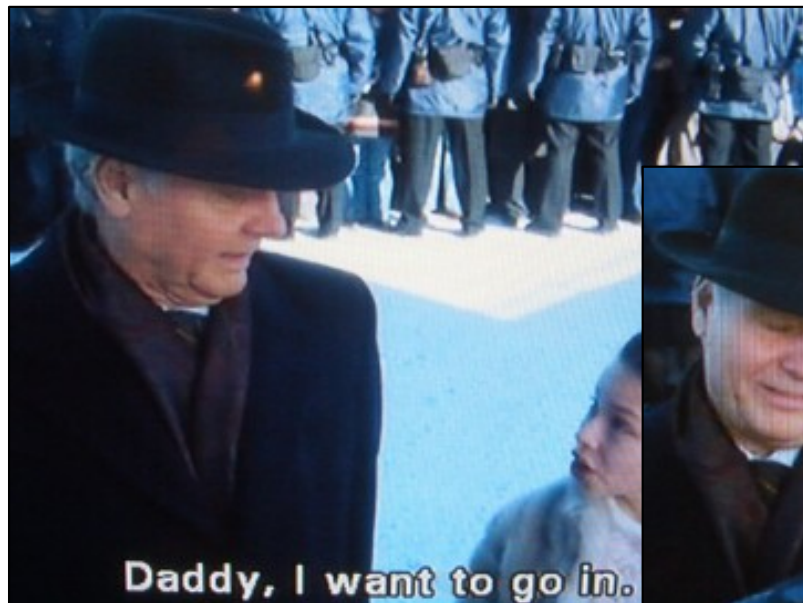
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- Time flies while you're having fun
- Stay young: fly fast and low
- How to spend more time with your kids
- How to make your wife younger

# Humor - make time go faster

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- Charlie and the Chocolate Factory



# Chapter 1

- Introduction