Time and Frequency Transfer

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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

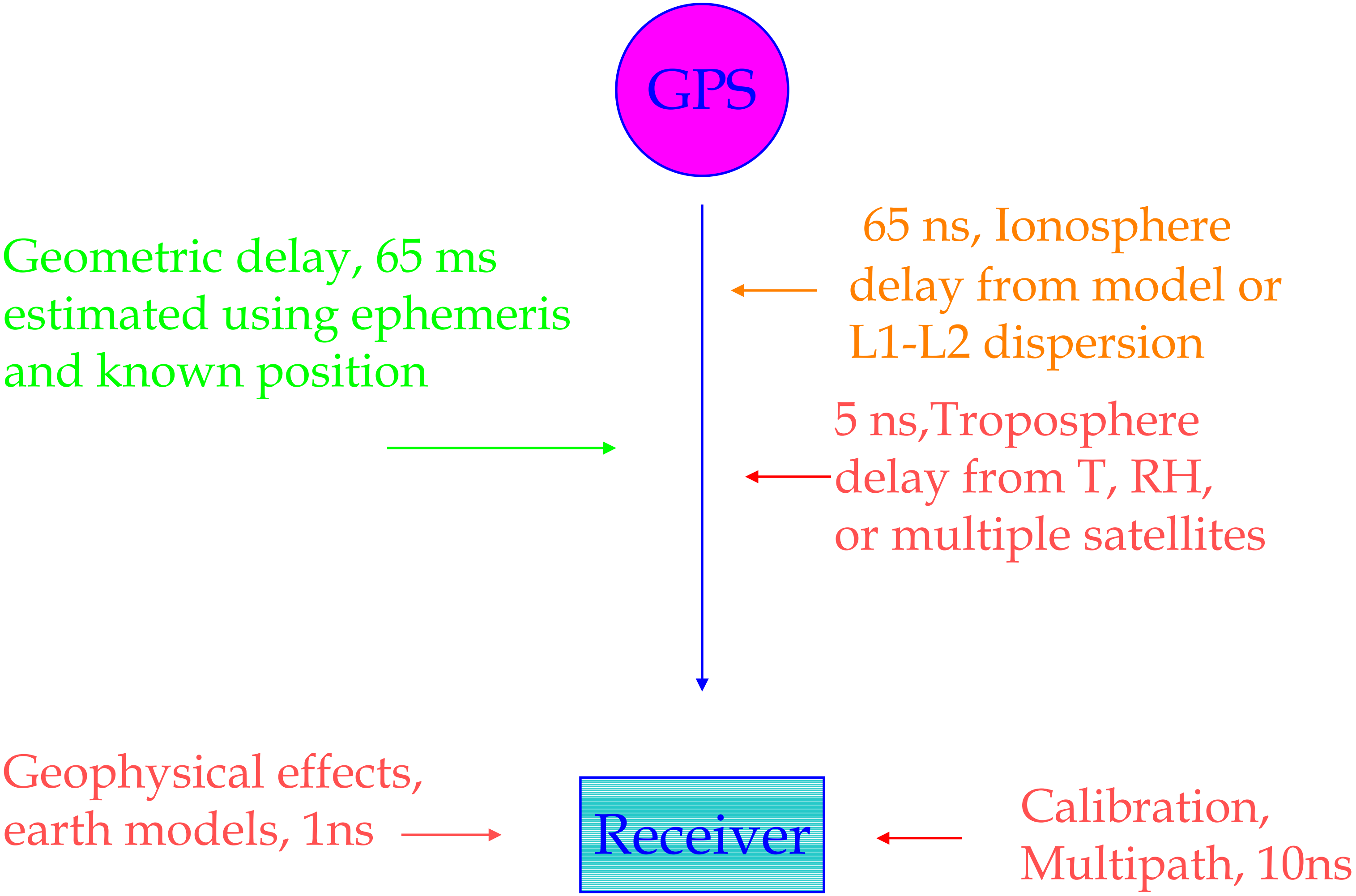
- Time distribution depends on accuracy of channel delay
  - Delay through each link in the chain must be known
  - Minimum path delay 3 μs/km

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



GPS

Geometric delay, 65 ms estimated using ephemeris and known position

65 ns, Ionosphere delay from model or L1-L2 dispersion

5 ns,Troposphere delay from T, RH, or multiple satellites

Geophysical effects, earth models, 1ns

Receiver

Calibration, Multipath, 10ns

Real-world limitations

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

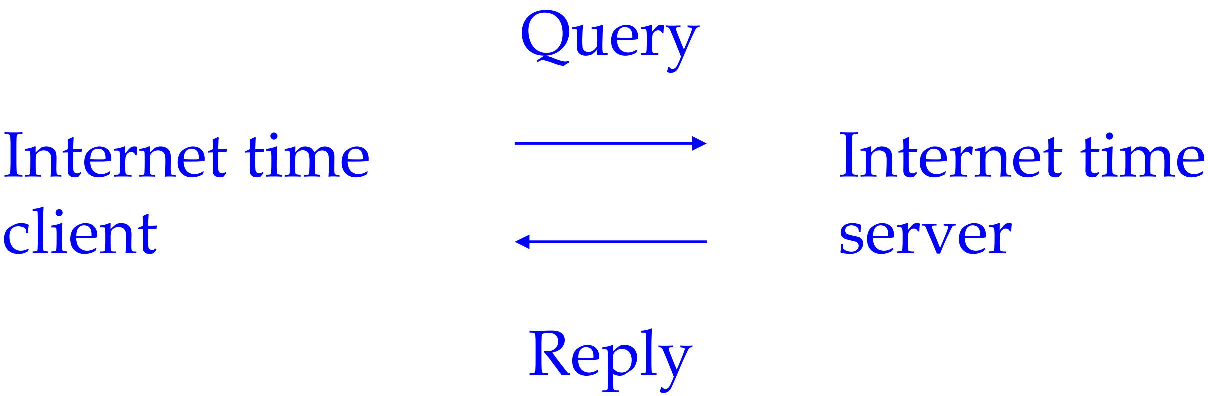
Real-world limitations

- 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: 1μs
  - possible: 50 ns
  - Very hard: 10 ns or less

Two-way methods



Query

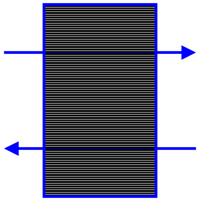
Internet time
client

Internet time
server

Reply

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



Query

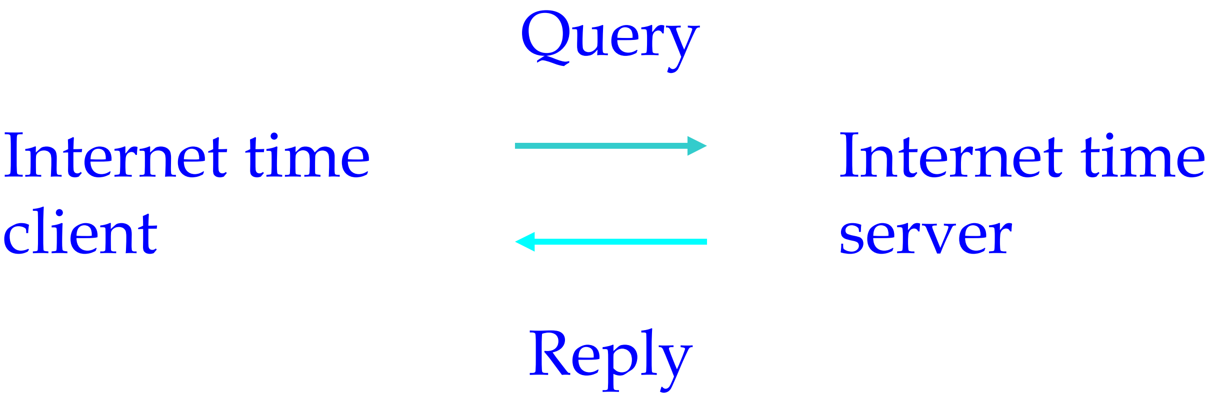
Internet time
client

Internet time
server

Reply

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

Real-world limitations -- 2



Query

Internet time client

Internet time server

Reply

Path dispersion:

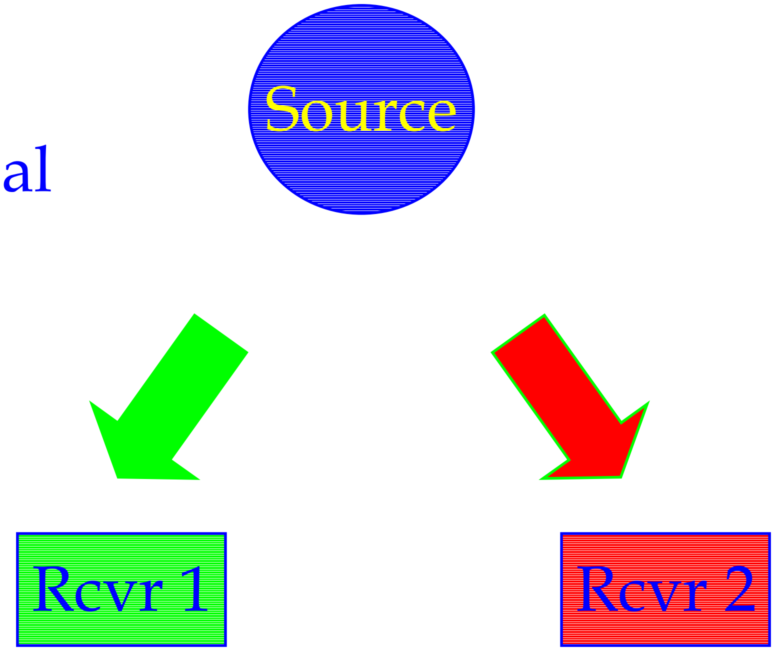
- Physical path are not the same

Time dispersion:

- Messages are not sent at the same time

Common-view method

Path delays
are nearly equal



Source

Rcvr 1

Rcvr 2

T1= t(1) -s

T2= t(2) -s

Δt= T1-T2

Real-world limitations

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

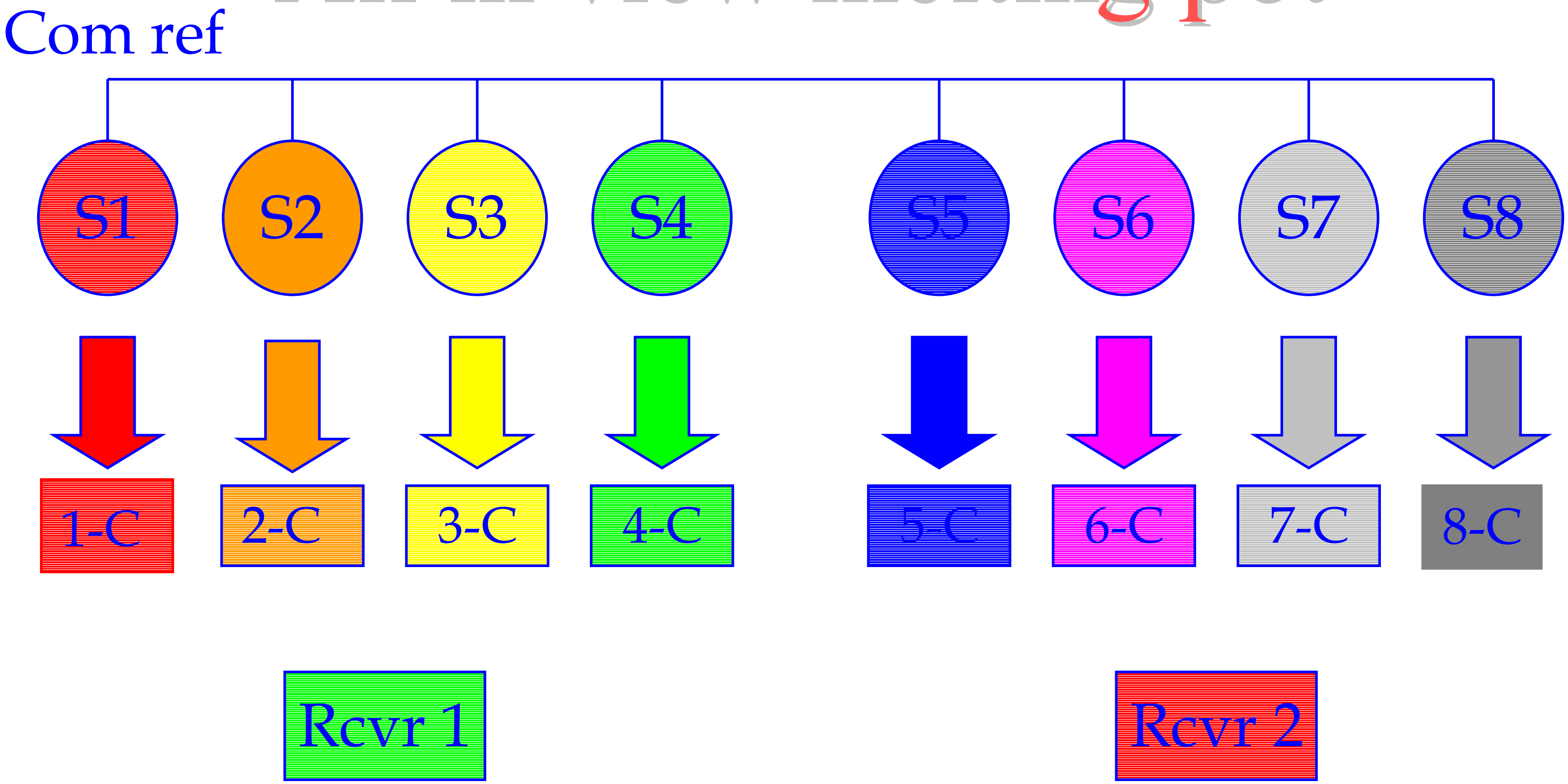
Real-world limitations

- 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



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

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

$\Delta T=\Delta_1-\Delta_2$

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 µs/24 hrs ~ 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, …

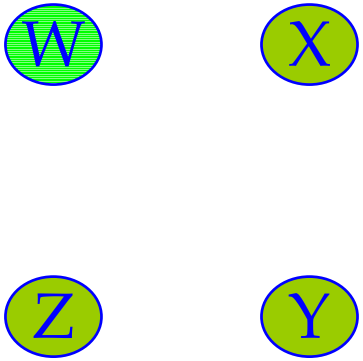
Renaissance of low-frequency

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



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

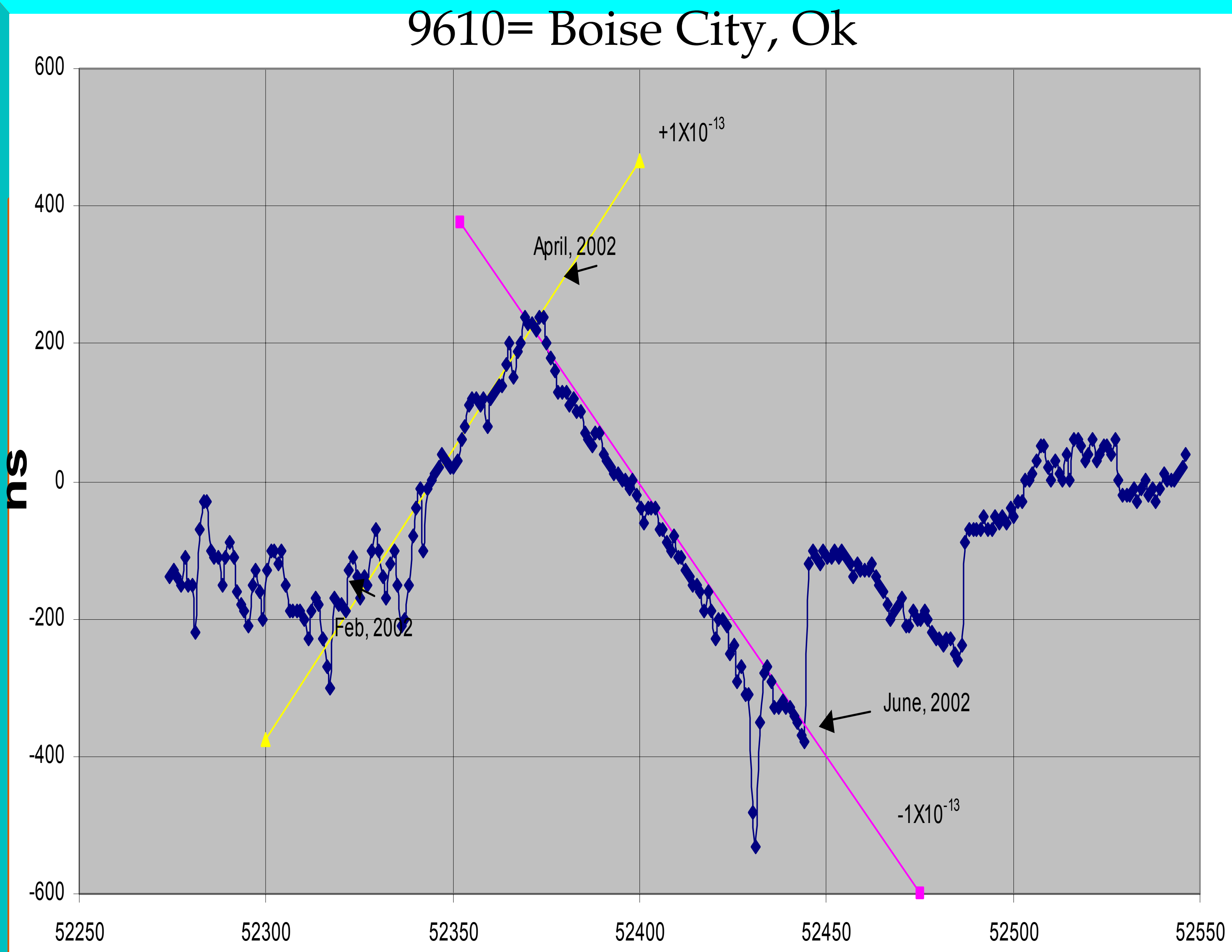
Loran - 3

- 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

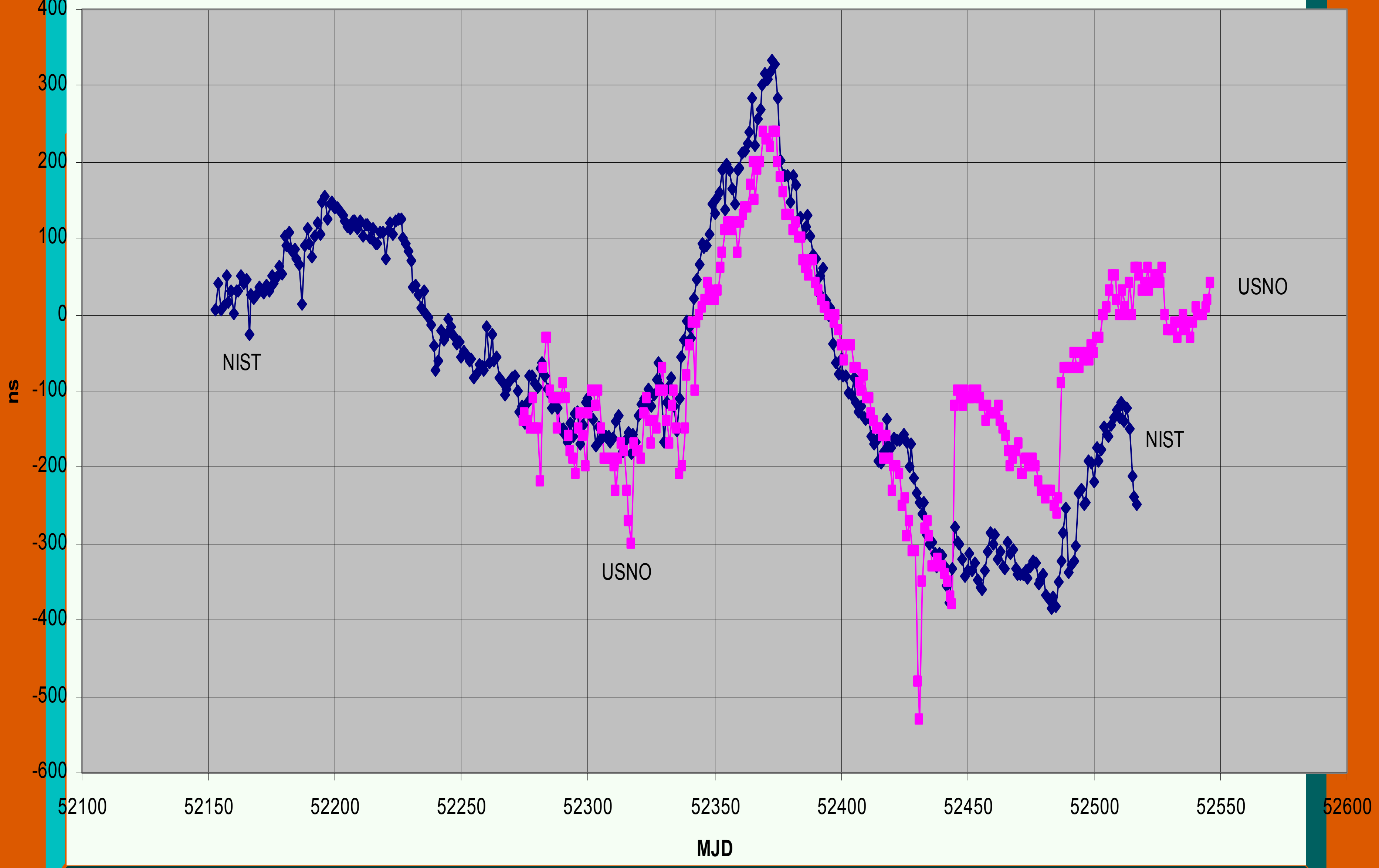
- Pulses “on time” only at a “TOC”
  - Difficult to use for simple time of day
- Observe signals from several chains
  - Use Multiple TOCs (Chain coincidence)
- Often used in common-view
  - Limited by anisotropies in the path delay

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

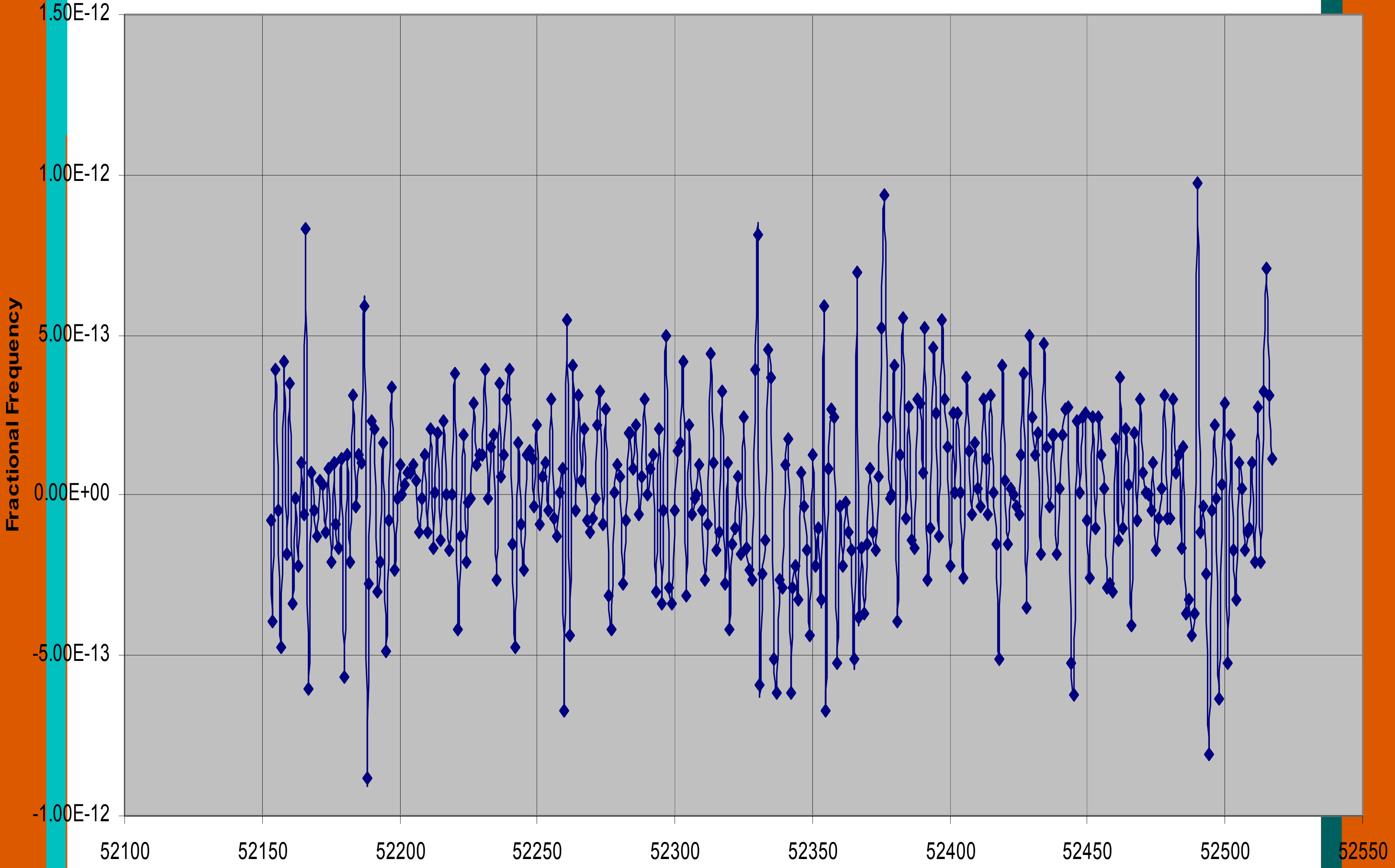


MJD (1 Jan 2002 - 29 Sep 2002)

Loran - NIST & USNO



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



Time from Loran

- Better than 1 μs 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
    - $1X10^{-12}$ 100% of the time
    - $5X10^{-13}$ 90% of the time
  - Supports telecom stratum-1 ($1X10^{-11}$)
    - **Assumes reference clock has adequate holdover stability consistent with 1-day averaging time**
  - Cannot support high-end cesium device
      - $2X10^{-14}$ with 1 day of averaging

Renaissance of Loran

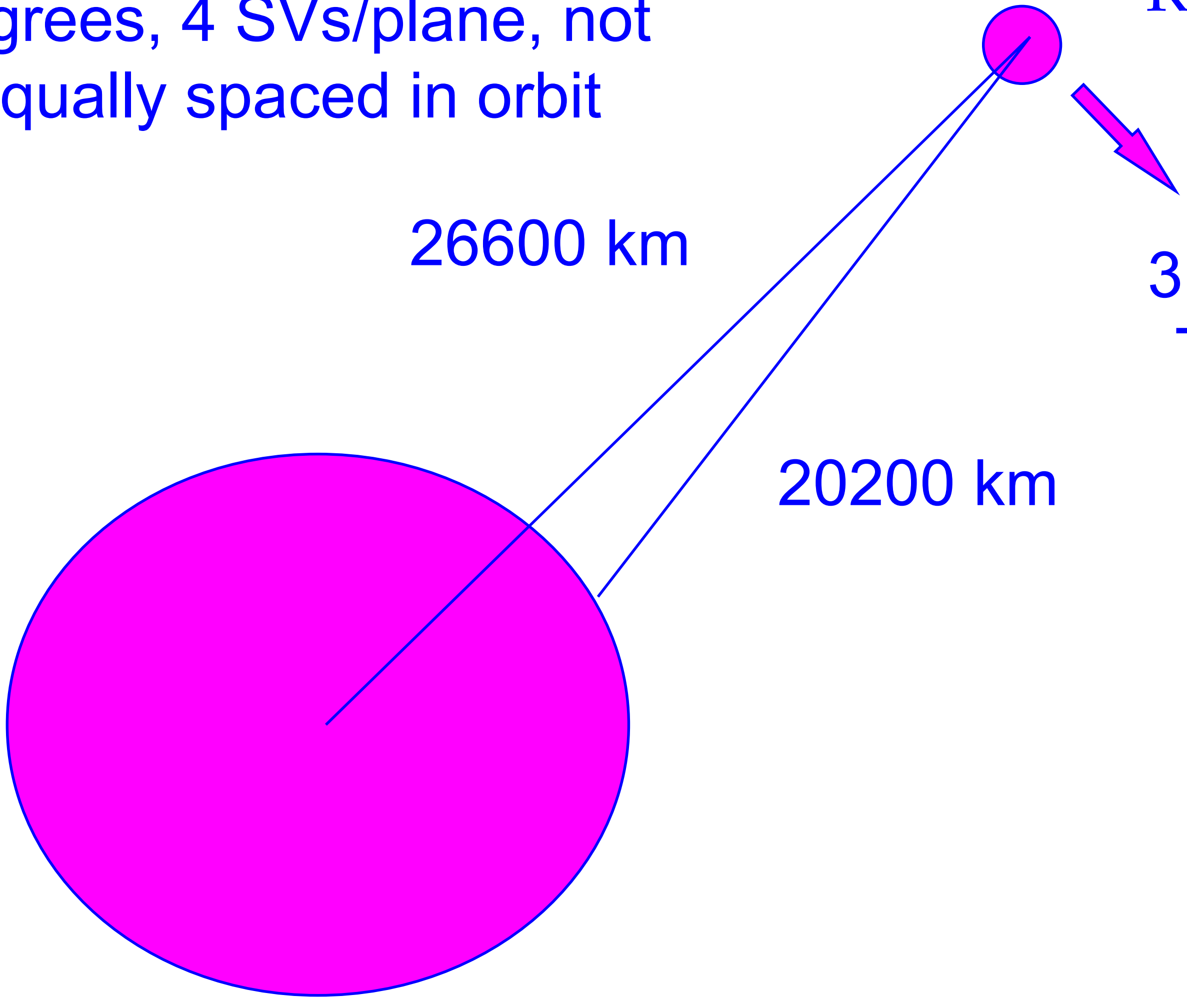
Shut down scheduled several times

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



$R \cong 4.2R_e$

26600 km

3.87 km/s
T=12 hr

20200 km

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)

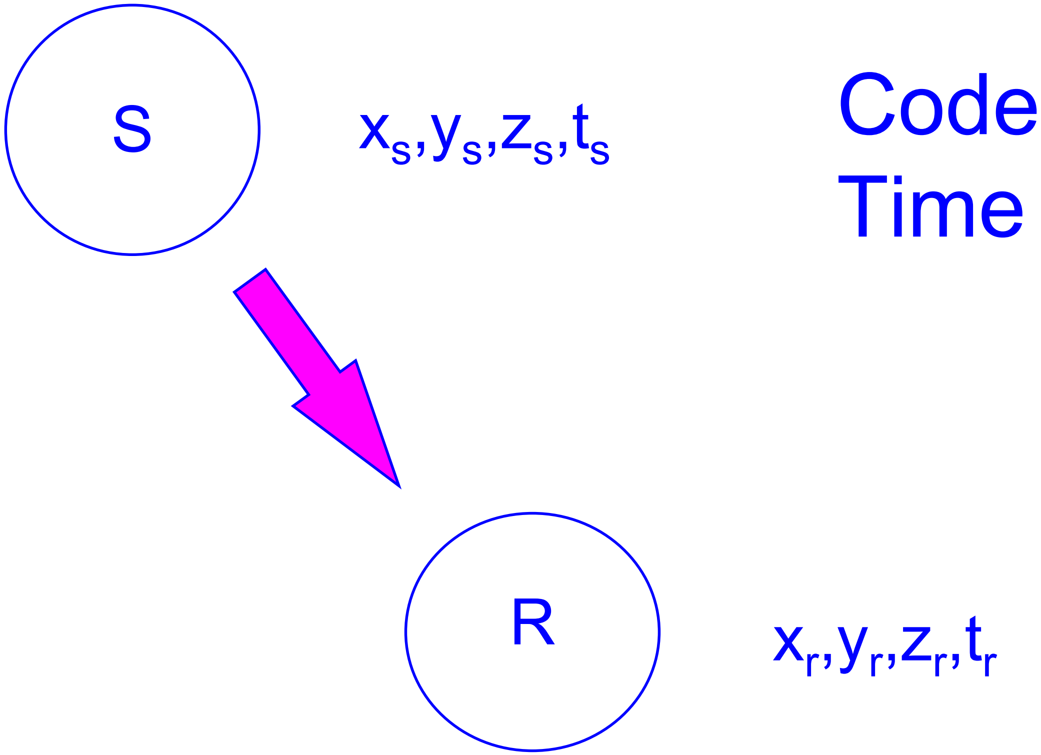
Using the SV Signals

- 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

Code-based Time transfer



S

x_s,y_s,z_s,t_s

R

x_r,y_r,z_r,t_r

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

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:

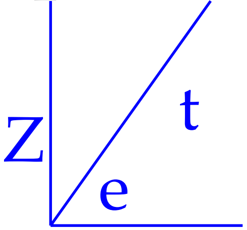
  L1 + C*(L1-L2)= (1+C)*L1 - C*L2

  - 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(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:

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

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

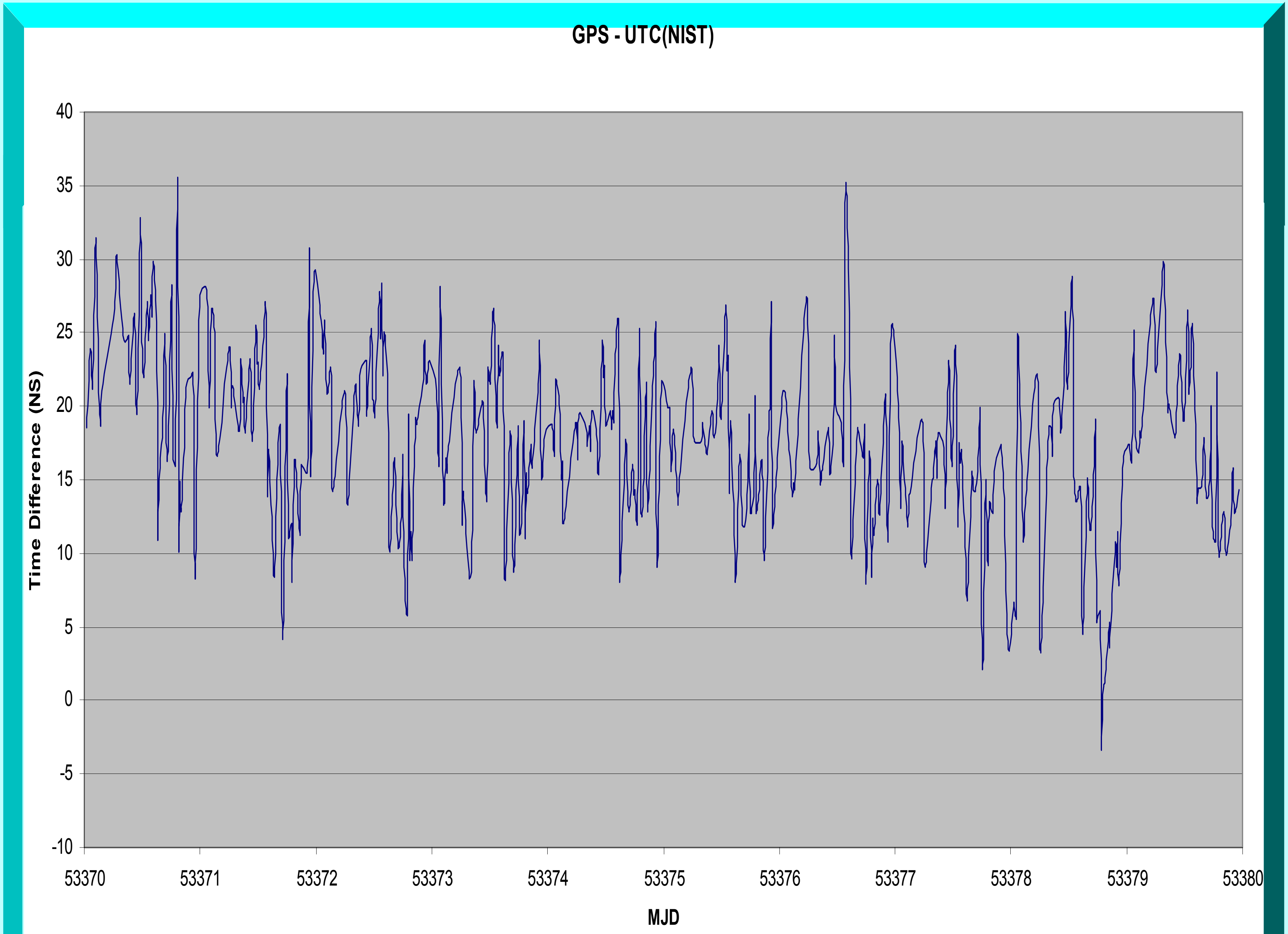
- Use simulator driven from known clock
  - complicated and expensive
  - can test for receiver design problems
- Short-baseline common view using common clock and “standard” receiver
  - differential multipath will not cancel
- Some evidence that methods are ***not*** equivalent

Correction 4: Multipath

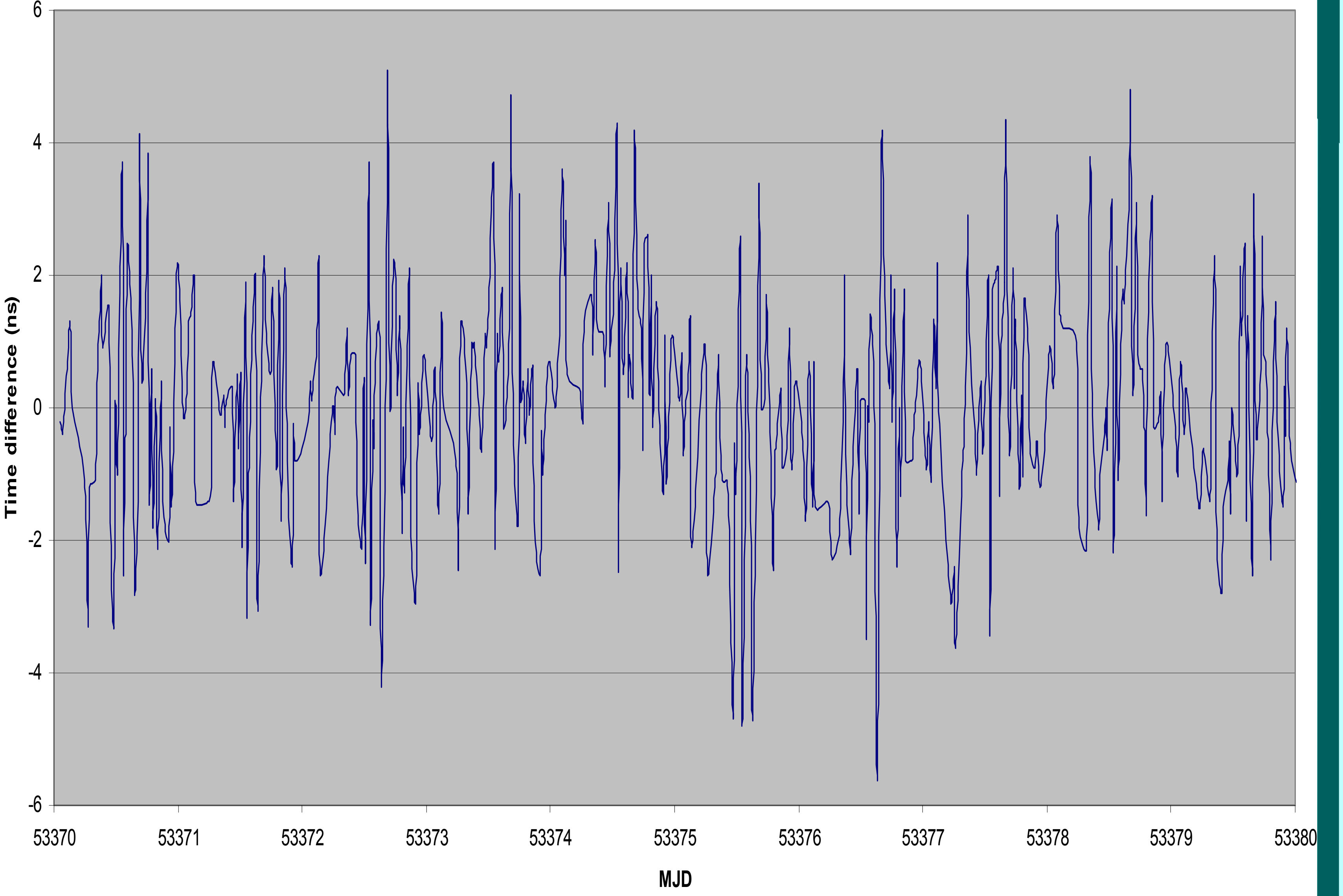
- Reflections from ground and nearby objects
- Reflections at cable connectors, …
- Reflections at impedance mis-match
  - Systematic effect: effective path longer
- Coping with multipath:
  - Ground planes, choke rings, multiple element antennas (electrically steered)
  - Attenuators in cables, antenna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

Code-based timing receivers

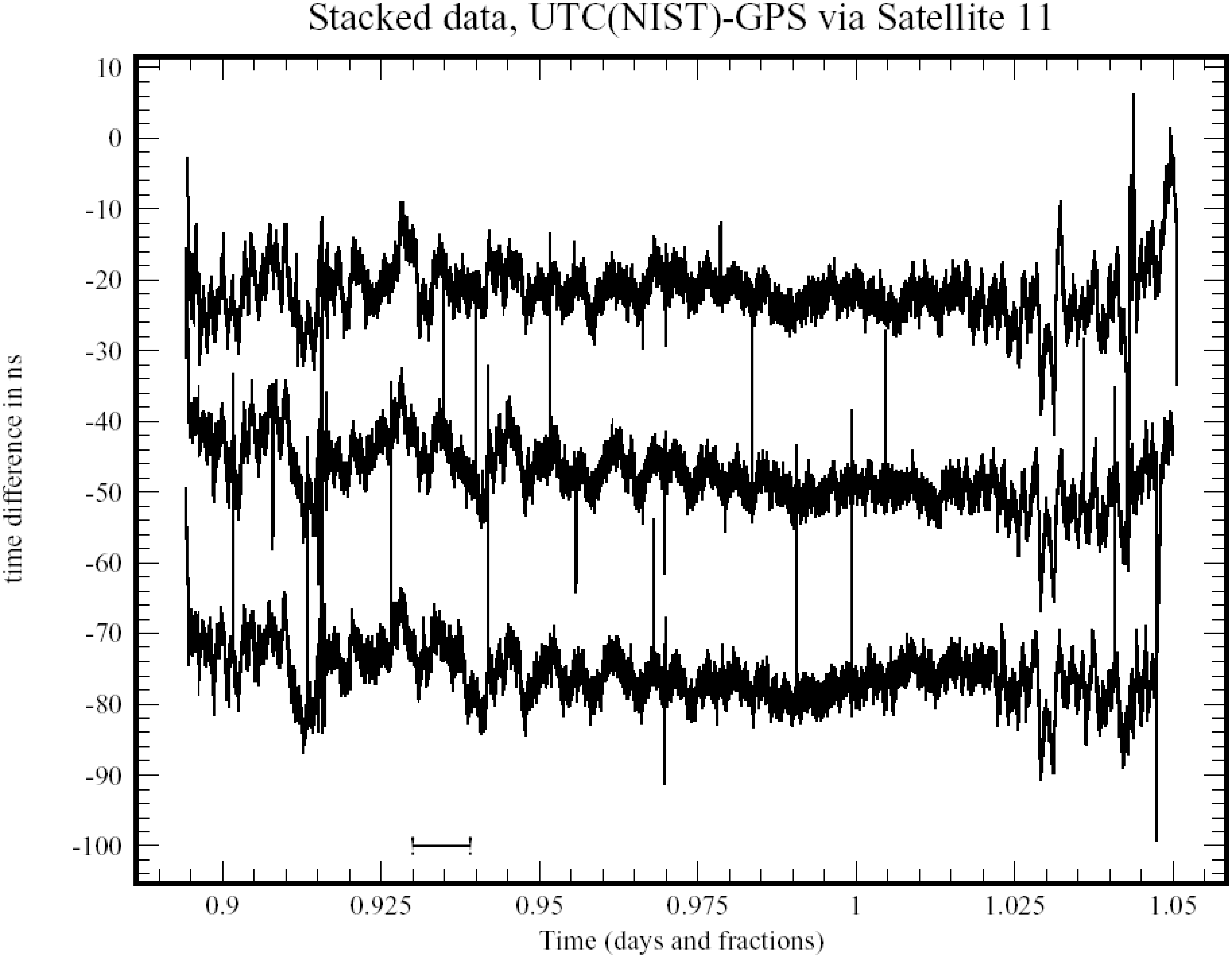
- Single channel “NBS” type
  - Needs a tracking schedule for common view
- 8 or 12 channel receivers designed for timing
  - Pseudorange/time offset of each SV available separately
  - Can implement all-in-view “melting-pot”
- No current receiver is optimum


GPS - UTC(NIST)
Time Difference (NS)
40
35
30
25
20
15
10
5
0
-5
-10
53370
53371
53372
53373
53374
53375
53376
53377
53378
53379
53380
MJD

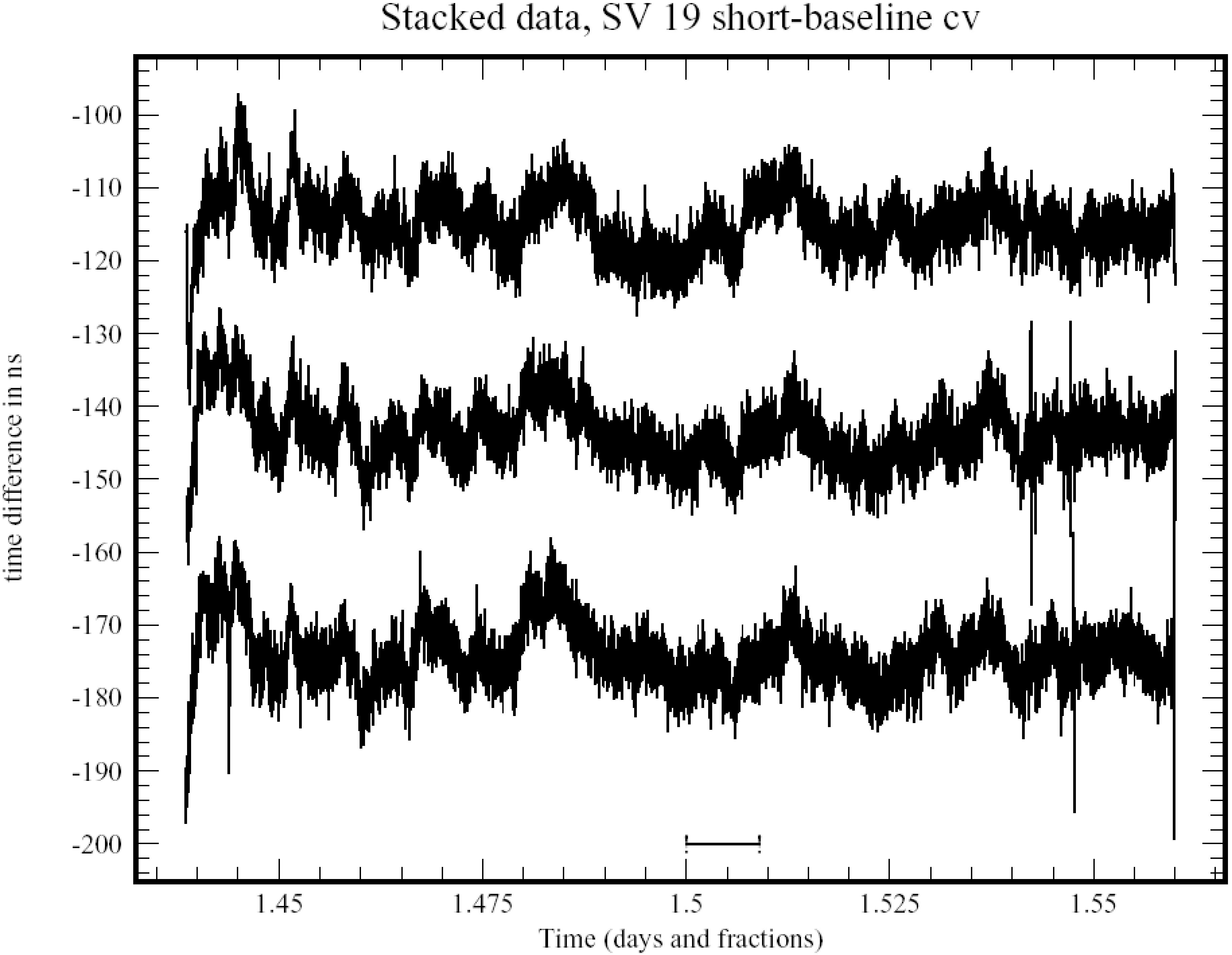
Common View



6
4
2
0
-2
-4
-6
Time difference (ns)
53370
53371
53372
53373
53374
53375
53376
53377
53378
53379
53380
MJD

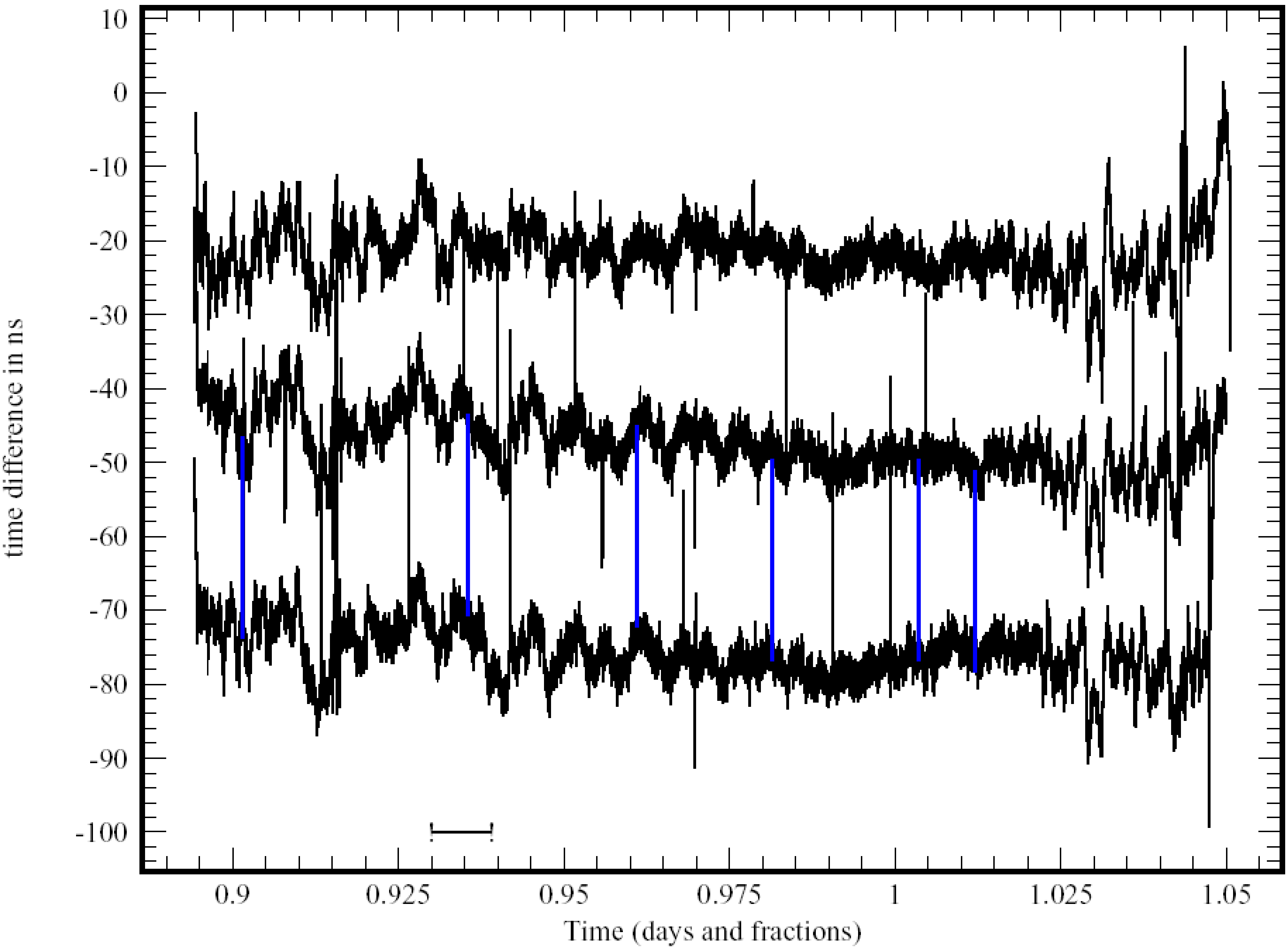


Stacked data, UTC(NIST)-GPS via Satellite 11

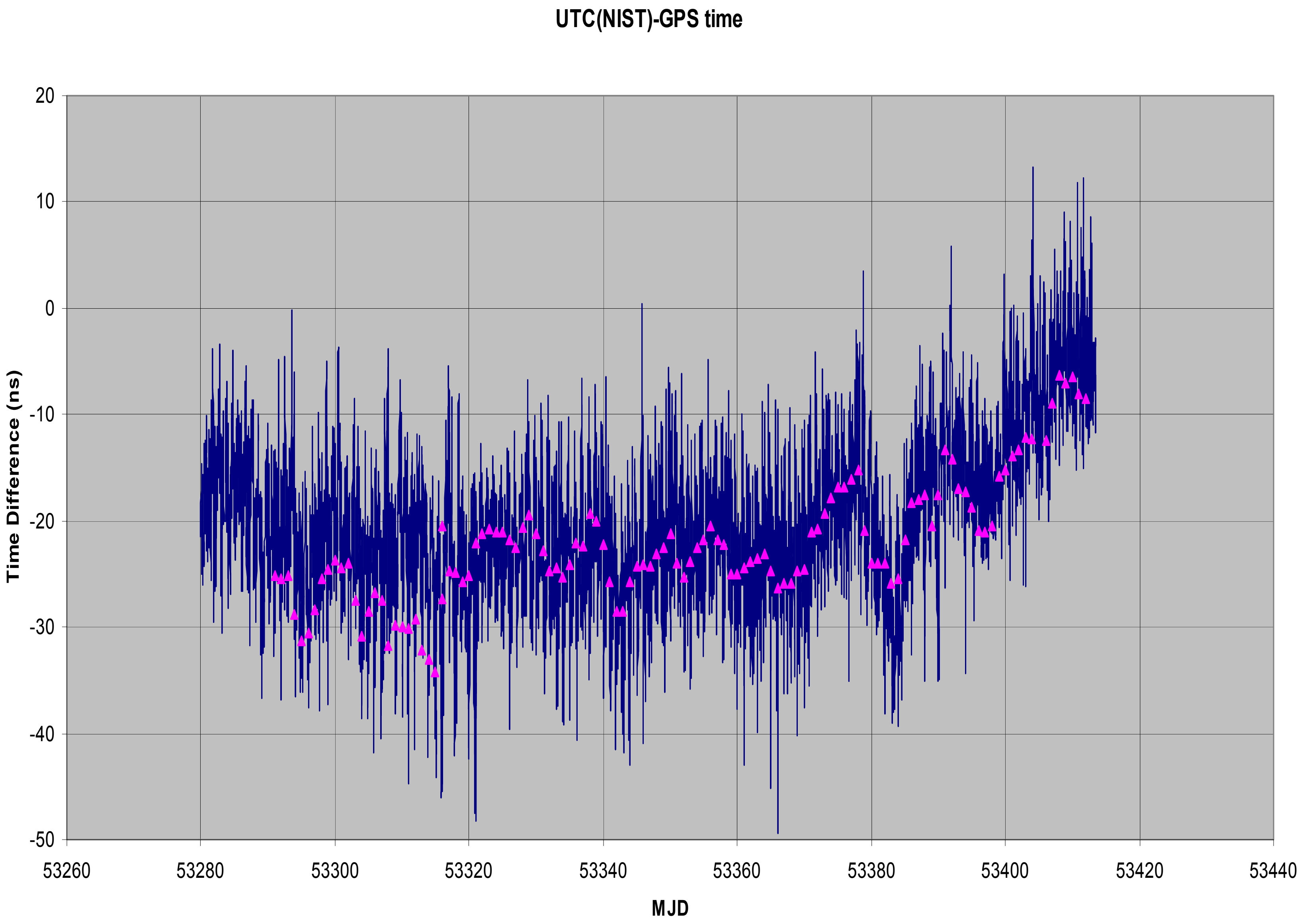

Stacked data, SV 19 short-baseline cv
time difference in ns
-100
-110
-120
-130
-140
-150
-160
-170
-180
-190
-200
1.45
1.475
1.5
1.525
1.55
Time (days and fractions)

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
Time Difference (ns)
20
10
0
-10
-20
-30
-40
-50
53260
53280
53300
53320
53340
53360
53380
53400
53420
53440
MJD

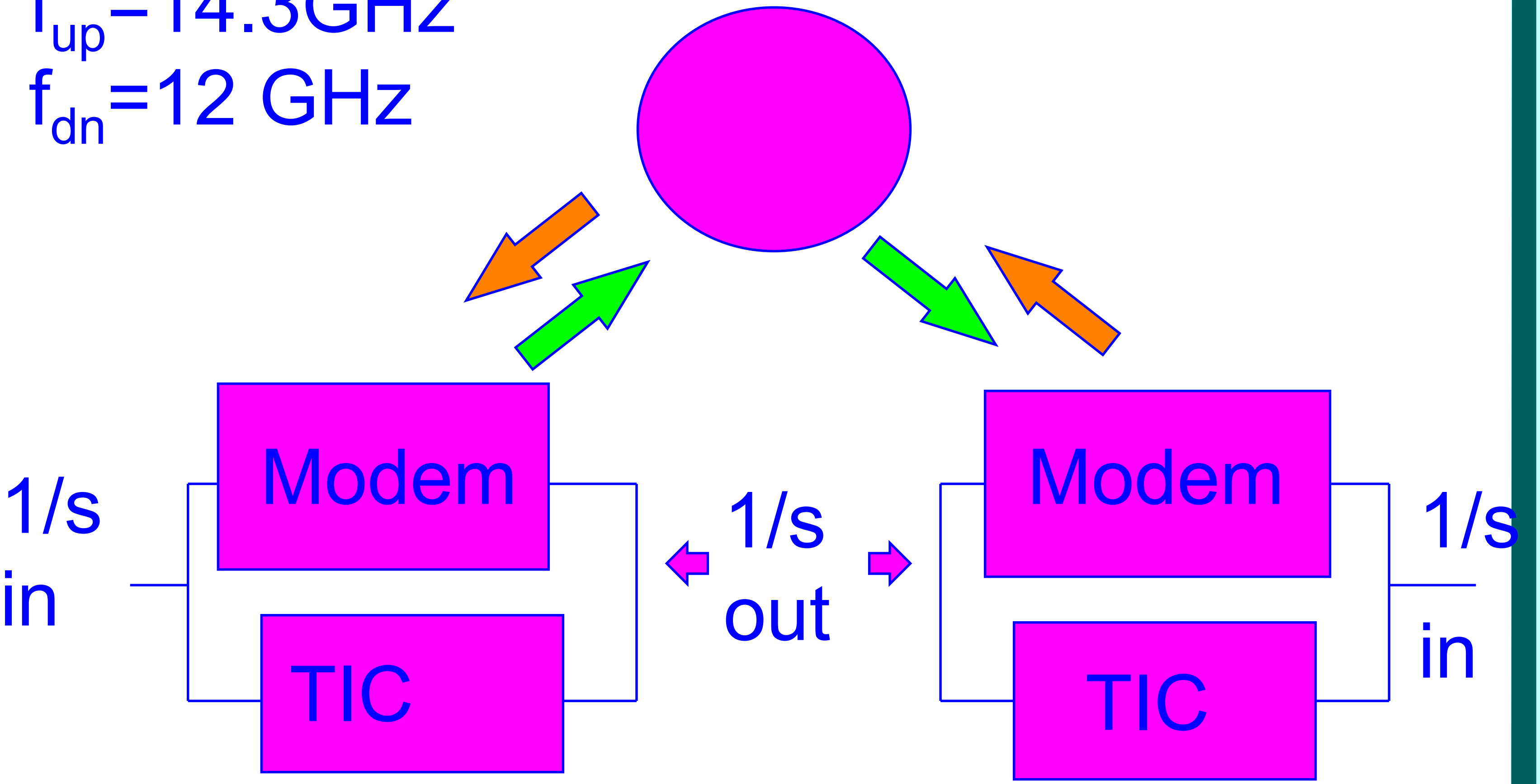
Carrier-phase GPS measurements

- Carrier and code from same oscillator
- Carrier period 1000X smaller that 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_{up}=14.3GHz

f_{dn}=12 GHz



1/s in

Modem

TIC

1/s out

Modem

TIC

1/s in

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

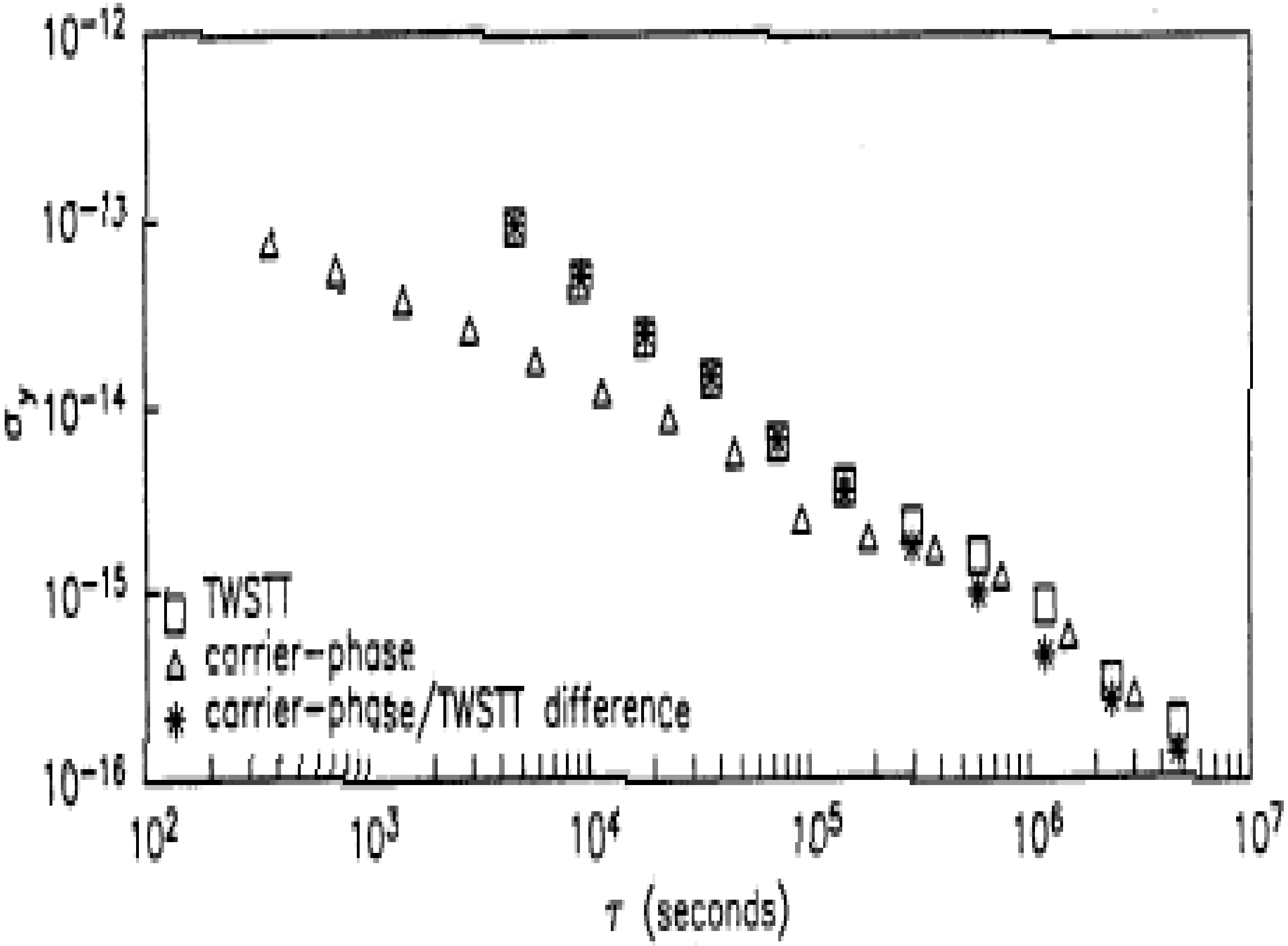
- Satellite time is expensive
- hardware is complicated and expensive, station is active and requires approval
- delays through satellite transponders may vary with time or direction or as different transponders are used
- calibration procedure of ground-station complicated
  - delay is sensitive to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

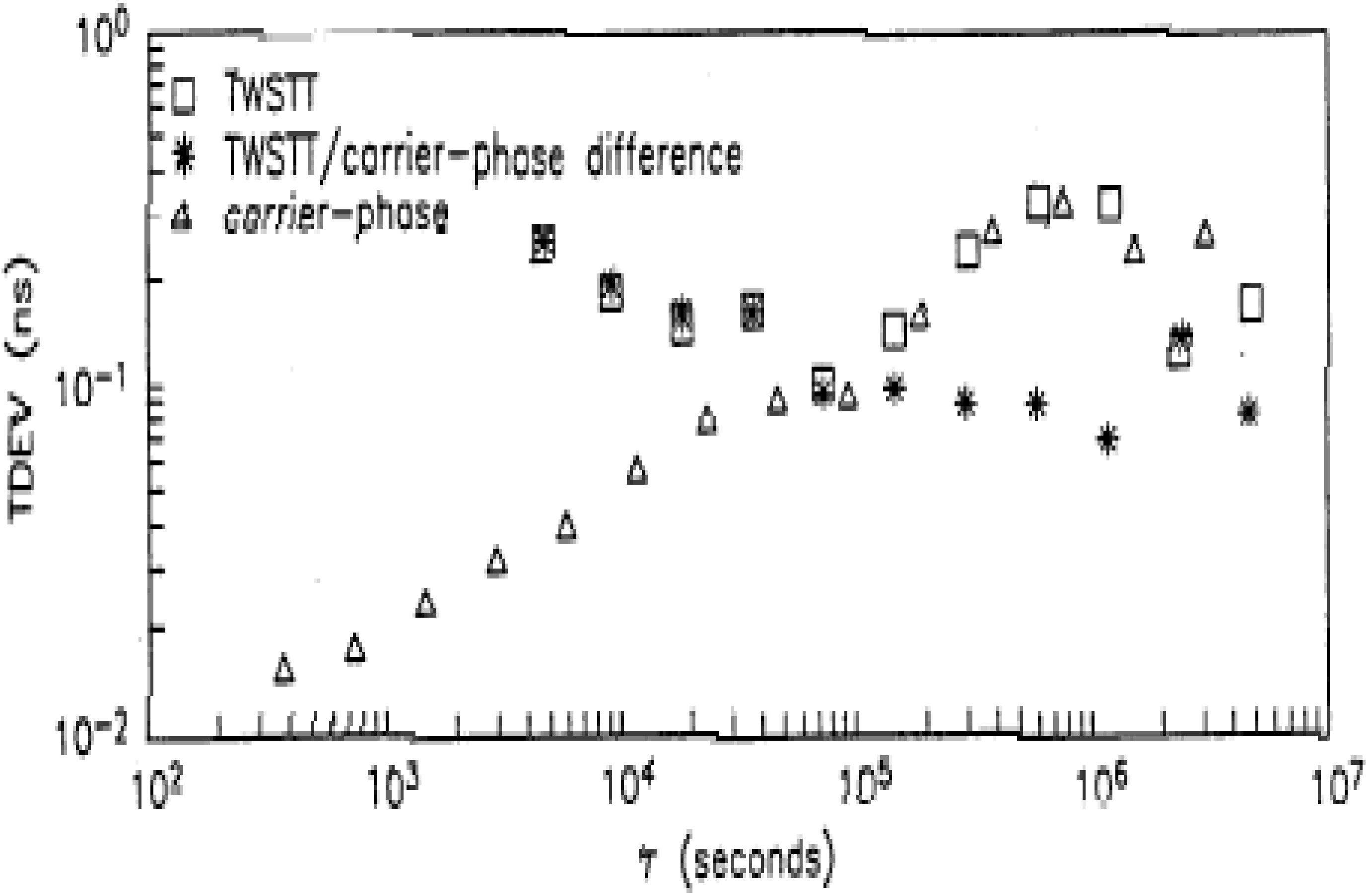
Comparison of C-P and 2-way

- 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


σ_y
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^2
10^3
10^4
10^5
10^6
10^7
τ (seconds)
□ TWSTT
△ carrier-phase
✱ carrier-phase/TWSTT difference



□ TWSTT
✱ TWSTT/carrier-phase difference
△ carrier-phase
TDEV (ns)
10^0
10^-1
10^-2
10^2
10^3
10^4
10^5
10^6
10^7
τ (seconds)

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 ~ 1-2 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.

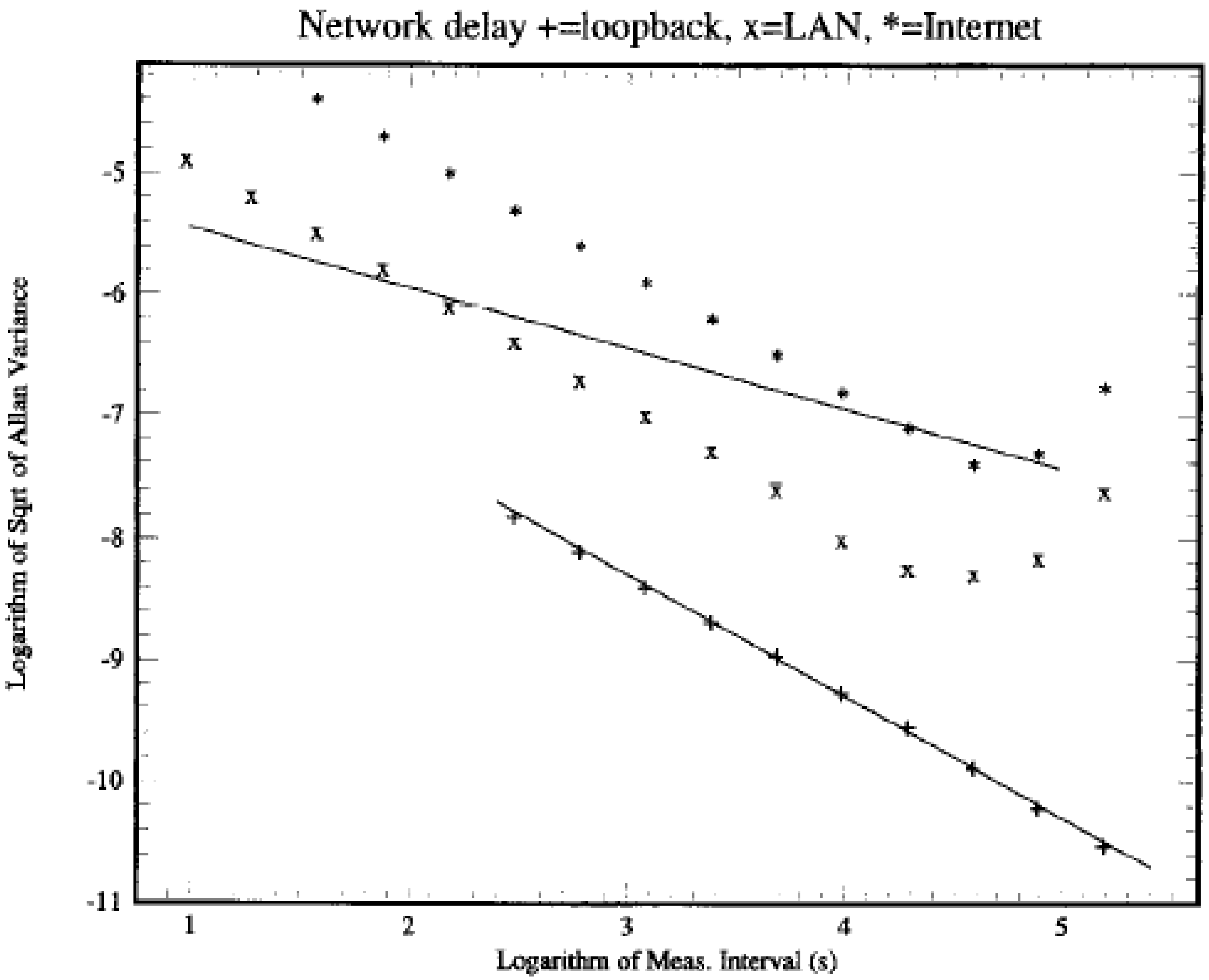
- Protocol can support authentication
  - Not widely used
- Protocol can support notice of and correction for leap seconds
  - Can be used to calculate TAI from transmitted UTC time stamps
- NIST operates 14 independent servers
  - Geographically separated to minimize delay to users and reduce single 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
Logarithm of Sqrt of Allan Variance
-5
-6
-7
-8
-9
-10
-11
1
2
3
4
5
Logarithm of Meas. Interval (s)

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.