

Time and Frequency Transfer

Judah Levine

Time and Frequency Division
National Institute of Standards
and Technology

Boulder, Colorado 80305

jlevine@boulder.nist.gov

Topics I will discuss

- Requirements and limitations: path delay, receiver calibration, local effects
- Methods: one-way, two-way, common-view, all-in-view
- Systems: low-frequency systems (WWVB and Loran), GPS, other satellites, telephone lines, and the Internet
- Algorithms for clock discipline
 - What do you do with the data after you get it?

Introduction

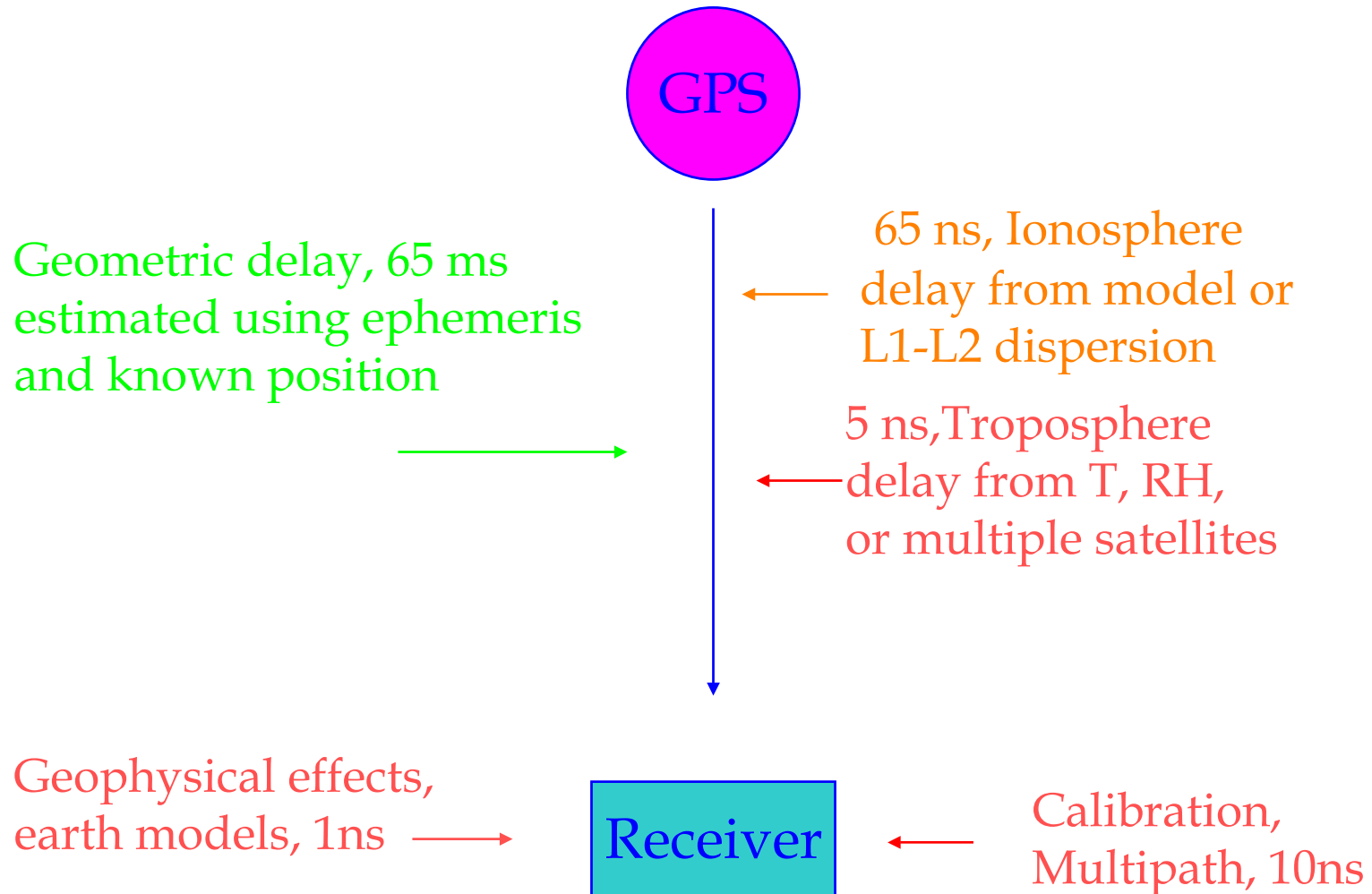
- Time distribution depends on accuracy of channel delay
 - Delay through each link in the chain must be known
 - Minimum path delay $3 \mu\text{s}/\text{km}$

Introduction

- Frequency distribution depends only on the stability of the delay
 - Delay through each link in the chain must be constant
 - Measurement of the delay not necessary

Methods for estimating the delay

One-way distribution methods



Real-world limitations

- Errors in the model parameters
 - Broadcast ephemeris errors
 - Troposphere zenith delay

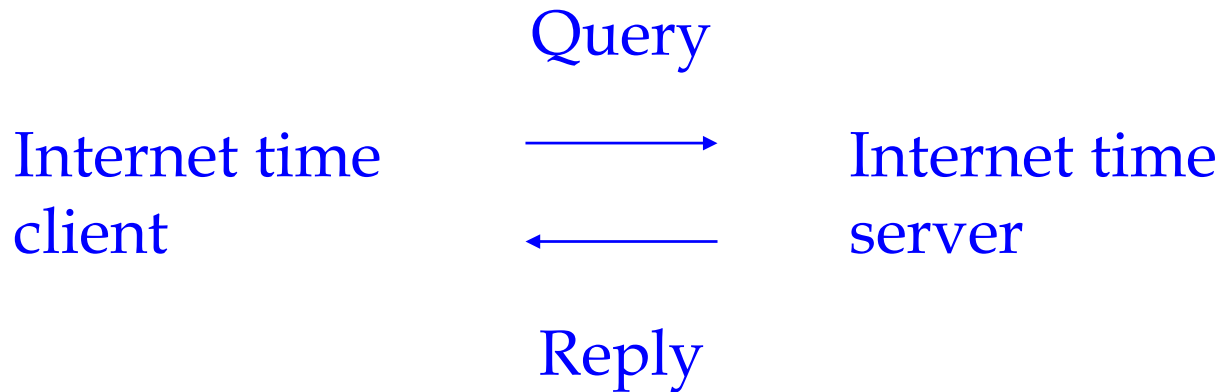
Real-world limitations

- Effects not modeled
 - Multipath reflections
 - Temperature sensitivity of the antenna cable
 - Effective delay through the receiver

Real-world limitations

- How well does it work for GPS?
 - Easy: $1\mu\text{s}$
 - possible: 50 ns
 - Very hard: 10 ns or less

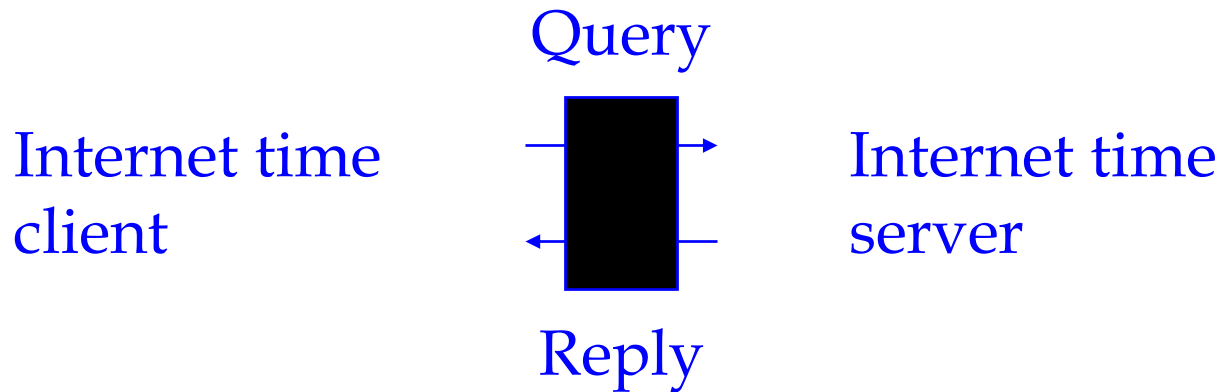
Two-way methods



Client-server delay= one-half of round-trip value
(can be measured by client or by server)

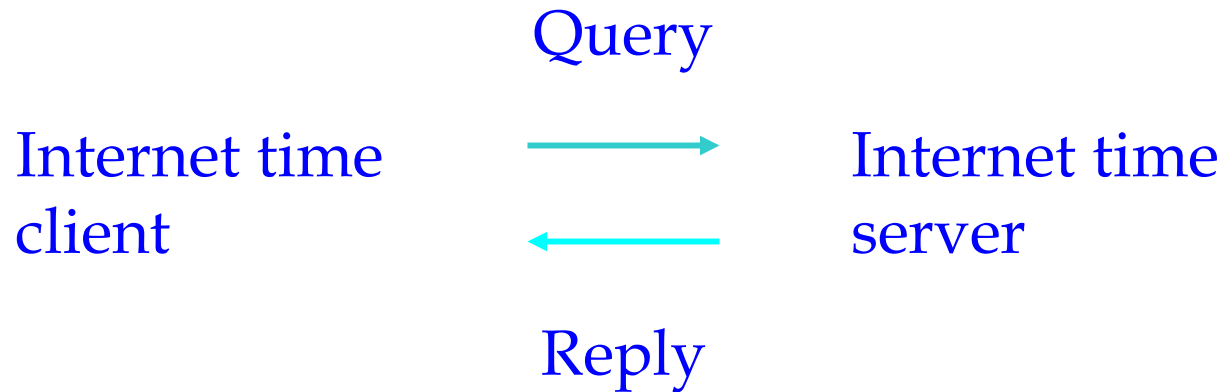
Error= (asymmetry)×(path delay)

Real-world limitations -- 1



Physical path has elements that are hard to characterize: network routers and gateways, modems and satellite transponders, etc.

Real-world limitations -- 2



Path dispersion:

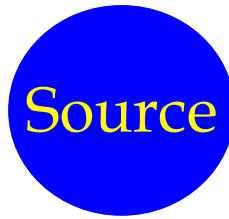
Physical path are not the same

Time dispersion:

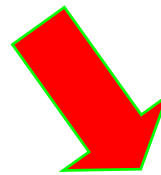
Messages are not sent at the same time

Common-view method

Path delays
are nearly equal



$$T1 = t(1) - s$$



$$T2 = t(2) - s$$

$$\Delta t = T1 - T2$$

Real-world limitations

- Paths are not of equal delay
 - Estimate of difference introduces errors
 - Ionosphere, troposphere are different

Real-world limitations

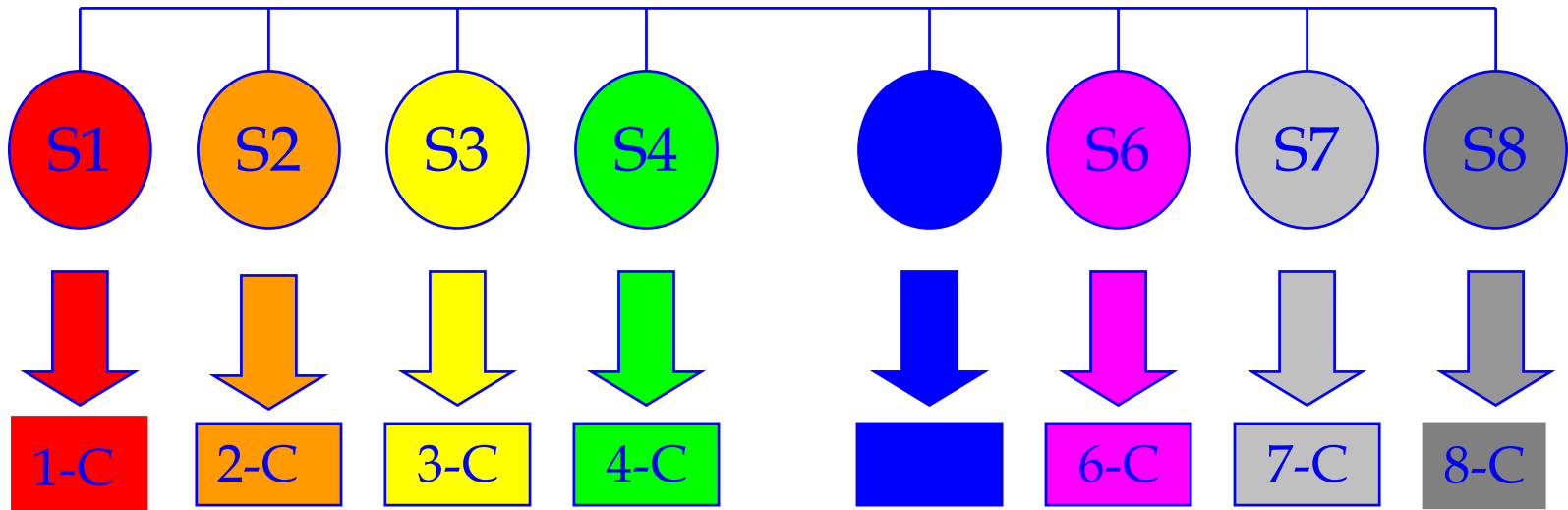
- Local effects are not common and don't cancel
 - Multipath reflections
 - Temperature sensitivity of receiver

Real-world limitations

- Sites are too far apart to see a common source
 - NIST/Boulder and Australia

All in view melting pot

Com ref



Rcvr 1

Rcvr 2

$$\Delta_1 = (S1 + S2 + S3 + S4) / 4$$

$$\Delta_2 = (S5 + S6 + S7 + S8) / 4$$

$$\Delta T = \Delta_1 - \Delta_2$$

Real-world limitations

- Same as one-way and common-view
- Errors in link between satellite clocks and common reference

Comparison of the methods

- Two-way
 - Requires only a symmetrical path delay
 - Including symmetry of end-point hardware
 - Error proportional to asymmetry and delay
 - Not always possible or practical
 - No casual associations

Comparison of the methods

- Common-view
 - Attenuates common-mode effects
 - Does not improve local problems
 - Works best when paths are nearly equal

Comparison of the methods

- Melting pot
 - Many of the advantages of common view
 - Can work even if there is no common source
 - Really an ensemble of one-way measurements
 - Requires better modeling of paths and clocks

Comparison of the methods

- One way
 - Works when nothing else is available
 - Simple and often good enough

Common-view vs. Melting pot

- Common view
 - More problems are common-mode and will be attenuated by the subtraction
- Melting pot
 - More measurements are possible; measurement noise will be attenuated

Common-view vs. Melting pot

- Very short baseline: methods identical
- Short baseline: C-V probably wins
- Long-baseline: M-P probably wins

Distribution Systems

- Low-frequency ground-based services
 - WWVB and similar stations
 - Loran and e-Loran
- GPS (also GLONASS and Galileo)
- Two-way systems
 - Communications satellites
 - Digital systems using the Internet, or dial-up telephone lines

Low-frequency services

- WWVB (60 kHz) and its friends (< 100kHz)
 - Model path delay to 10 ms or better
 - Variation in delay near sunrise and sunset
 - Path delay stability (over 24 hrs): few μs
 - $1 \mu\text{s}/24 \text{ hrs} \sim 10^{-11}$ (as good as a rubidium standard)
 - Easy to receive, modest power provides continental coverage, usually with no outside antenna.
 - Used for wall clocks, wrist watches, simple automation
 - Correction for daylight saving time, leap seconds, ...

Renaissance of low-frequency

Early use was for frequency calibrations:

Delay is very stable over 24 hours

Increased power supports consumer applications

Wrist watches, wall clocks, ...

Cheaper and simpler than GPS

Loran - 1

- Transmits high-peak-power pulses using carrier at 100 kHz
 - Multiple (at least 3) synchronized stations
 - A Loran “chain,” 1 is master, rest are slaves
 - Geometry guarantees unique identification

W

X

Z

Y

Geometrical
delay cannot
reverse ordering

Loran - 2

- Shape of pulses very carefully controlled
- Original recipe has no additional information and was intended primarily for hyperbolic navigation
- Enhanced Loran will add time of day and other information

Loran - 3

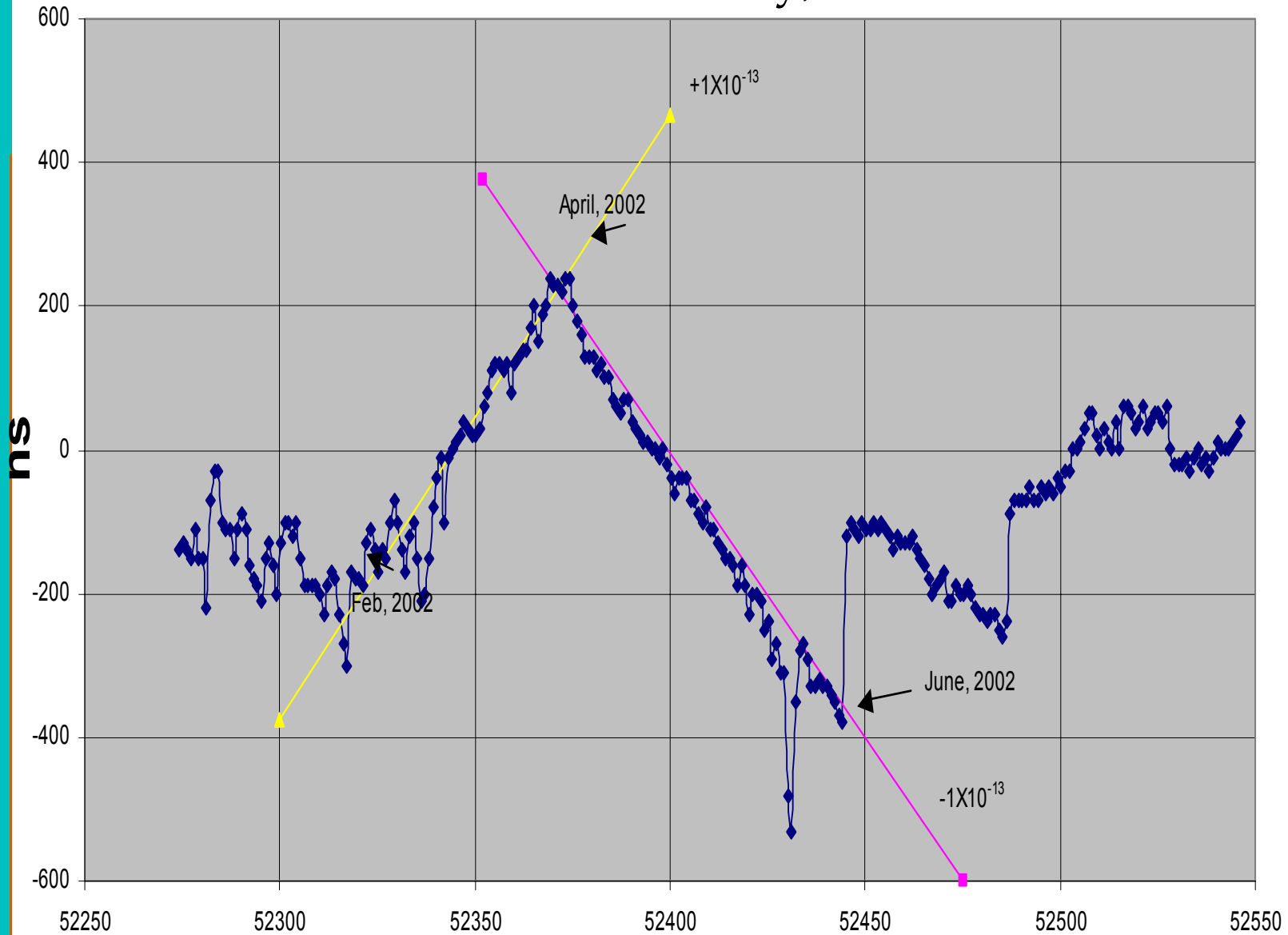
- Stations in each chain identified by time interval between pulses
 - Seneca, NY (master of 9960 chain)
 - pulse period of 99.6 ms (10+ pps), TOC=4m9s
 - Fallon, NV (master of 9940 chain)
 - Pulse period of 99.4 ms (10+ pps), TOC=8m17s

Loran - 4

- Pulses “on time” only at a “TOC”
 - Difficult to use for simple time of day
- Observe signals from several chains
 - Use Multiple TOCs (Chain coincidence)
- Often used in common-view
 - Limited by anisotropies in the path delay

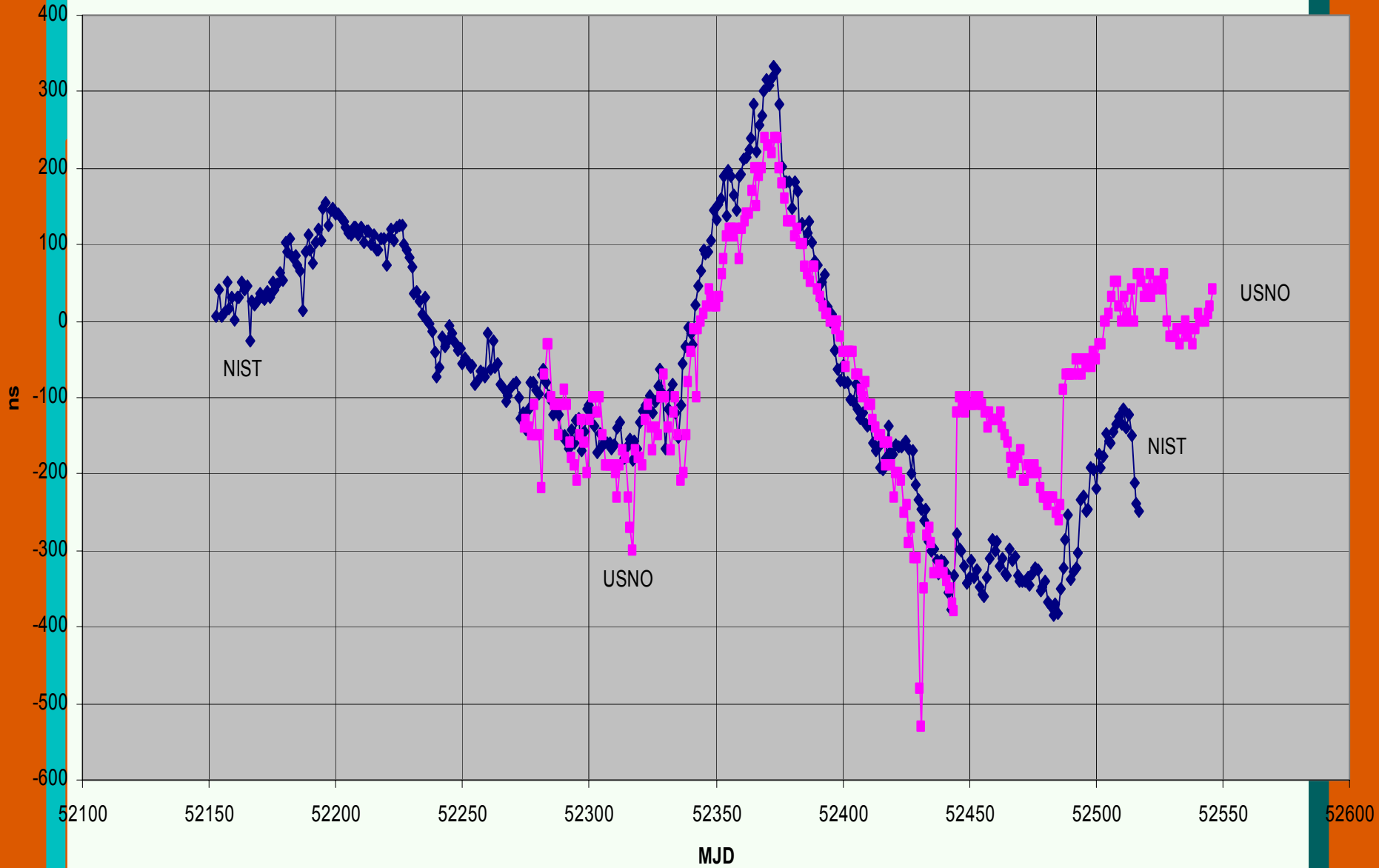
UTC(GPS)-9610 Master (Data provided by USNO)

9610= Boise City, Ok

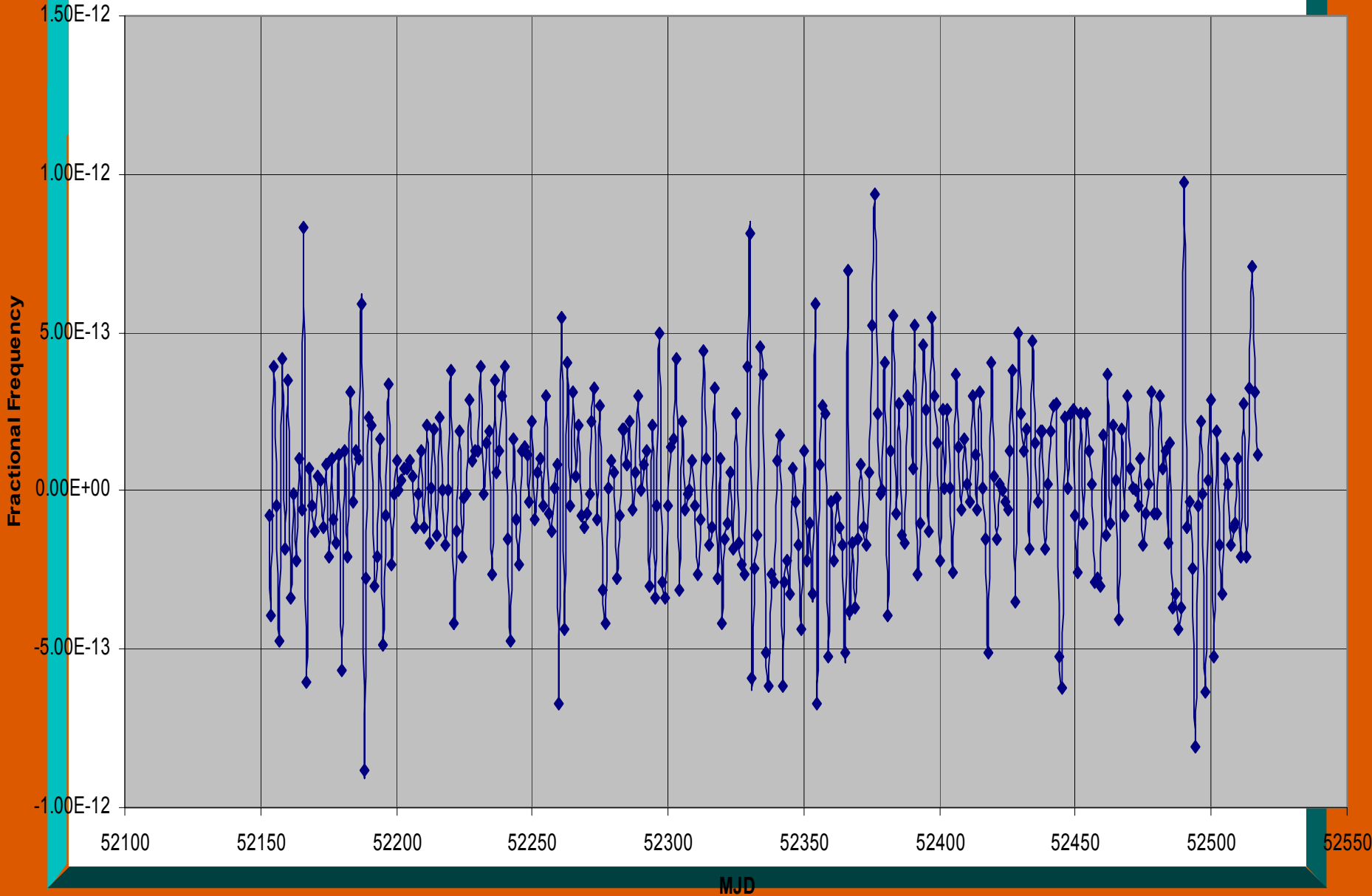


MJD (1 Jan 2002 - 29 Sep 2002)

Loran - NIST & USNO



y(1day), Loran - UTC(NIST)



Time from Loran

- Better than 1 μ s 100% of the time
- Sometimes much better than this – can reach 60 ns RMS
 - Significant variability with time and location
 - Long-period variations, especially over land
 - **Your mileage may vary**
- Can support almost all routine civilian timing applications
- Scientific, research, national labs, need something better

Frequency from Loran

- One-day average
 - Fractional frequency accuracy of
 - 1×10^{-12} 100% of the time
 - 5×10^{-13} 90% of the time
 - Supports telecom stratum-1 (1×10^{-11})
 - **Assumes reference clock has adequate holdover stability consistent with 1-day averaging time**
 - Cannot support high-end cesium device
 - 2×10^{-14} with 1 day of averaging

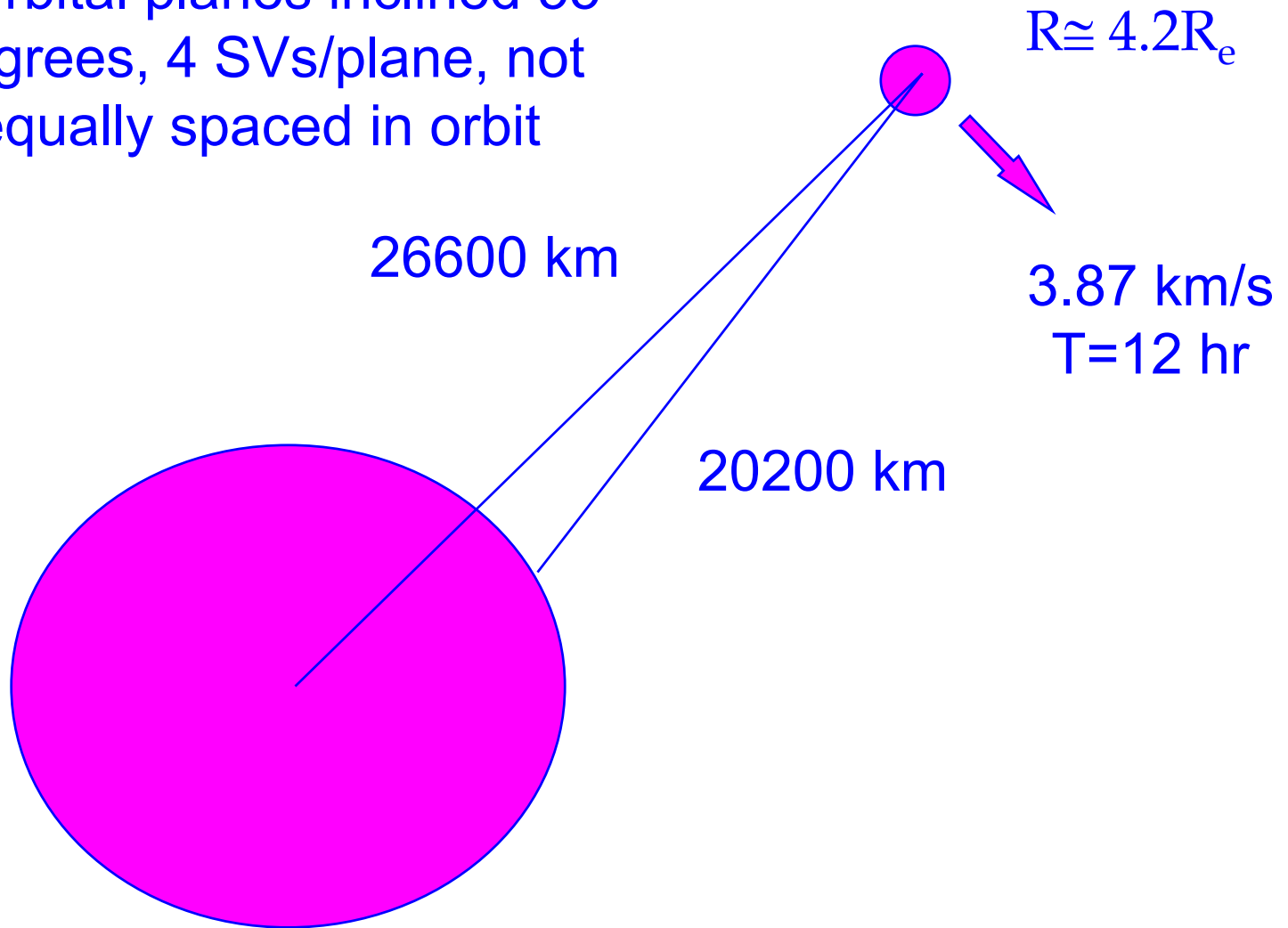
Renaissance of Loran

Shut down scheduled several times

Now proposed as backup for GPS
Almost impossible to jam

Time and frequency accuracy can support
almost all civilian applications

GPS: 24 SVs (+ spares)
6 Orbital planes inclined 55
degrees, 4 SVs/plane, not
equally spaced in orbit



GPS System Time

- “Composite clock”
 - average of ground and space clocks
- Steered to UTC(USNO)
 - Prediction of offset in navigation message.
- Incorporates the 19 leap seconds that were in UTC as of 1980
 - Time ignores subsequent leap seconds
 - Count of leap seconds in nav. message

Time and the GPS satellites

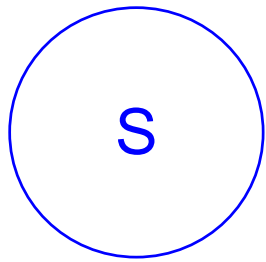
- PRN code transmission derived from on-board atomic clock
 - L1 freq= 1575.42 MHz, L2= 1227.6 MHz
 - C/A (1.023 MHz) code on L1
 - P code (10.23 MHz) on L1 and L2
 - Generally encrypted
- Navigation message computed on the ground and uploaded periodically
- Navigation message has:
 - *Predicted* orbital parameters of satellite
 - *Predicted* offset of satellite clock from GPS time
 - *Predicted* offset of GPS system from UTC(USNO)

Using the SV Signals

- The Pseudorange
 - cross correlate received prn signal with local copy of code derived from SV number and time.
 - maximum in correlation gives apparent difference between SV time and local clock.

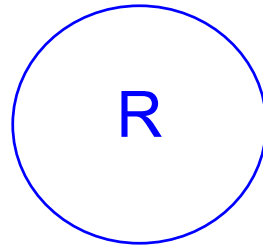
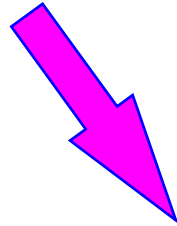
Using the SV Signals

- Correct pseudorange using orbit, known station position, SV-GPS clock offset,...
- Result is local clock - GPS time via 1 satellite
 - Raw data rate typically 1 measurement/s using local 1 Hz ticks



x_s, y_s, z_s, t_s

Code-based Time transfer



x_r, y_r, z_r, t_r

$$t_r - t_s = \frac{\sqrt{(x_r - x_s)^2 + (y_r - y_s)^2 + (z_r - z_s)^2}}{c} + \Delta t_{r-s} +$$

ionosphere + troposphere + hardware + ...

Correction 1: Ionosphere

- Refractivity (excess delay) proportional to “total electron content” (TEC)
- TEC affects L1-L2 dispersion as well
 - Measure dispersion to estimate TEC
 - Use TEC value to correct L1 data
- L1, L2 carriers have identical P code
 - L1-L2 does not require decrypting the code

Correction 1: Ionosphere

- Range is linear combination of signals on L1 and L2:

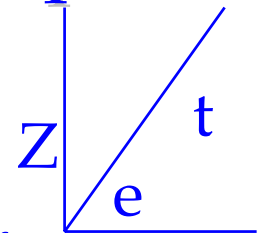
$$L1 + C*(L1-L2) = (1+C)*L1 - C*L2$$

- Corrected range noiser by $\sqrt{(1+c)^2 + c^2} \approx 3$

- Single-frequency common view may be better choice for short baseline

Correction 2: Troposphere

- Refractivity (excess delay) depends on integrated density
 - Non-dispersive at radio frequencies
- Assume homogeneous and isotropic
 - Effect proportional to path length
 - Zenith delay / $\sin(\text{elev angle})$
 - Zenith delay estimated from data or from surface measurements of P, T, ...
- Usually $Z < 6$ ns, often ignored



Correction 2: Troposphere

- More accurate mapping functions
 - Niell mapping function:

$$T_z = \frac{1}{1 + \sin() + \frac{1}{1 + \sin()} + \dots}$$

Most important at low elevation angles

Correction 3: Station Delays

- Antenna, cable and receiver delay
 - Affected by ambient temperature
- GLONASS satellites transmit on different frequencies
 - receiver front-end delay may depend on satellite
- Not improved by common-view
- Not improved by two-way unless symmetrical

Calibration of receiver delay

- Use simulator driven from known clock
 - complicated and expensive
 - can test for receiver design problems
- Short-baseline common view using common clock and “standard” receiver
 - differential multipath will not cancel
- Some evidence that methods are *not* equivalent

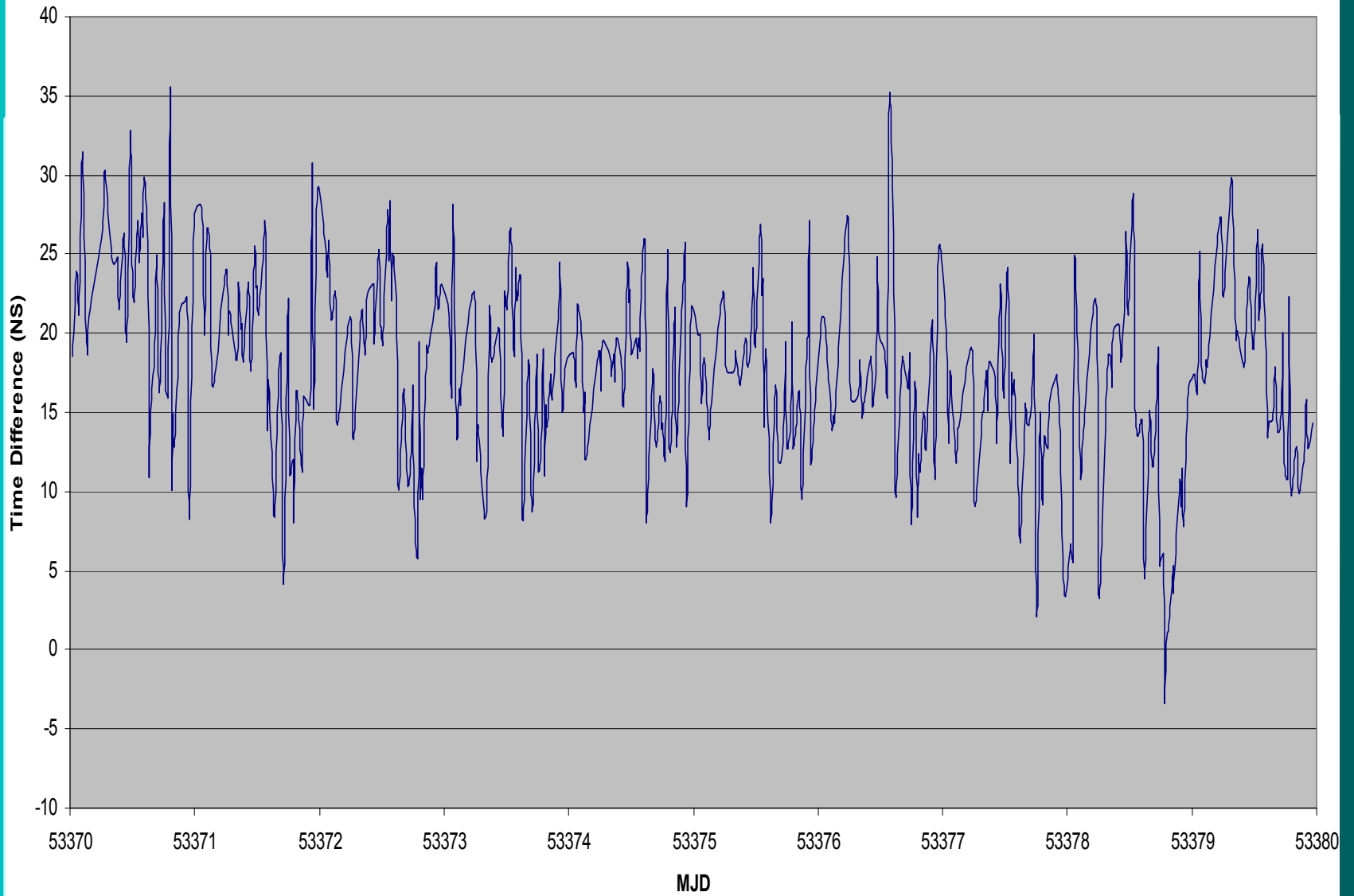
Correction 4: Multipath

- Reflections from ground and nearby objects
- Reflections at cable connectors, ...
- Reflections at impedance mis-match
 - Systematic effect: effective path longer
- Coping with multipath:
 - Ground planes, choke rings, multiple element antennas (electrically steered)
 - Attenuators in cables, antenna down-conversion
 - Advanced receiver correlation

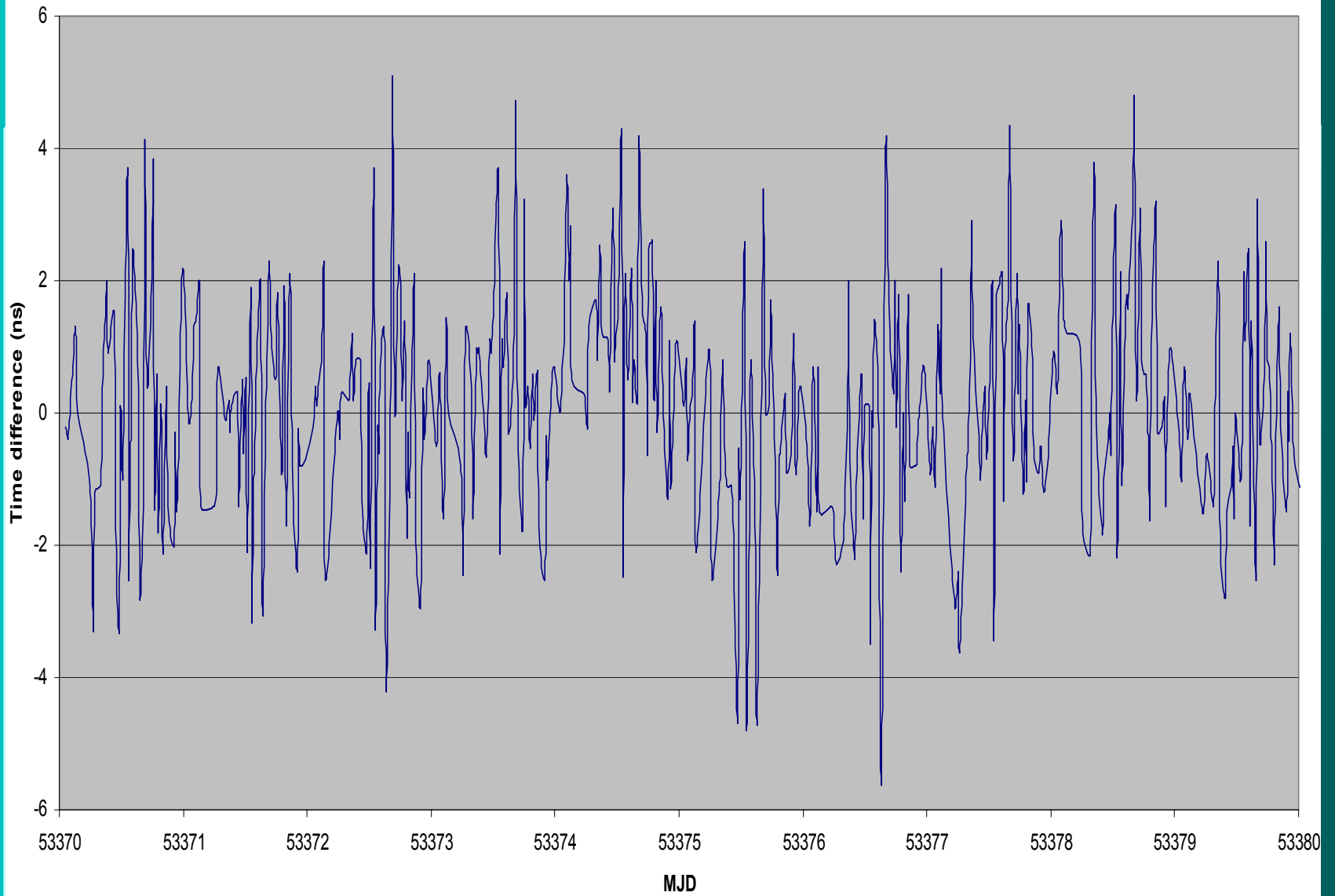
Code-based timing receivers

- Single channel “NBS” type
 - Needs a tracking schedule for common view
- 8 or 12 channel receivers designed for timing
 - Pseudorange/time offset of each SV available separately
 - Can implement all-in-view “melting-pot”
- No current receiver is optimum

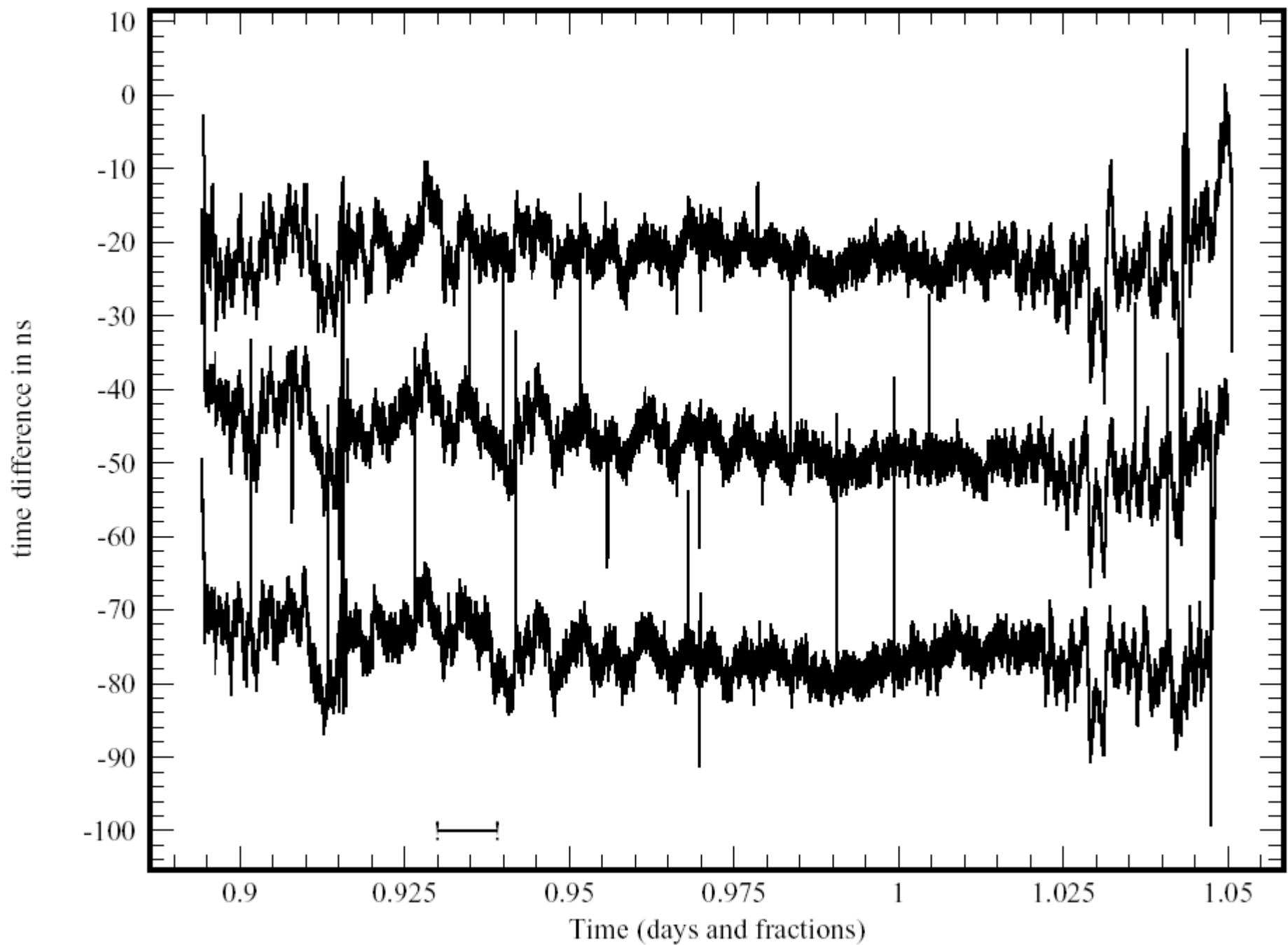
GPS - UTC(NIST)



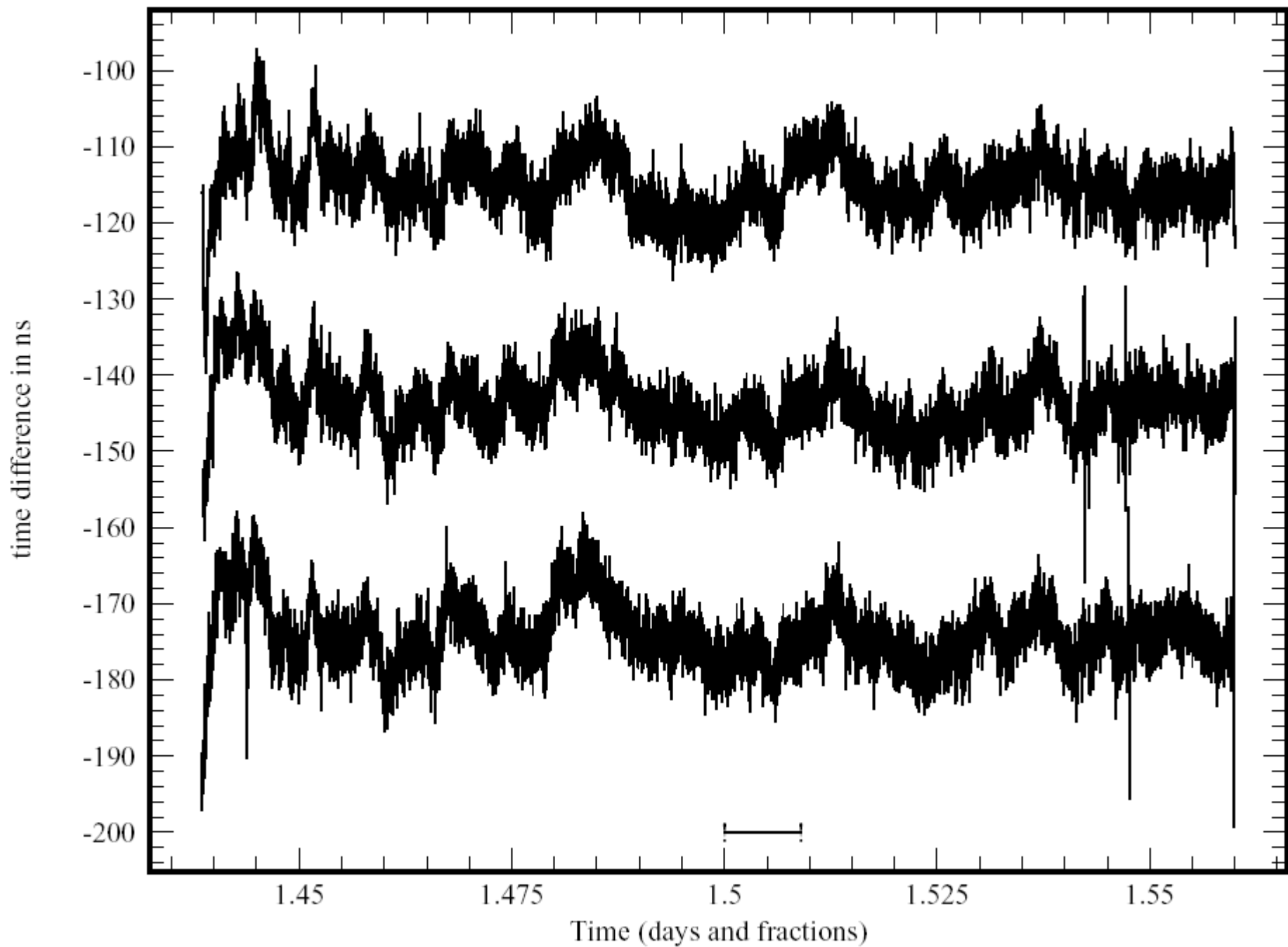
Common View



Stacked data, UTC(NIST)-GPS via Satellite 11



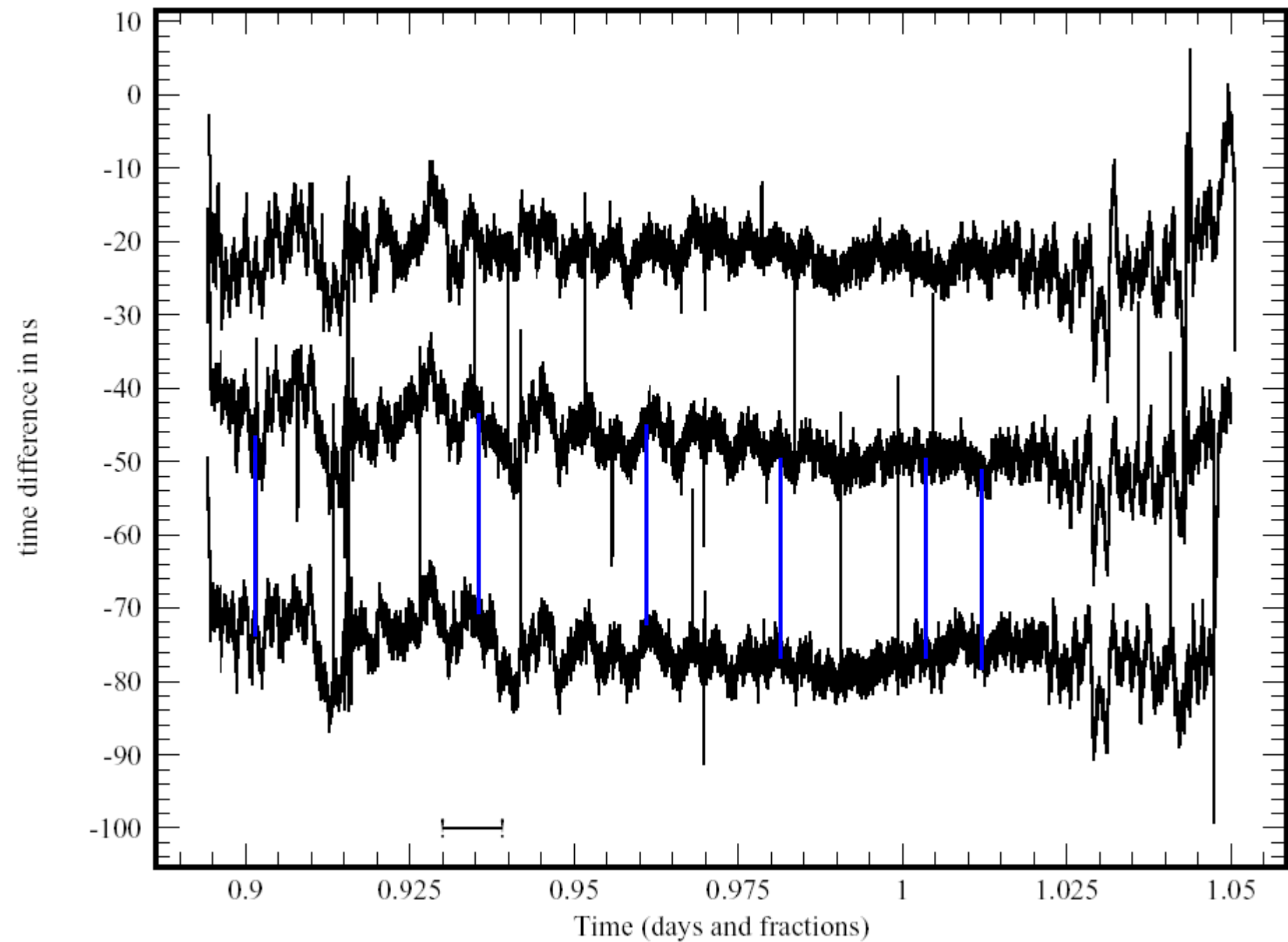
Stacked data, SV 19 short-baseline cv



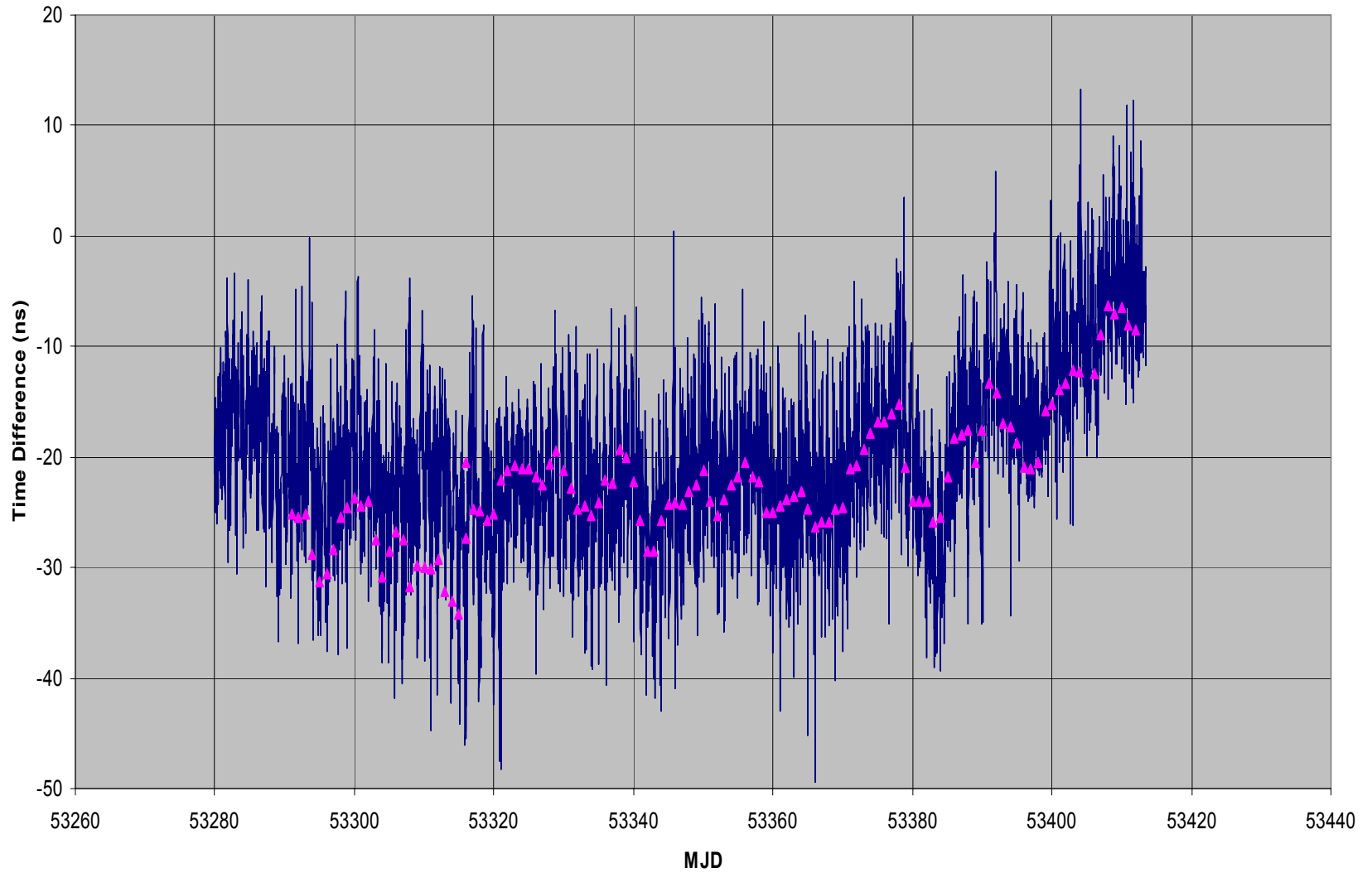
Dealing with multipath

- Computing sidereal-day frequency average and integrating
- Exact repetition period varies from one satellite to another
 - Function of orbital parameters

Stacked data, UTC(NIST)-GPS via Satellite 11



UTC(NIST)-GPS time

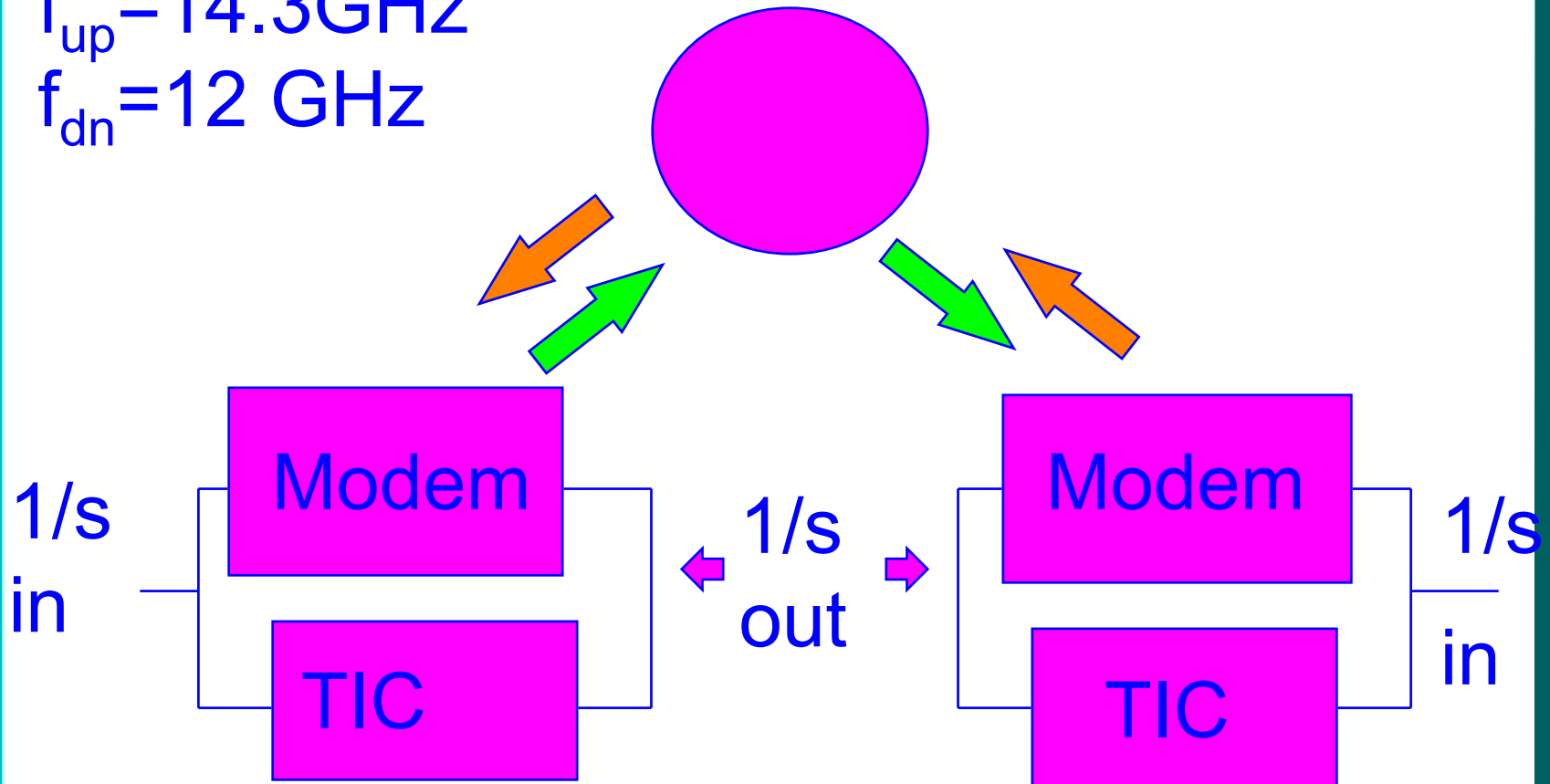


Carrier-phase GPS measurements

- Carrier and code from same oscillator
- Carrier period 1000X smaller than code
 - corresponding increase in resolution
 - Increased sensitivity to most perturbations and errors
 - Requires post-processed precise orbits, clock estimates, ionosphere, ..
- Integer cycle ambiguities make time transfer more difficult than frequency

Two-way Satellite time transfer

$$f_{\text{up}} = 14.3 \text{ GHz}$$
$$f_{\text{dn}} = 12 \text{ GHz}$$



TWSTT capabilities

- Time stability of 0.1 ns
- Frequency transfer of 10^{-15} or a bit less
- Calibration is difficult
- Stability of hardware delay a possible problem
 - Delay generally changes if hardware is modified
- Accuracy generally limited by calibration using code-based GPS

Advantages of TWSTT

- Delay through atmosphere and through common hardware cancels in round-trip subtraction (at least to first-order).
 - Depends only on *symmetry* of delay
- Not affected by SA or military control
- Not sensitive to position of satellite
- Output in near-real time, no significant post-processing.
- Less multipath -- antenna directional

Disadvantages of TWSTT

- Satellite time is expensive
- hardware is complicated and expensive, station is active and requires approval
- delays through satellite transponders may vary with time or direction or as different transponders are used
- calibration procedure of ground-station complicated
 - delay is sensitive to temperature
- Users must establish cooperative schedule
 - Occasional or passive users cannot be supported

Comparison of C-P and 2-way

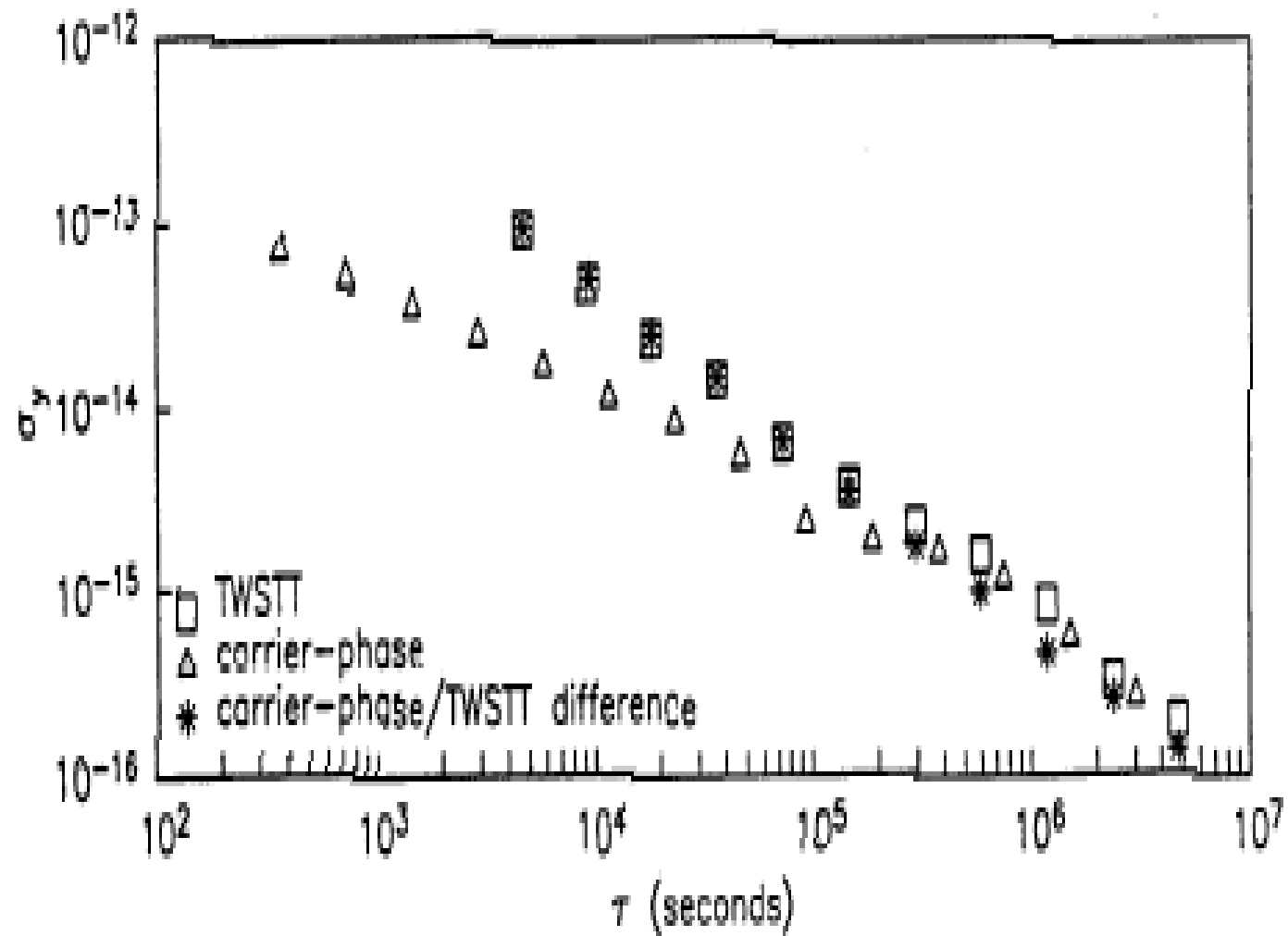
● Carrier phase

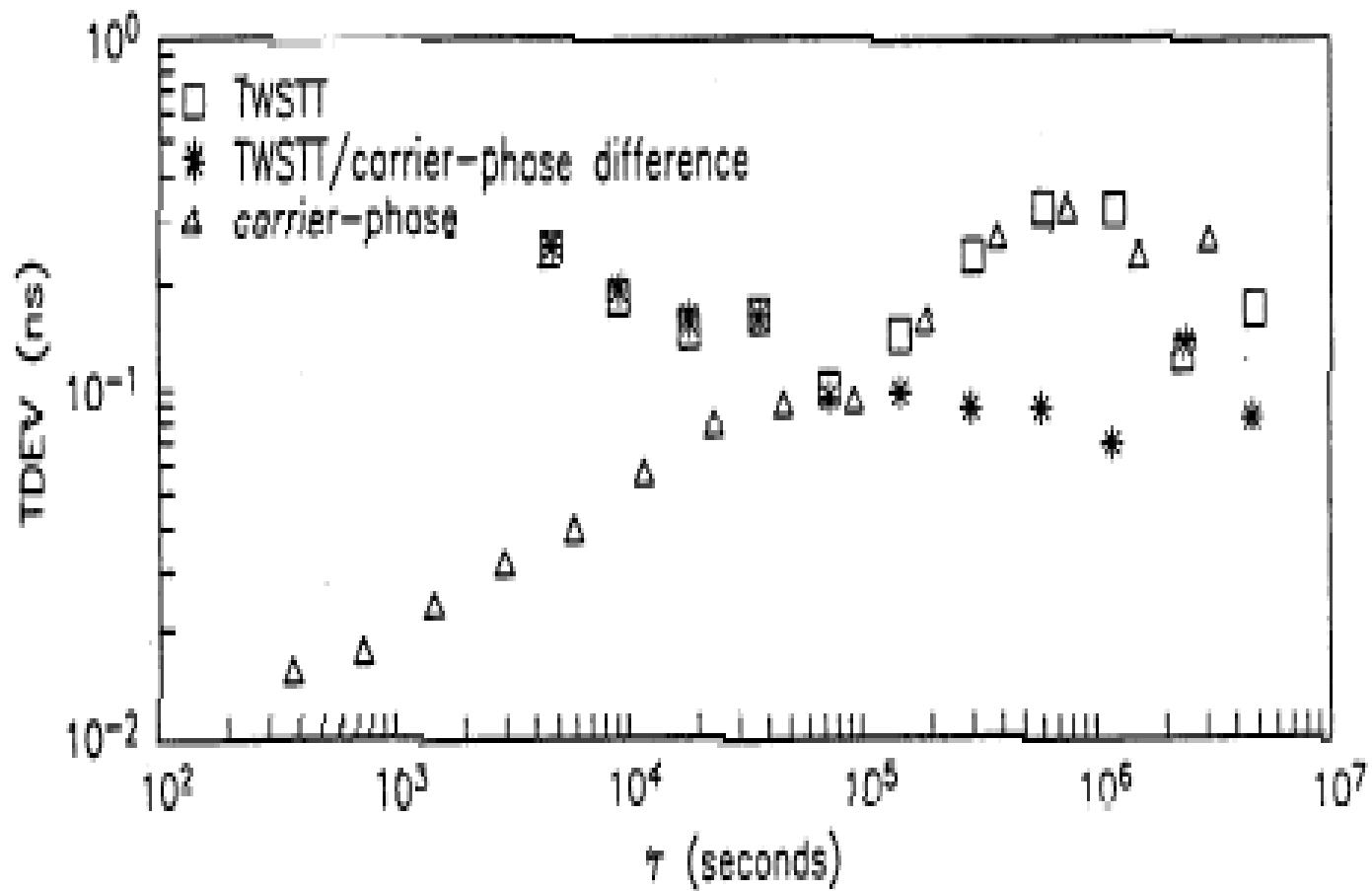
- Supports casual associations
- No operating costs for data acquisition
- Short-term noise lower (< 50 ps)
- Requires significant post-processing
- Depends on outside support for orbits, ...
- Long-period fluctuations may limit performance in some applications

Comparison of C-P and 2-way

● Two-way

- No post-processing – results available immediately
- Longer-term noise not worse, but not well known
- Receiver is complicated and requires approval
- Satellite time costs money
- No casual associations





Digital Systems - 1

- NIST ACTS dial-up telephone service
 - 6 independent servers in Boulder linked to clock ensemble, 30 telephone lines.
 - Telephone number: 303 494 4774
 - Server measures round-trip delay using echo of on-time marker character from client end
 - Subsequent on-time markers are advanced to arrive at client system on time.
 - Symmetry of delay limited by modems
 - Stability of time transfer $\sim 1\text{-}2$ ms
 - Accuracy depends on modem, typically < 5 ms

Digital Systems - 2

● Internet services

- Network Time Protocol (NTP)
 - Protocol described in RFC 1305
- Client measures round-trip delay using echo of query to server
- Symmetry depends on path details
 - Stability and accuracy ~ 10-20 ms
- Communication protocol independent of clock discipline algorithm

Network Time Protocol – cont.

- Protocol can support authentication
 - Not widely used
- Protocol can support notice of and correction for leap seconds
 - Can be used to calculate TAI from transmitted UTC time stamps
- NIST operates 14 independent servers
 - Geographically separated to minimize delay to users and reduce single points of failure
 - Servers currently receive about 20,000 requests/s

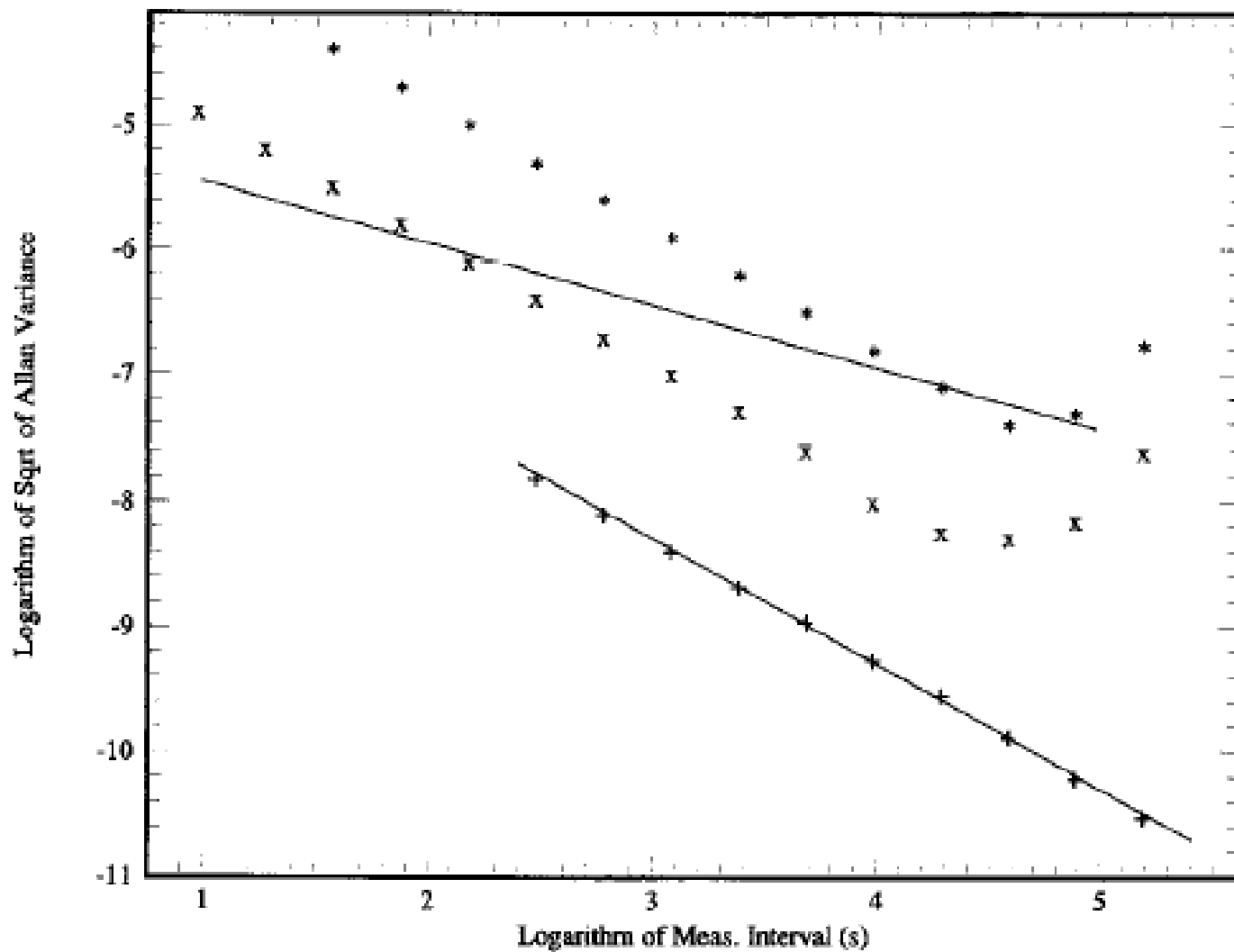
simple one-way protocols

- Simple-NTP, daytime, time, RDATE, DATE
 - Simple delay estimator (or no estimate)
 - “set and forget” - no fancy statistics
- Suited for small systems and those with no always-on network connection
 - Laptops, many PCs
- NIST NTP servers also support these protocols

How do we use the data?

- Can we distinguish among
 - Noise in the device under test
 - Fluctuations in the channel delay
 - A problem with the remote clock
 - Extreme case: is the remote clock broken?
- Separation of variance
 - At short times, local clock is quieter than remote clock seen through a noisy channel
 - Flicker and random walk of local clock make it worse than remote clock at longer times

Network delay +=loopback, x=LAN, *=Internet



Cost/benefit analysis

- If all calibration requests have the same cost, then process cost, $C \sim 1/\tau$
- $T = TDEV$ of synchronized clock:

$$T = \tau \times \sigma_y(\tau)$$

$$\text{Quality} = Q = 1/CT = 1/\sigma_y(\tau) = 1/\tau^{-k} = \tau^k$$

- $k > 0$, white or flicker phase noise
- $k < 0$, flicker or RW frequency noise
- Performance regions: best/most expensive, optimum, worse/cheaper

Optimum operating point

- Use an interval between calibrations, that corresponds to the minimum value of $\sigma_y(\tau)$
 - $\tau \sim 20,000$ seconds for typical computer clock

Summary

- Presented methods for estimating the transmission delay
 - One-way, two-way, common-view, ...
- Described methods used for transmitting time and frequency information
 - WWVB, Loran, GPS, Internet, ...
- Discussed methods for designing clock discipline algorithms based on performance of the local clock and the network link
- Estimated cost/benefit ratio for synchronization processes

For more information

- List of publications of the NIST time and frequency division are in the publications menu of our web page:
tf.boulder.nist.gov
- Many of these publications are on-line
- “Time and Frequency Measurement” by C. Hackman and D. B. Sullivan, published by the American Association of Physics Teachers, 1996.