Carrier Phase Frequency Biases in Receivers Used for UTC-Generation

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With much help and advice from
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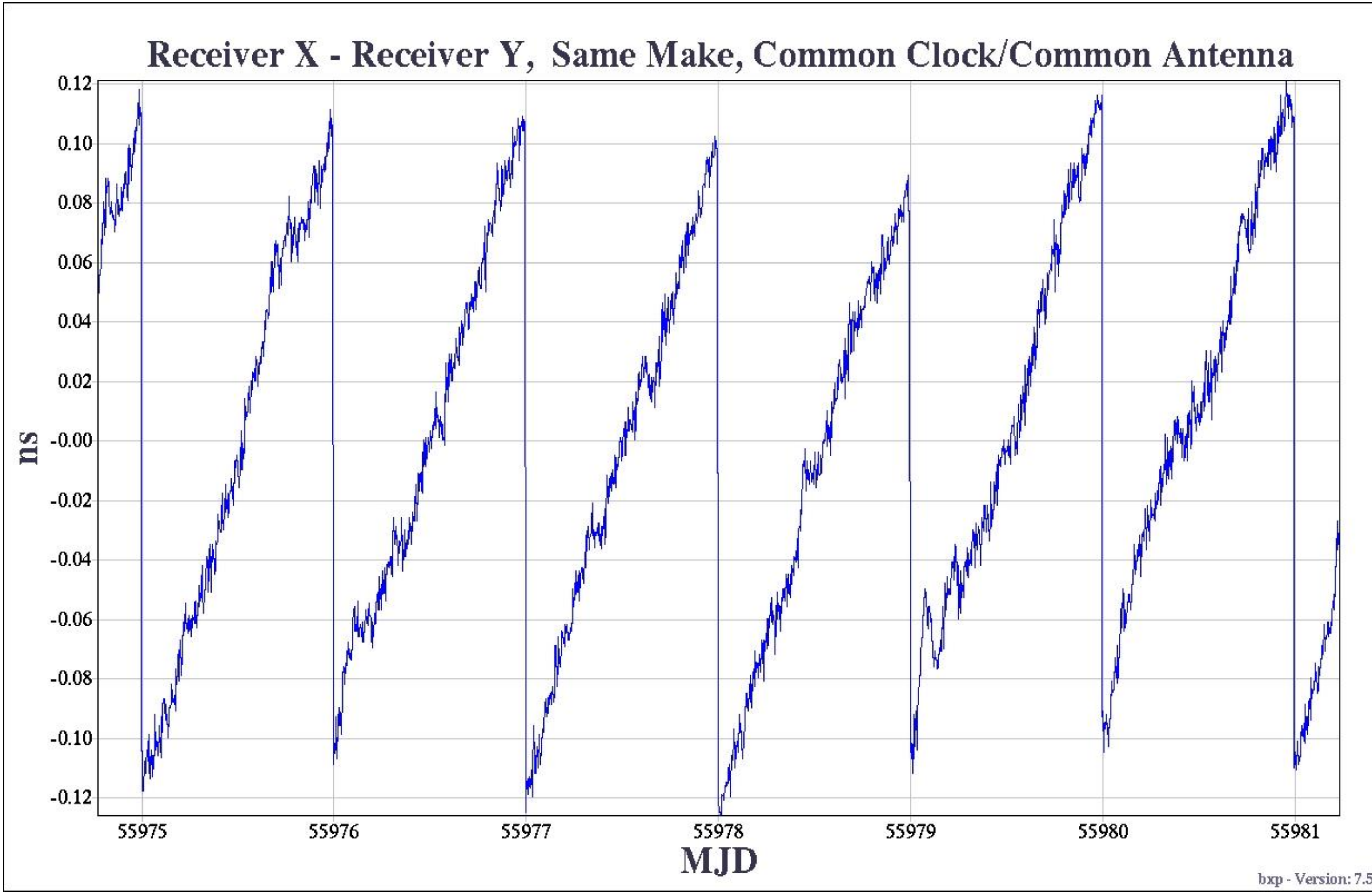
An Old Observation

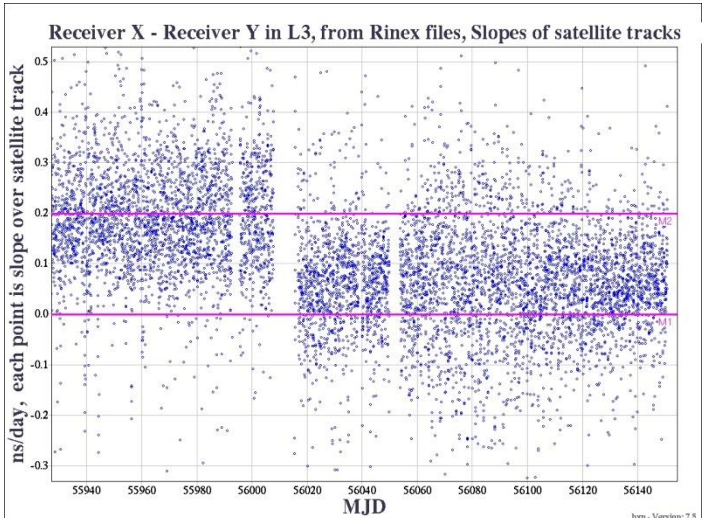


Brief Review

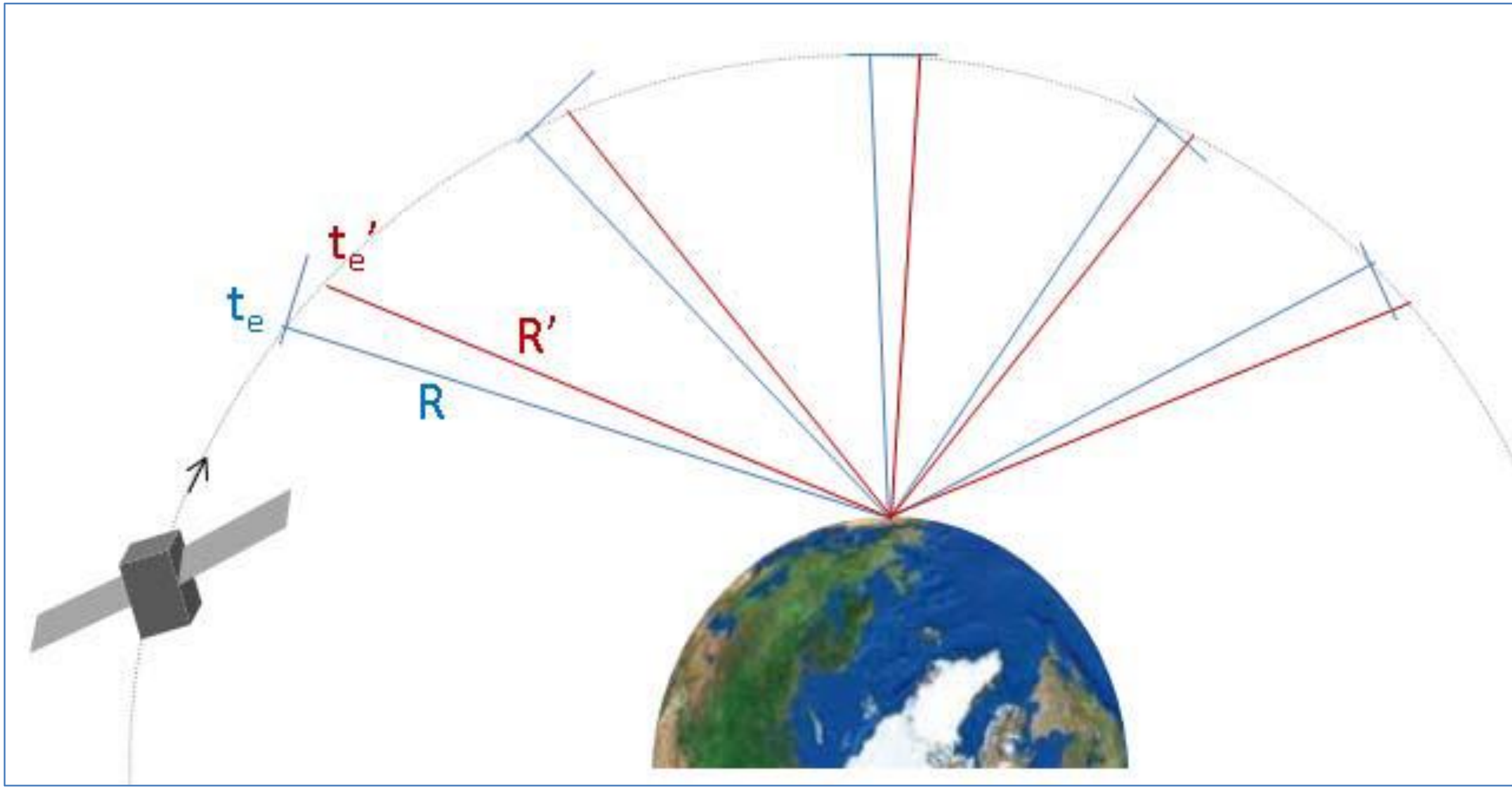
- Phase has >>=10,000 times the weight of code
  - Code = pseudorange
  - Phase = phase of carrier
- Phase dominates over code for all but time
  - phase determines the frequency too
- Code sets the constant of integration of frequency
  - Which is the time
  - Ambiguity parameters relate code and phase
- Day-boundary jumps caused by noise and systematics of the code
  - See for example Matsakis, Senior, and Cook PTTI-01

Explanation: code and phase disagree
there is a slope difference

- For RINEX data from each satellite track
  - Generate difference between receivers for L1 and L2
    - Ionosphere, orbits, clocks, multipath, etc. drop out
  - Average L1 and L2 to create L3
    - Found L1 and L2 gave same story individually
  - Fit to offset and slope of L3, for each completed satellite track
    - Offsets related to ambiguities and biases
    - Slopes ought to average to zero
    - They do not
  - See Marc Weiss, PTTI-12
    - And Rolf Dach too



One reason for code-phase disagreement

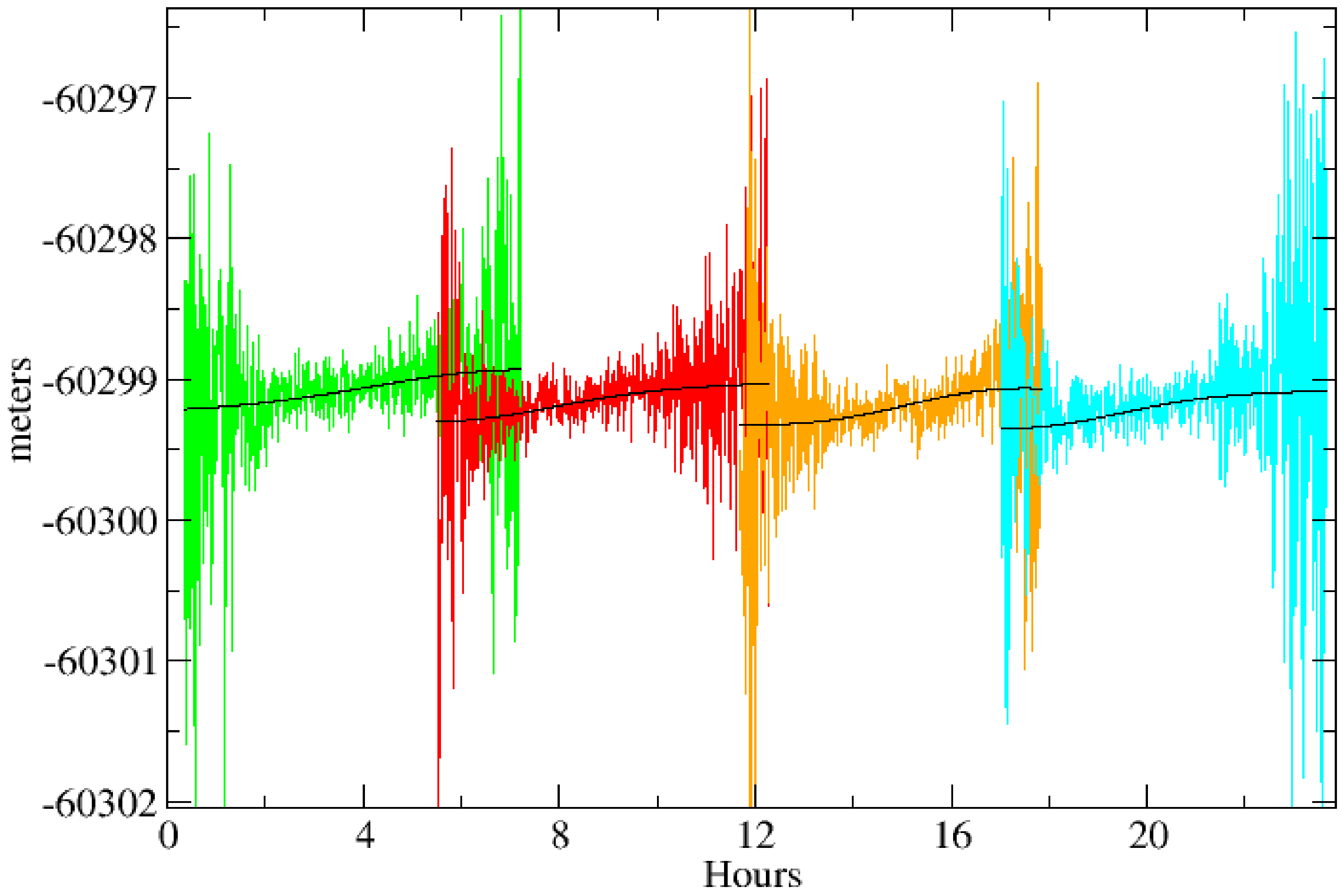


Code and phase data with same timetag may have different emission times

See Pascale Defraigne and Jean-Marie Sleewaegen,

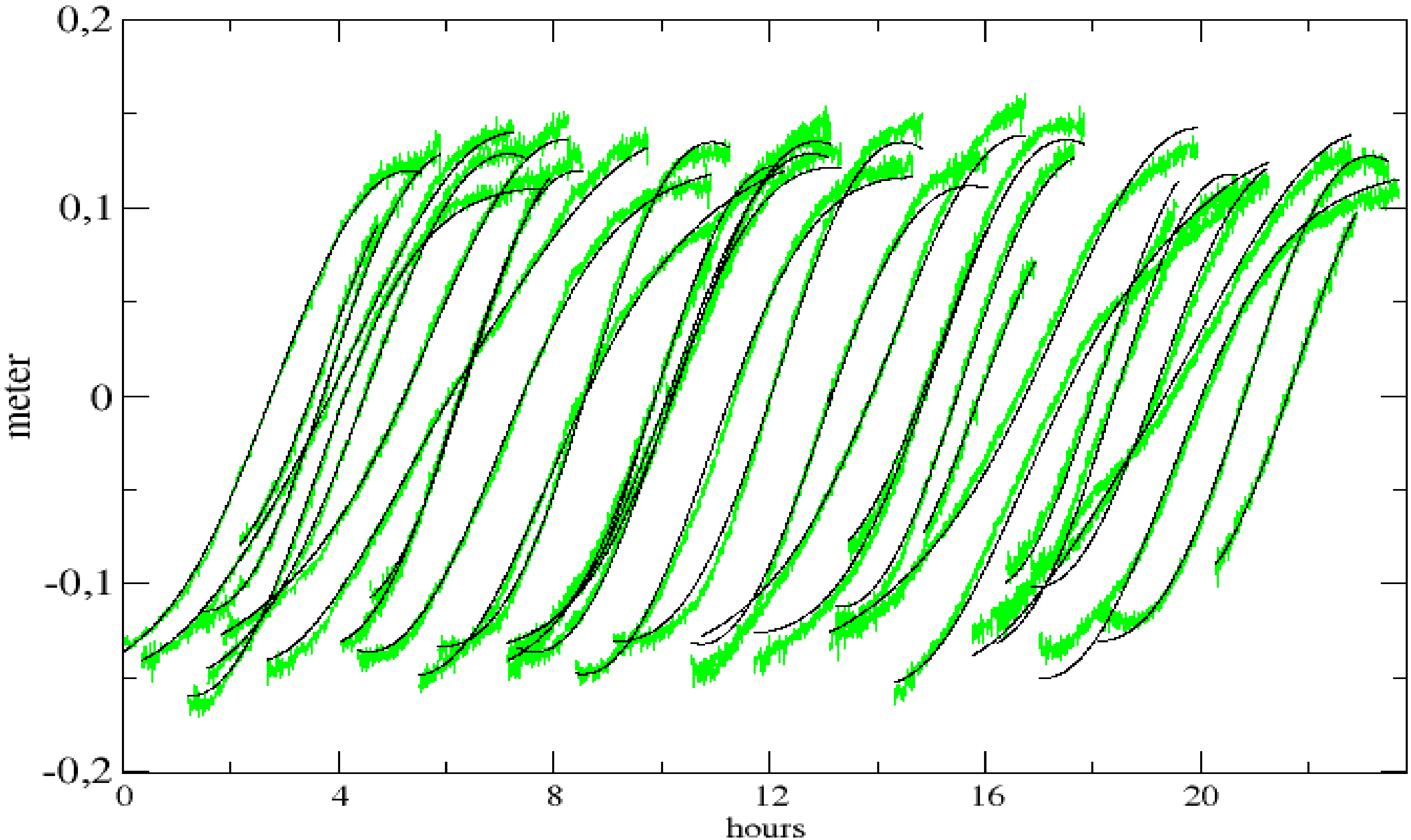
"Correction for Code-Phase Clock Bias in PPP", Proceedings of 2015 EFTF/IFCS

Common-clock Common Antenna *Code* differences due to 201 microsecond latching offset (error)



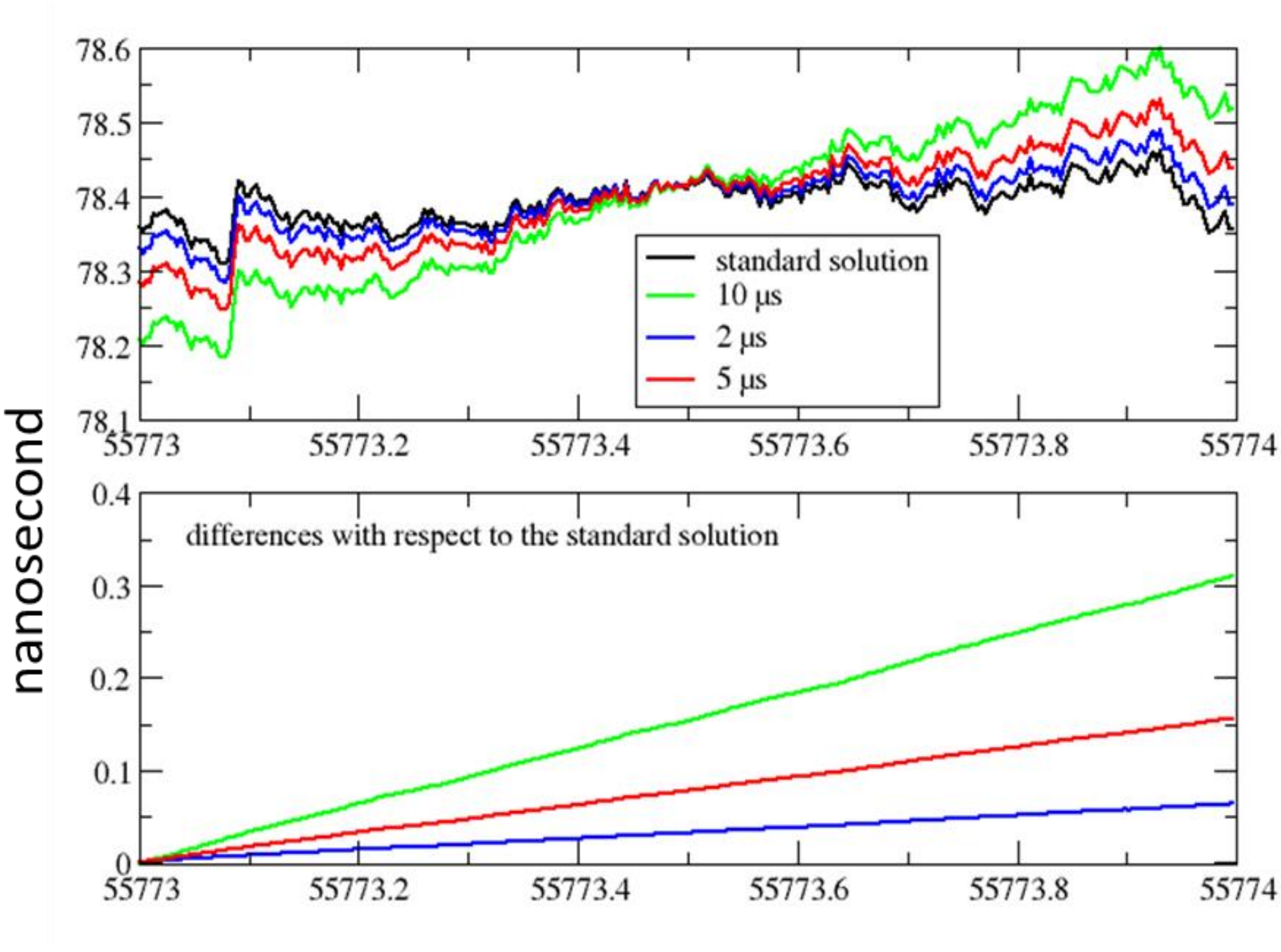
Colors indicate individual satellites

Common-clock Common Antenna *Phase* differences due to 201 microsecond latching offset (error)

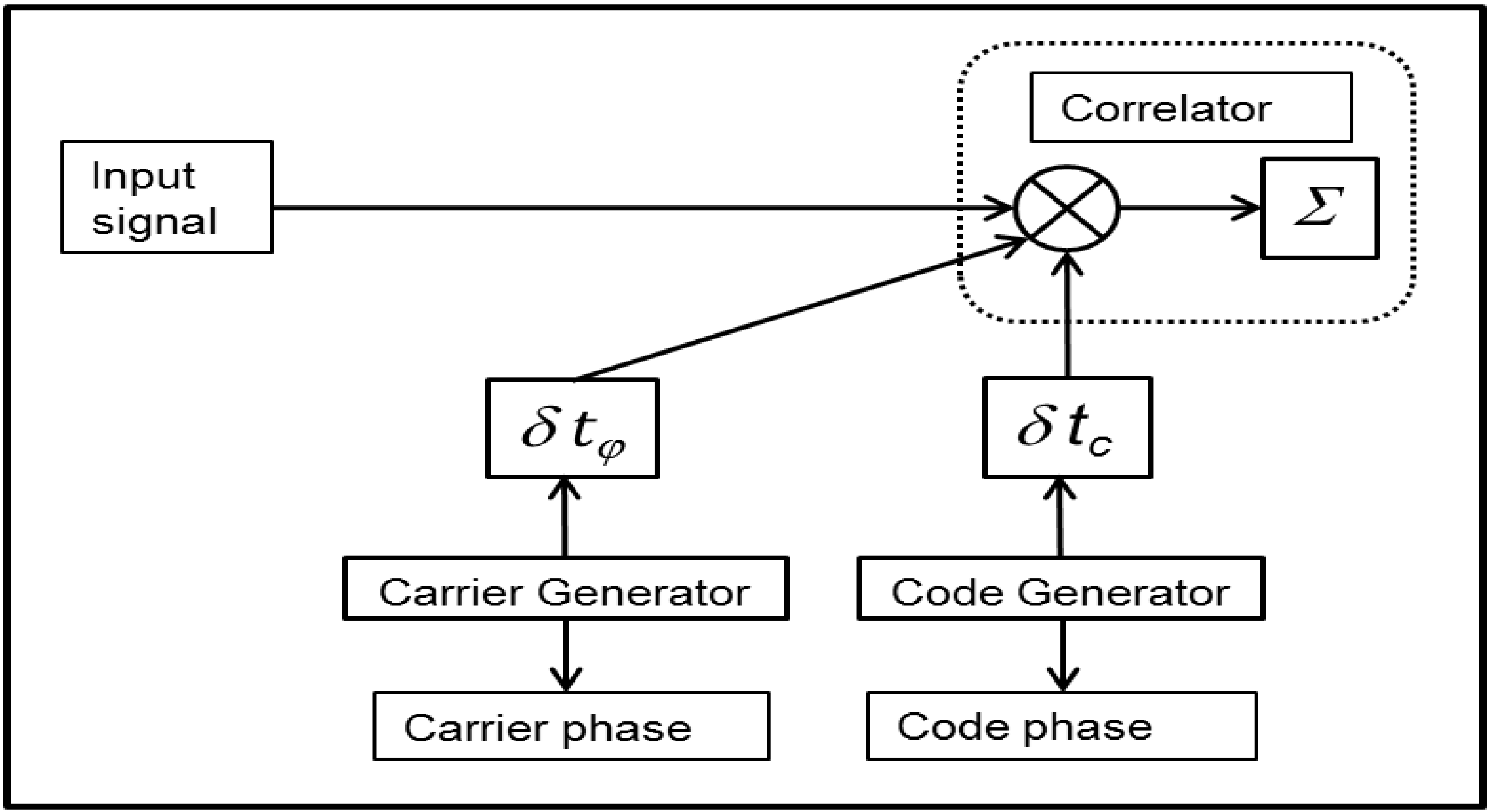


Green = observed, black = modelled

Simulated Impact of Latching Time Offset Between Code and Phase



Receiver internal delays also relevant



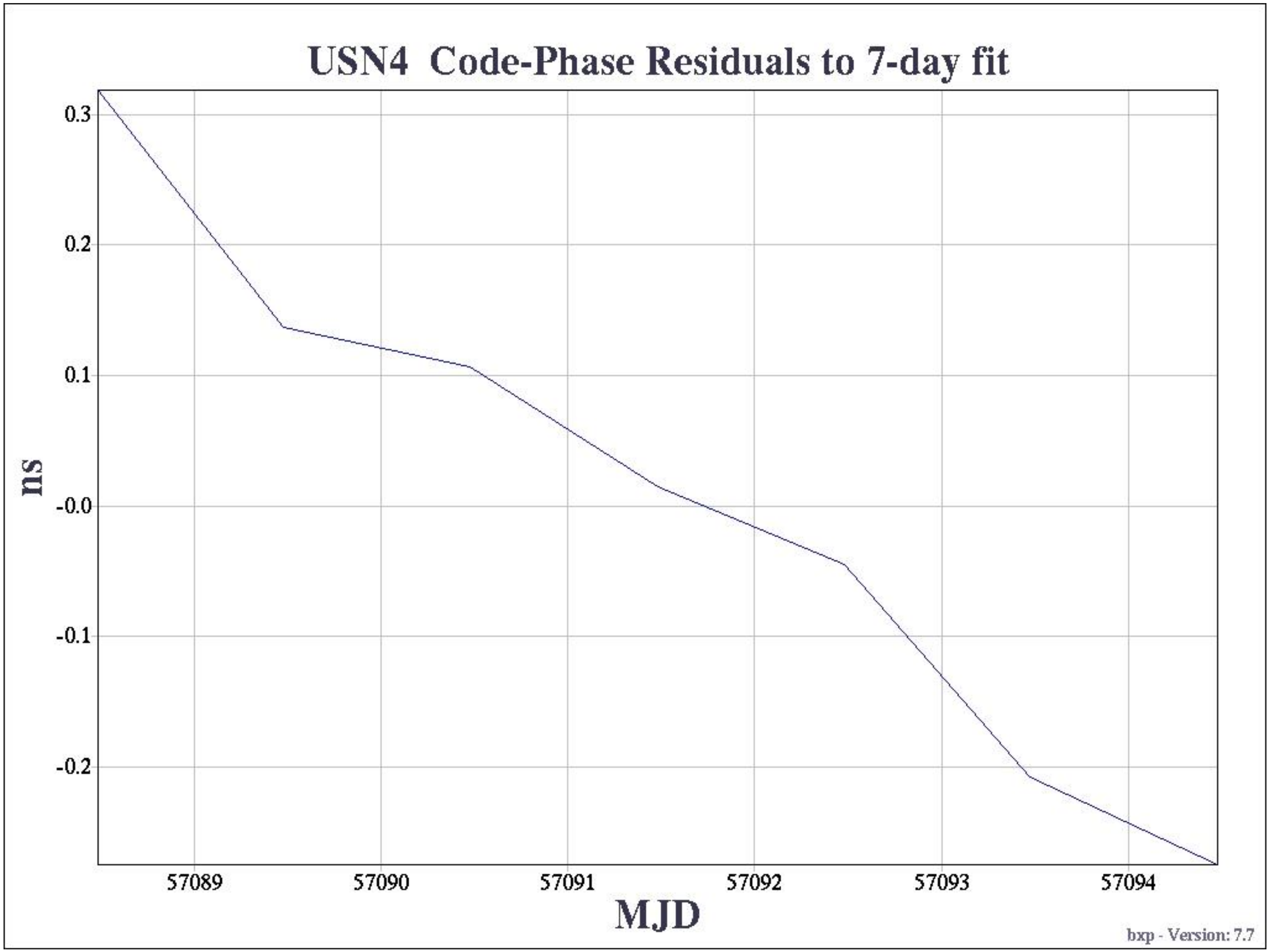
Summary for Receiver Design

- Receivers give carrier phase and code data same timetag
- Delays inside the receiver circuitry can cause constant offset in “latching times”
  - The carrier frequency is Doppler shifted to higher values when the satellite is rising
  - The carrier frequency is Doppler shifted to lower values when the satellite is setting
- A too-large latching time offset can therefore result in a systematic frequency difference
- It can be up to a few 100 ‘s ps/day
  - Though often much less
- Receivers can be designed with smaller latching time offsets
  - **1 μsec latching time offset can cause 30 ps/day frequency error**
- See Matsakis et. al. ION-PNT, 2015 and Defraigne et al., IFCS/EFTF 2015
- See also article in prep for Inside GNSS
  - Hopefully NovDec 2015 issue

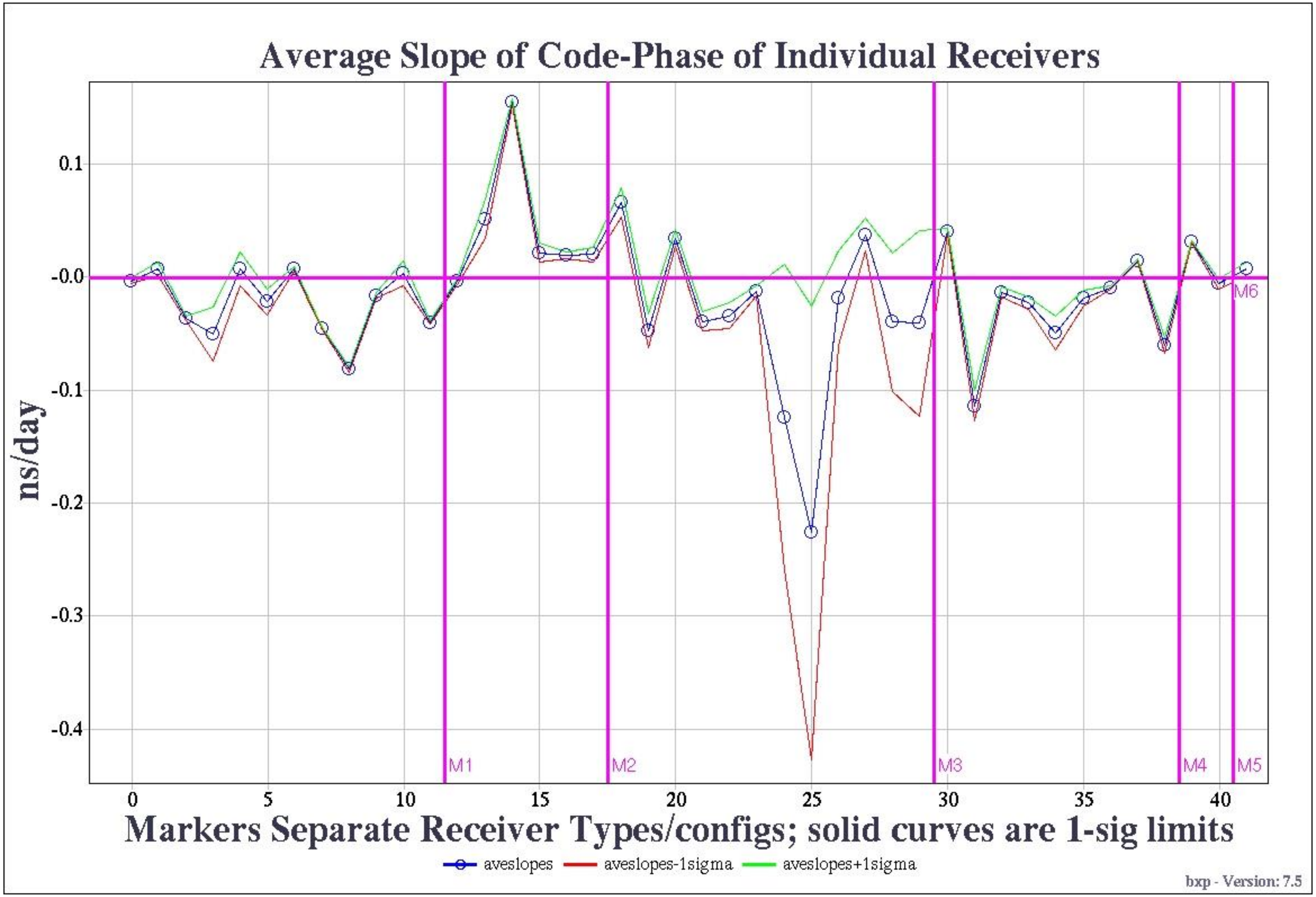
Extending the code-phase approach

1. Treat each receiver completely separately
2. Generate multiday PPP solution
3. Subtract phase residual from code residual
   - Orbits, clocks, first-order ionosphere, etc. drop out
   - Phase-Wind must be removed (NRCan's PPP does it)
4. Use only completed satellite tracks
5. A fit to offset and slope, per track, is too noisy
   - (Although OK in common clock, common antenna)
6. Observe the slope of code-phase over the entire solution
   - Non-zero slope = PROBLEM

From receiver USN4 (data are given to MGEX)

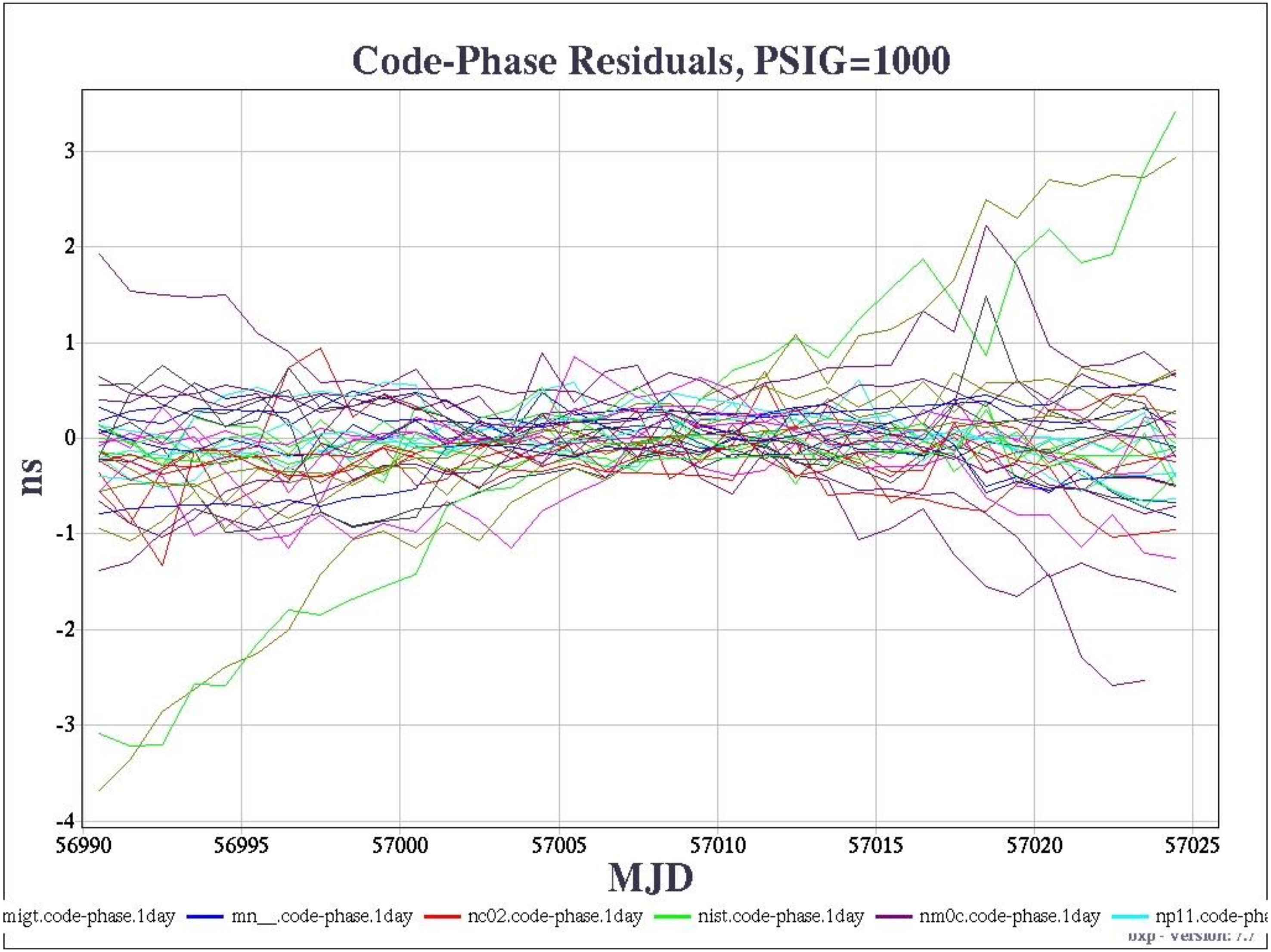


From all USNO's internal 7-day reductions



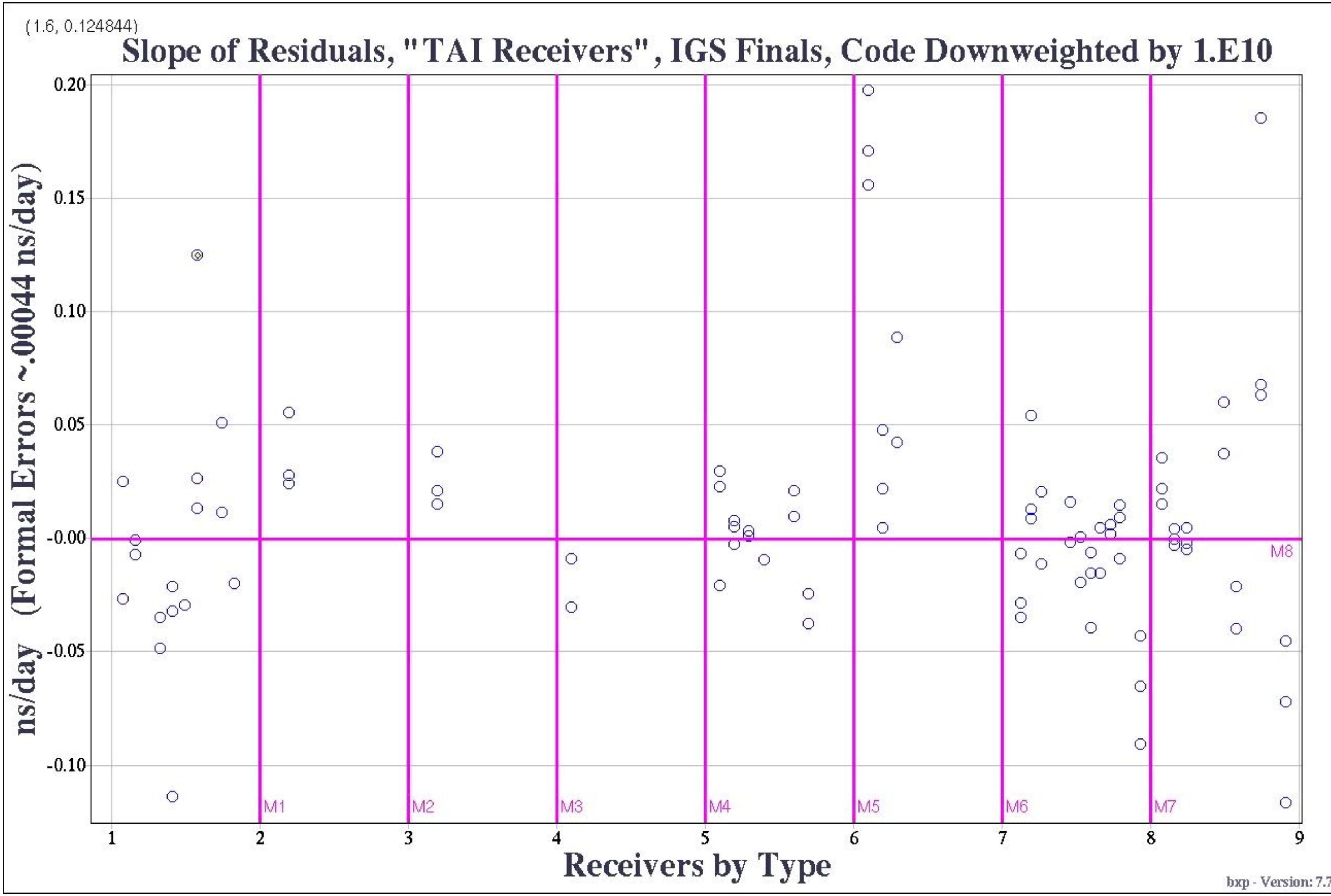
Code-Phase Residuals for Dec 2014

Phase/Code Weight Ratio = 10 billion = $(1000/.01)^2$



Reductions and advice provided by W. Wu (NTSC) and Z. Jiang (BIPM)

Frequency biases in receivers reporting to BIPM (Oct-Dec 2014)

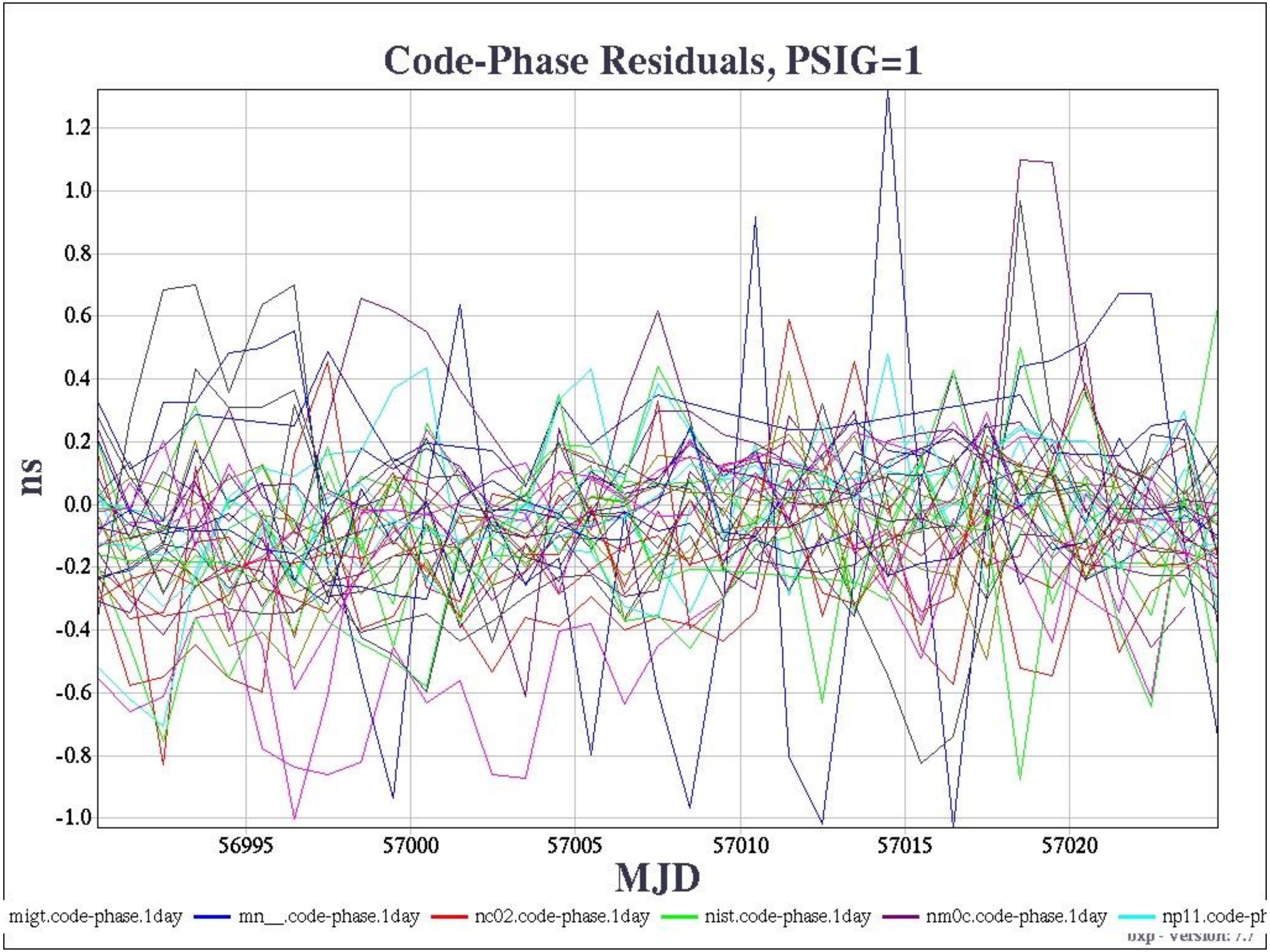


Why BIPM’s Reductions Not Affected

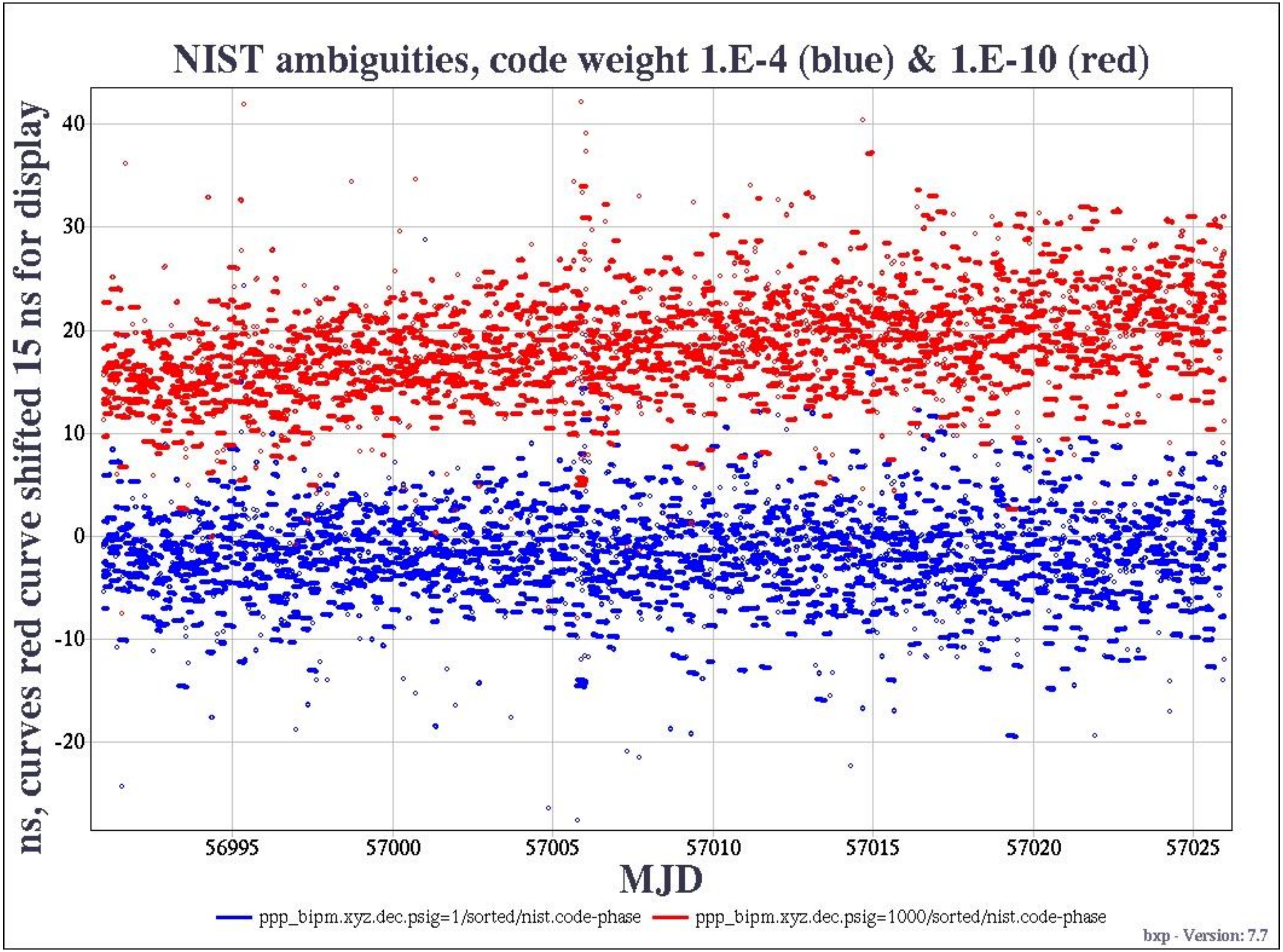
- BIPM does not downweight code by amount used to create previous slide (10 billion)
- BIPM downweights by 10,000
  - Because they found it works better
  - We think that’s due to floating ambiguities

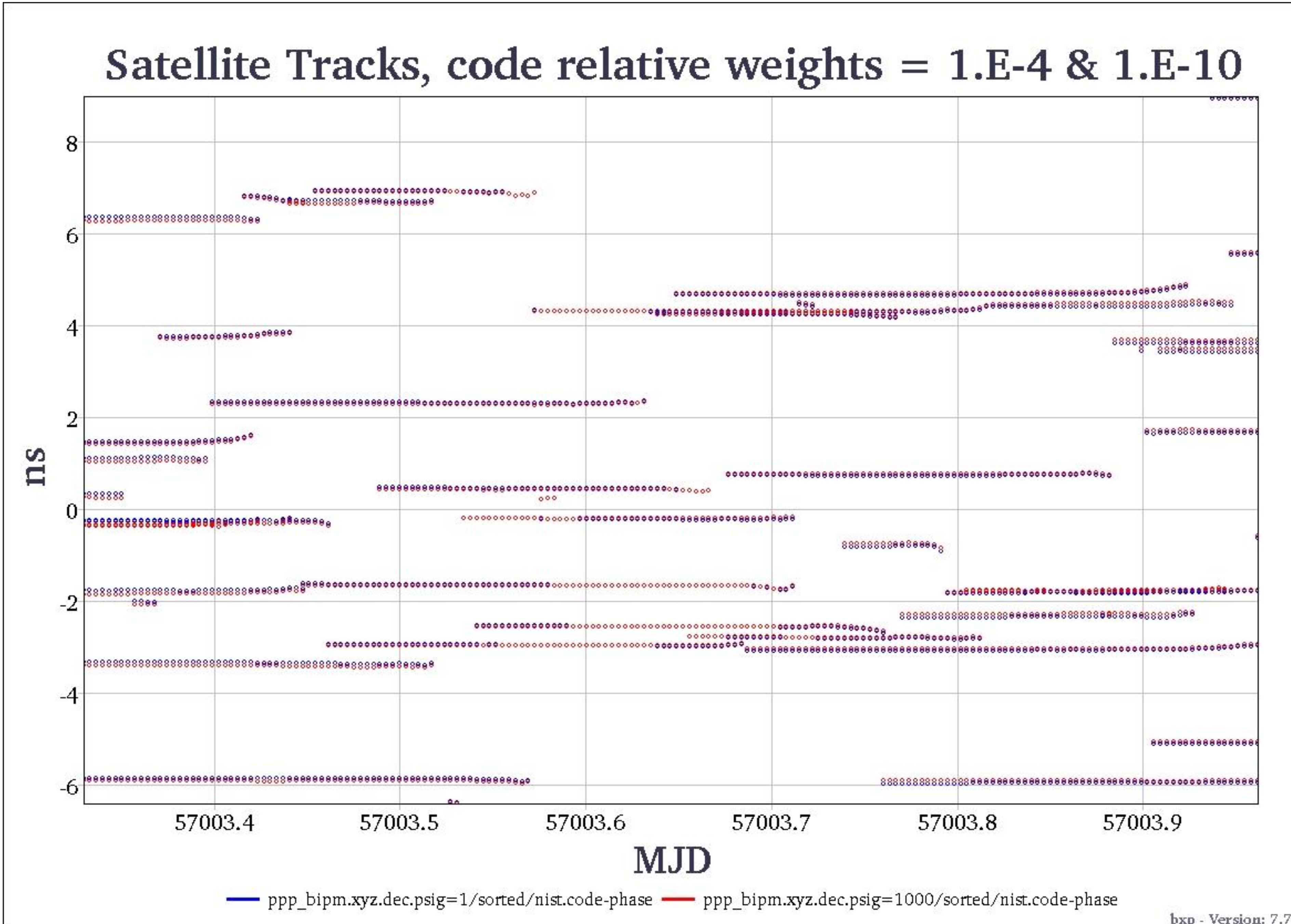
Dec 2014 Code-Phase Residuals

Weight Ratio = $(1.0/.01)^2$ = 10,000

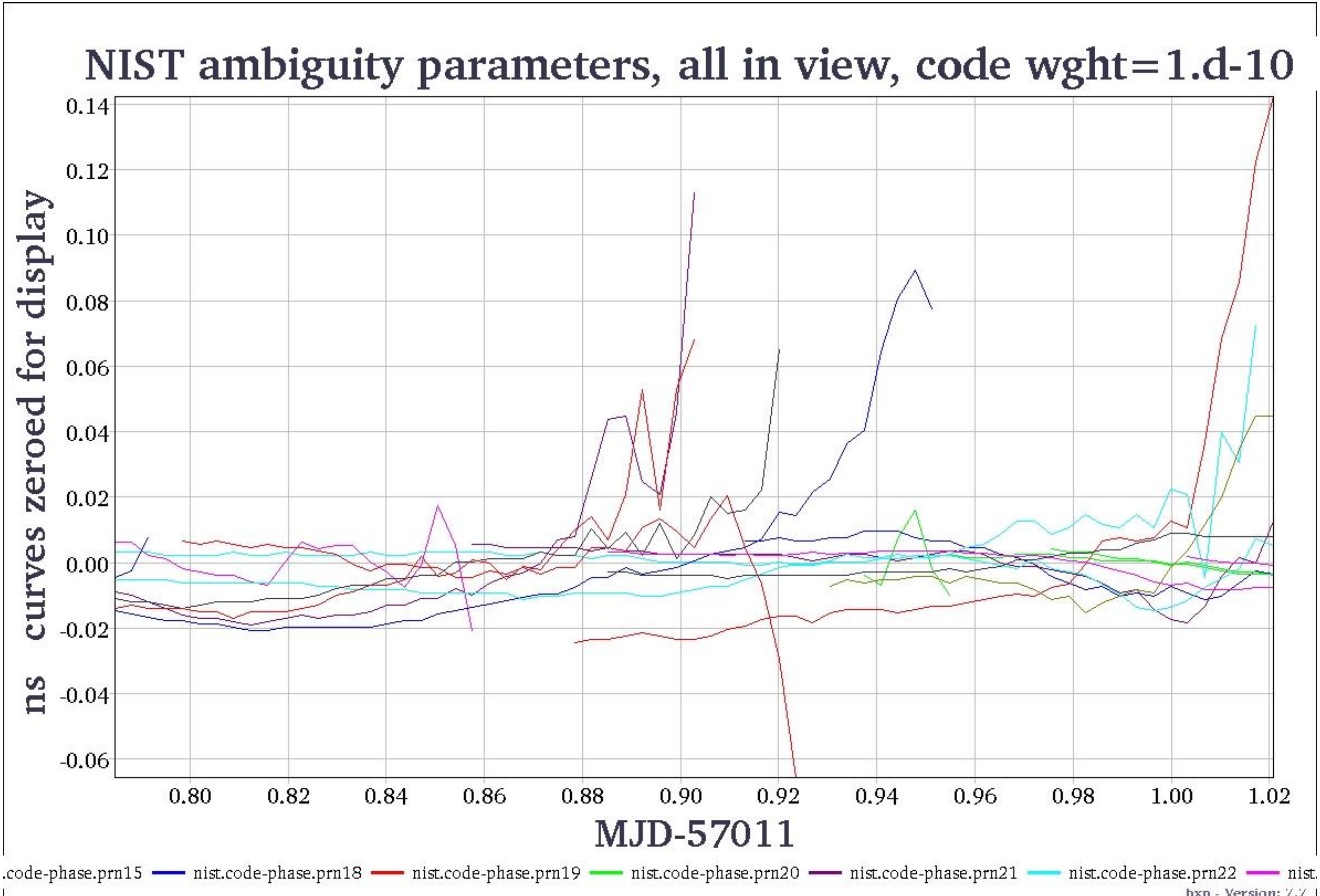


Ambiguities of 86,653 Observations, 1625 satellite passes




Satellite Tracks, code relative weights = 1.E-4 & 1.E-10
ns
8
6
4
2
0
-2
-4
-6
57003.4
57003.5
57003.6
57003.7
57003.8
57003.9
MJD
ppp_bipm.xyz.dec.psig=1/sorted/nist.code-phase
ppp_bipm.xyz.dec.psig=1000/sorted/nist.code-phase
bxp - Version: 7.7

Some ambiguities, backward pass



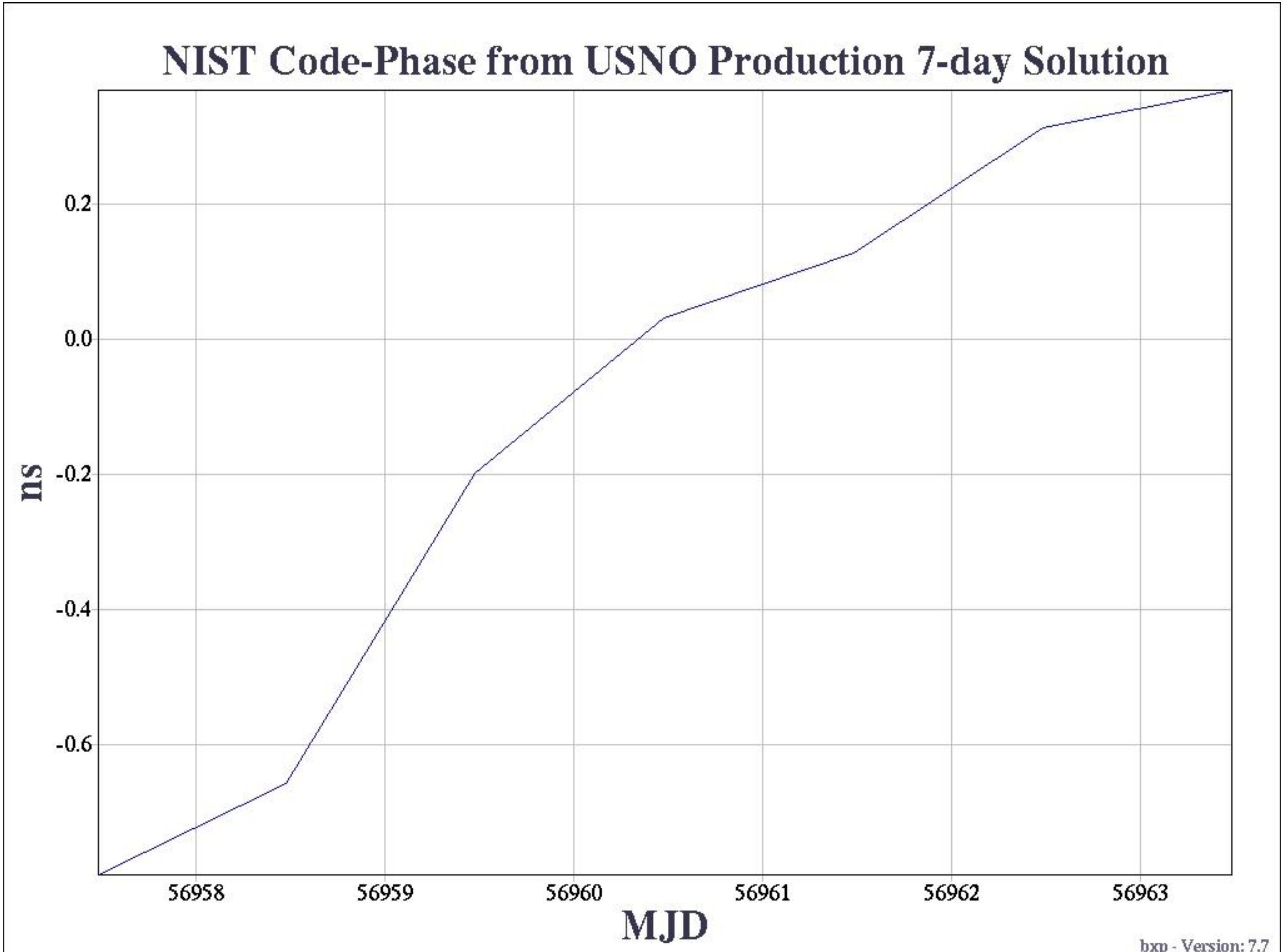
Conclusions for PPP & Floating Ambiguities

- Code influences frequency by lever-arm effect on relative ambiguities between satellite passes
  - BIPM weighting removes frequency-bias problem for 30-day solutions
  - BUT not for 1-day or 7-day solutions
- But note:
  - Using fixed ambiguities are being actively explored by many
  - Direct extraction from RINEX files also a possible way to study the code-phase bias problem.

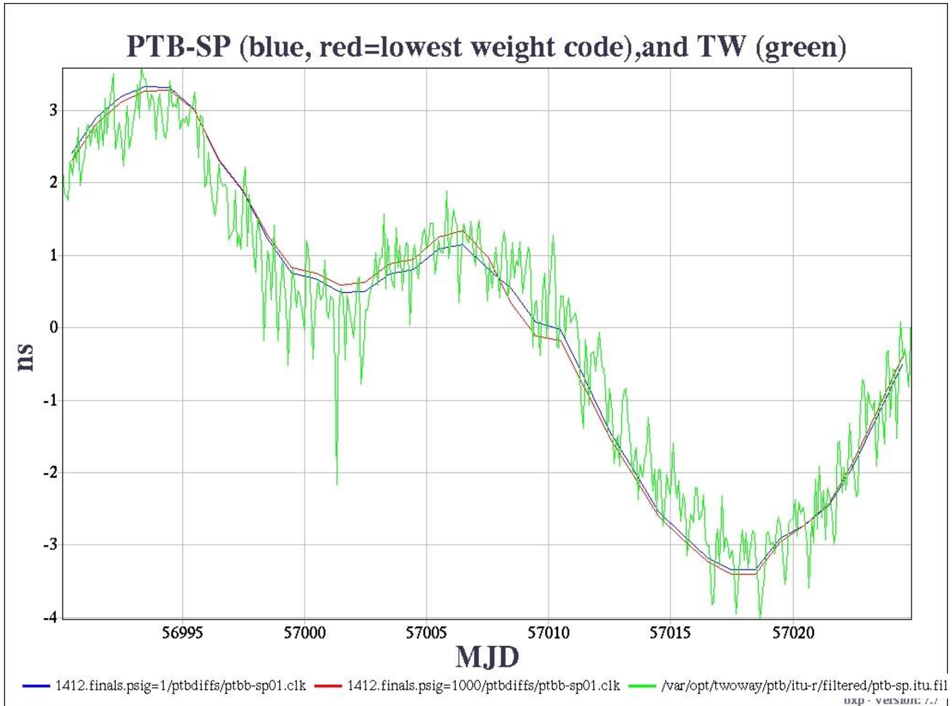
Disclaimer

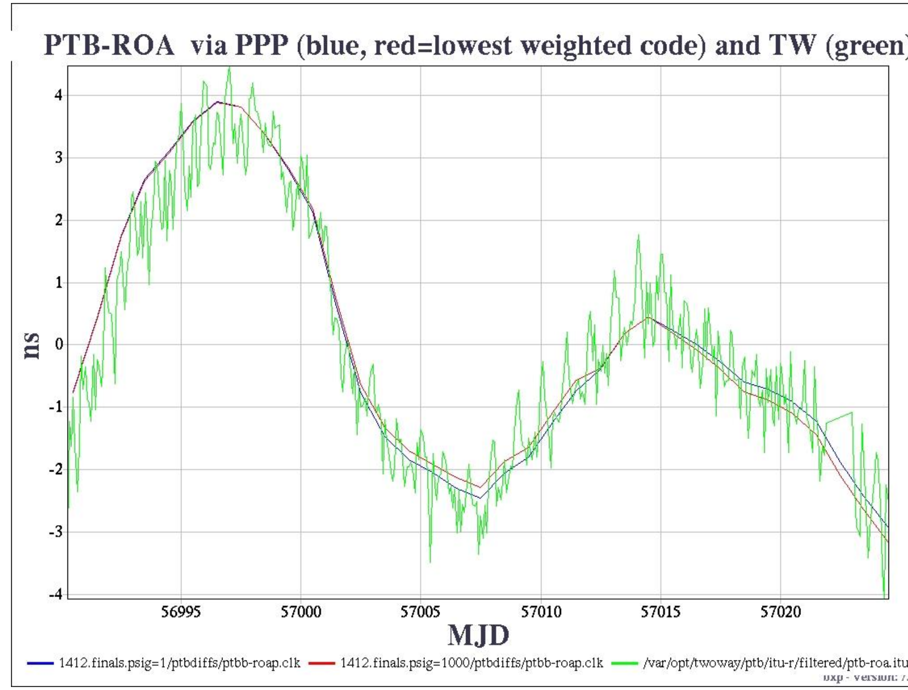
- USNO and ROB as a matter of policy do not endorse or unfavorably recommend commercial products
  - Manufacturers may be identified for scientific clarity
- Performances reported may not be characteristic of any product currently marketed
- Ancillary equipment could be the source of any deviations from ideality

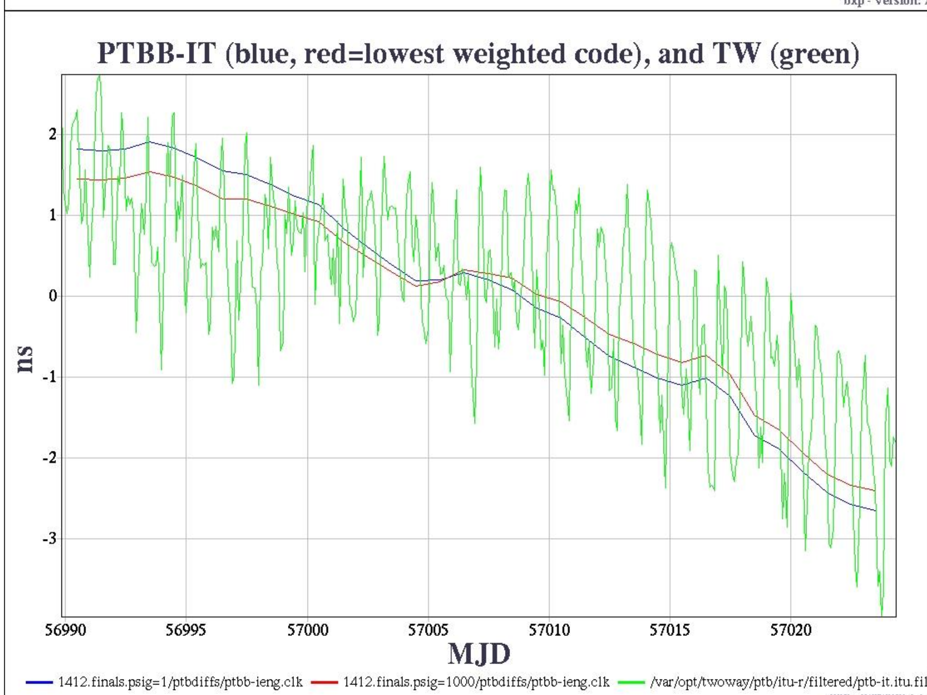
Backups

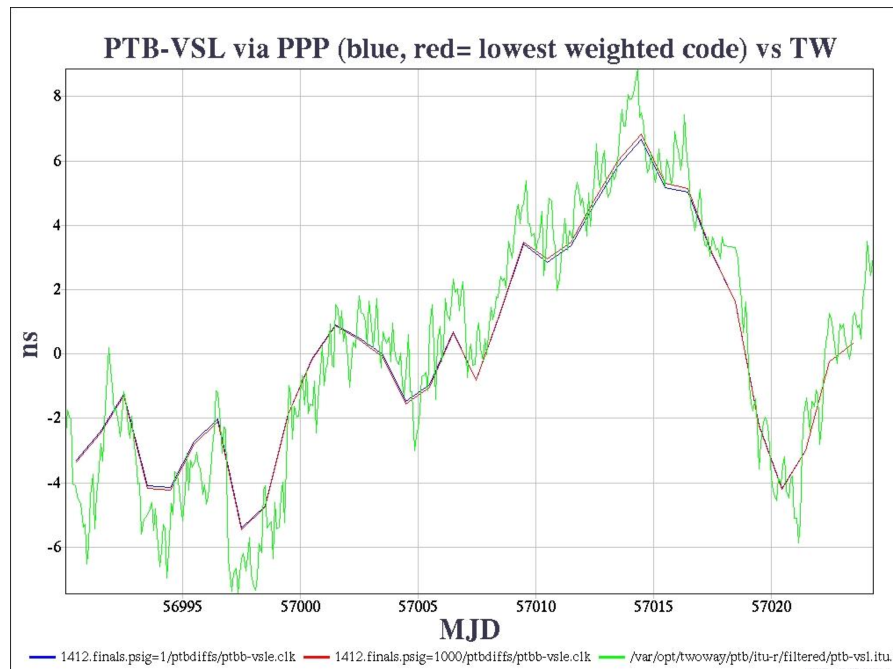


NIST Code-Phase from USNO Production 7-day Solution
ns
0.2
0.0
-0.2
-0.4
-0.6
56958
56959
56960
56961
56962
56963
MJD
bxp - Version: 7.7

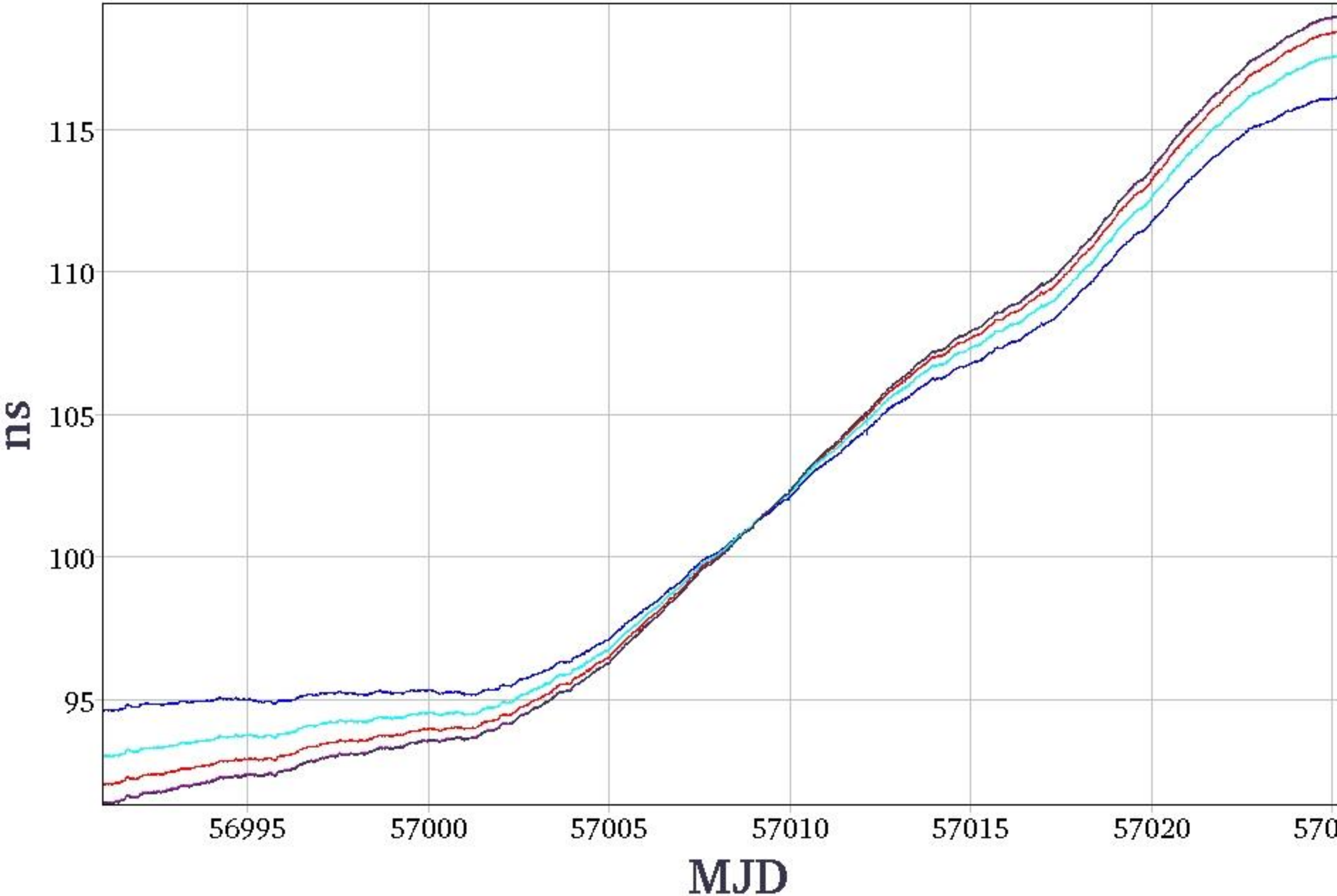

PTB-SP (blue, red=lowest weight code),and TW (green)
ns
MJD
1412.finals.psig=1/ptbdiffs/ptbb-sp01.clk
1412.finals.psig=1000/ptbdiffs/ptbb-sp01.clk
/var/opt/twoway/ptb/itu-r/filtered/ptb-sp.itu.fil


PTB-ROA via PPP (blue, red=lowest weighted code) and TW (green)
ns
MJD
1412.finals.psig=1/ptbdiffs/ptbb-roap.clk
1412.finals.psig=1000/ptbdiffs/ptbb-roap.clk
/var/opt/twoway/ptb/itu-r/filtered/ptb-roa.itu.fi


PTBB-IT (blue, red=lowest weighted code), and TW (green)
ns
MJD
1412.finals.psig=1/ptbdiffs/ptbb-ieng.clk
1412.finals.psig=1000/ptbdiffs/ptbb-ieng.clk
/var/opt/twoway/ptb/itu-r/filtered/ptb-it.itu.filt


PTB-VSL via PPP (blue, red= lowest weighted code) vs TW
ns
MJD
1412.finals.psig=1/ptbdiffs/ptbb-vsle.clk
1412.finals.psig=1000/ptbdiffs/ptbb-vsle.clk
/var/opt/twoway/ptb/itu-r/filtered/ptb-vsl.itu.fil

NIST clocks, varying PSIG. PSIG=1=least=blu

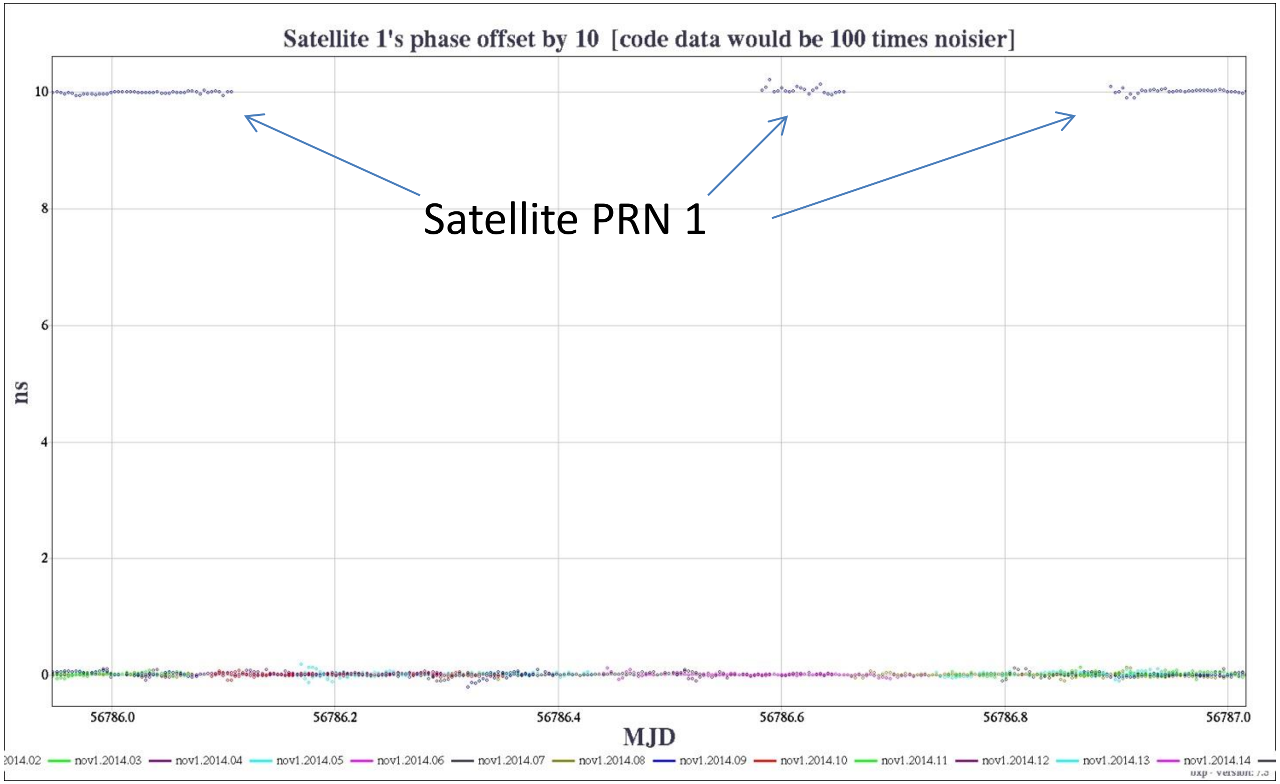


Considerations

- C-P bias, and other biases
    - They do not affect the slopes
- Some things affect code and phase unequally
  - Multipath
    - But any induced slopes would largely repeat daily
    - Exclude low elevations
  - Temperature and Humidity and Second-Order Ionosphere
    - In America, warmest part of day is UTC=18:00-24:00
    - Multiday solutions required
      - As many completed tracks start then as stop then
    - Second-order ionosphere
      - Absolute worst case for clocks: 10 ps (zenith)
  - Ambiguity parameter
    - Should be set by phase, except for overall constant
    - Just like clocks

An example of the interplay

- See Hackman, ION-ITM 2014
- PPP solutions generated at 5 mid-latitude sites
  - 10 ns added to phase and code of PRN1's RINEX files



An example of the interplay

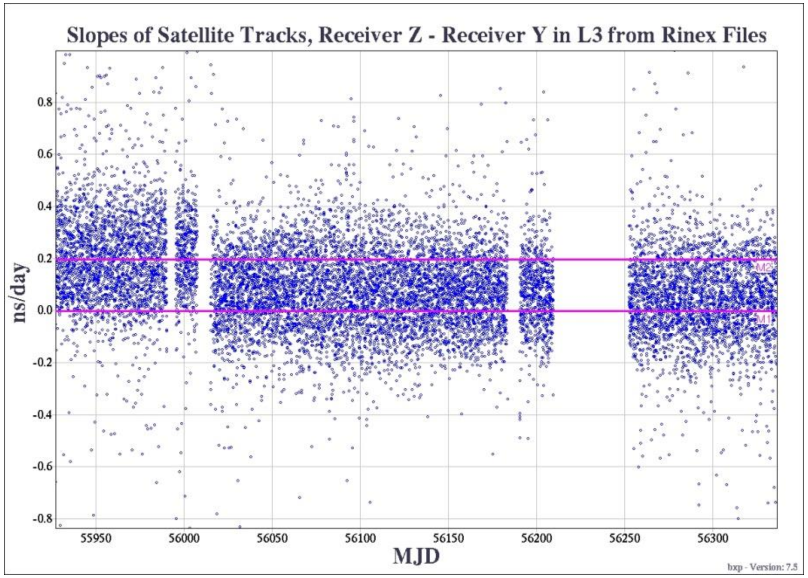
- Result was non-intuitive
  - No change in site positions
  - No change in site clock frequencies
  - No change in carrier-phase residuals
  - PRN1 code residuals absorbed 97% of the error
    - Other satellites shifted slightly, with opposite sign
  - Site clock daily averages shifted by 220-390 ps
    - Hint #1: 31/32 = 97%
    - Hint #2: 10 ns/32 = 312 ps
    - Hint #3: ambiguity parameters varied by same magnitude but opposite sign

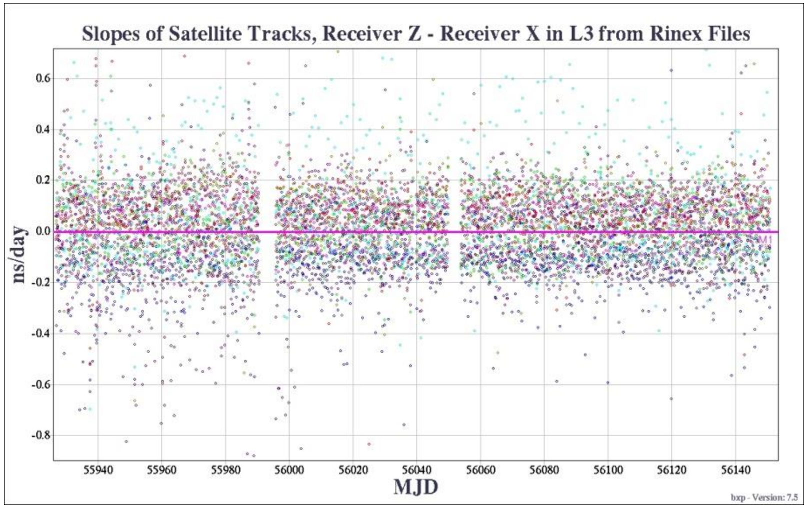
Resolution

- PRN1 ambiguity parameters
  - Set to make PRN1 phase data consistent with other satellites
  - Therefore, no change in the parameters determined by the phases
- PRN1’s 10-ns code error largely outvoted
  - Time of site clocks shifted by [10 ns/32 satellites]
  - Explains code residuals

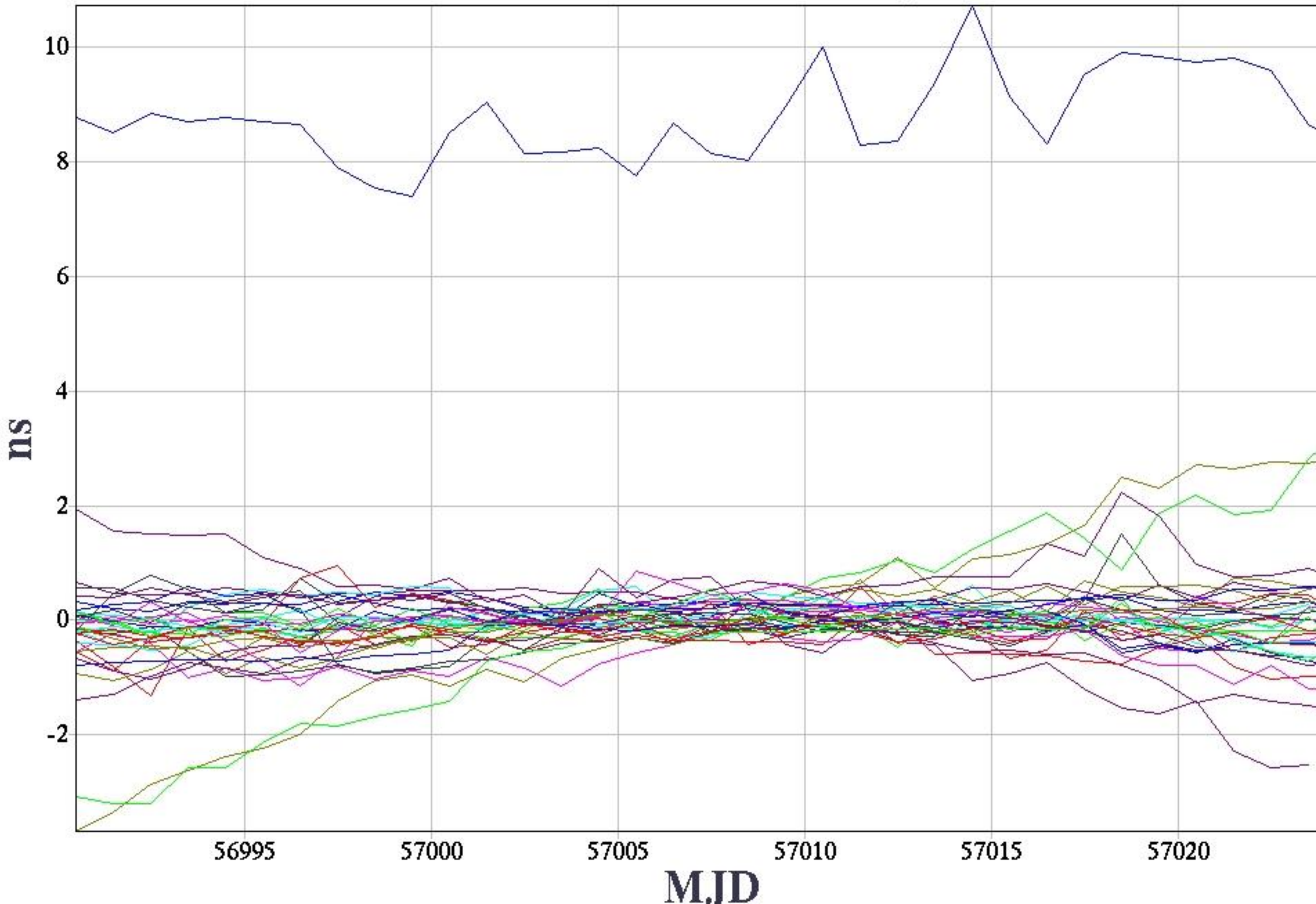
Third receiver identifies the miscreant

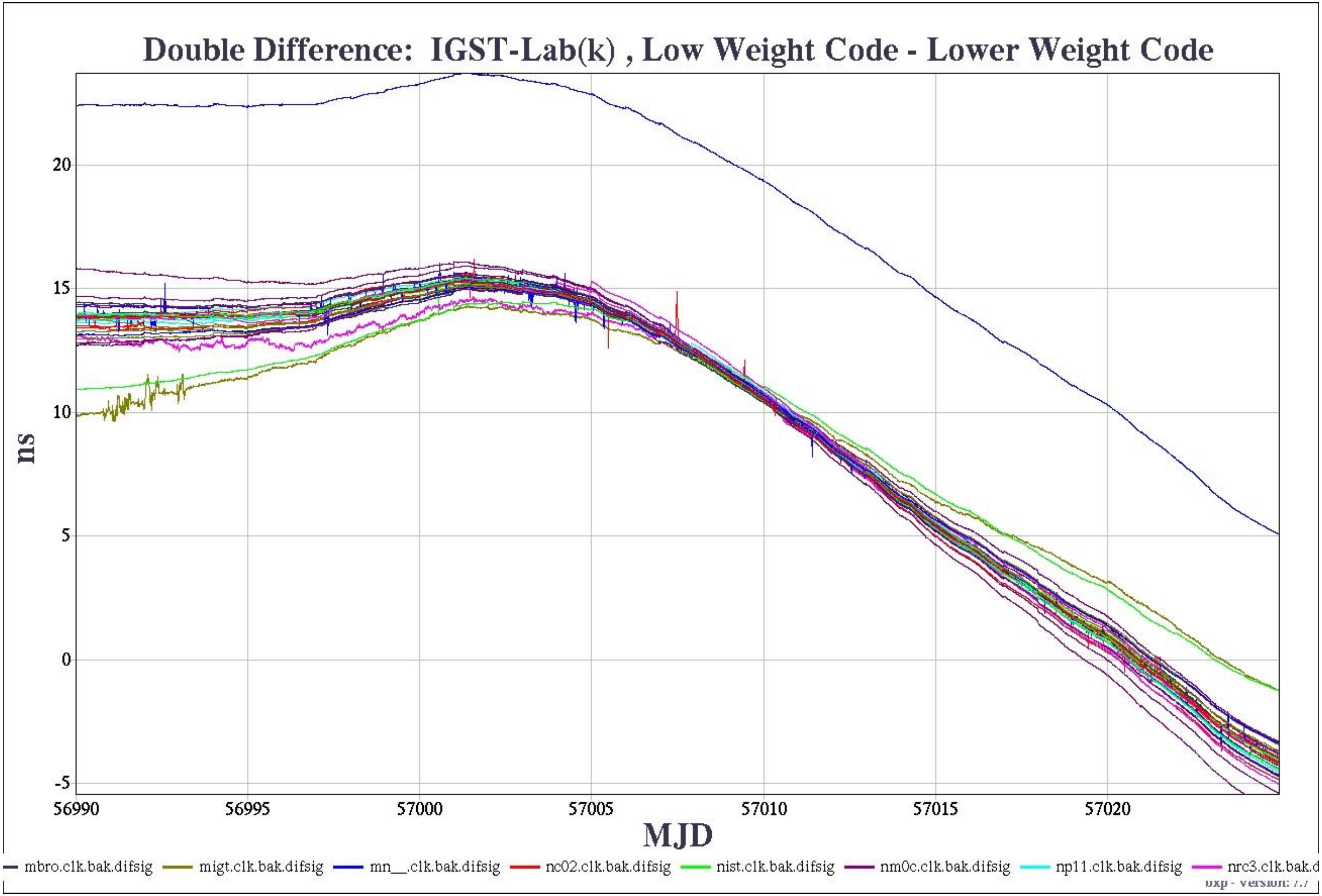
Improvement on MJD 56010 due to firmware change





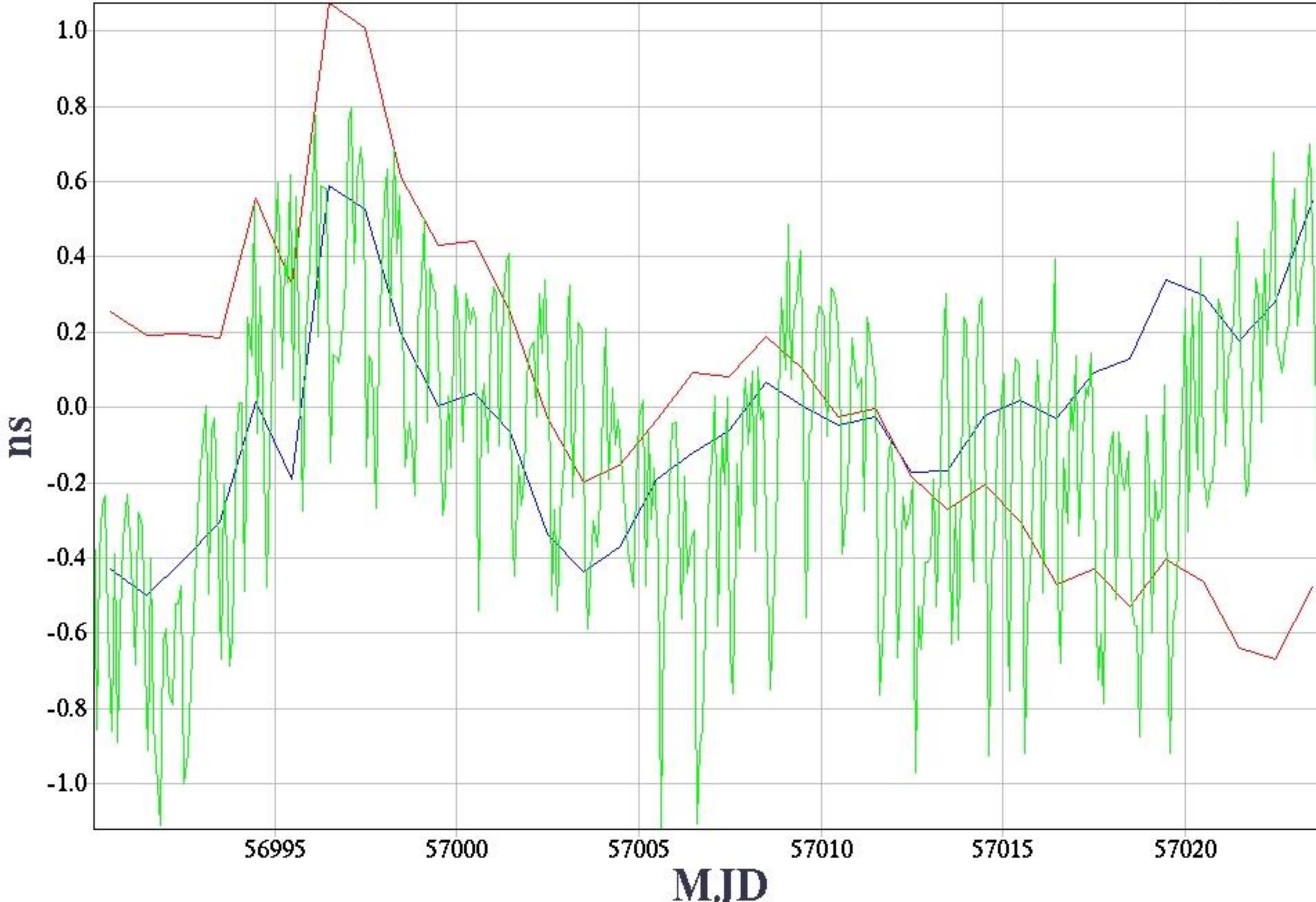
December 2014 Code-Phase Residuals, Weight Ratio=10,000,000,0

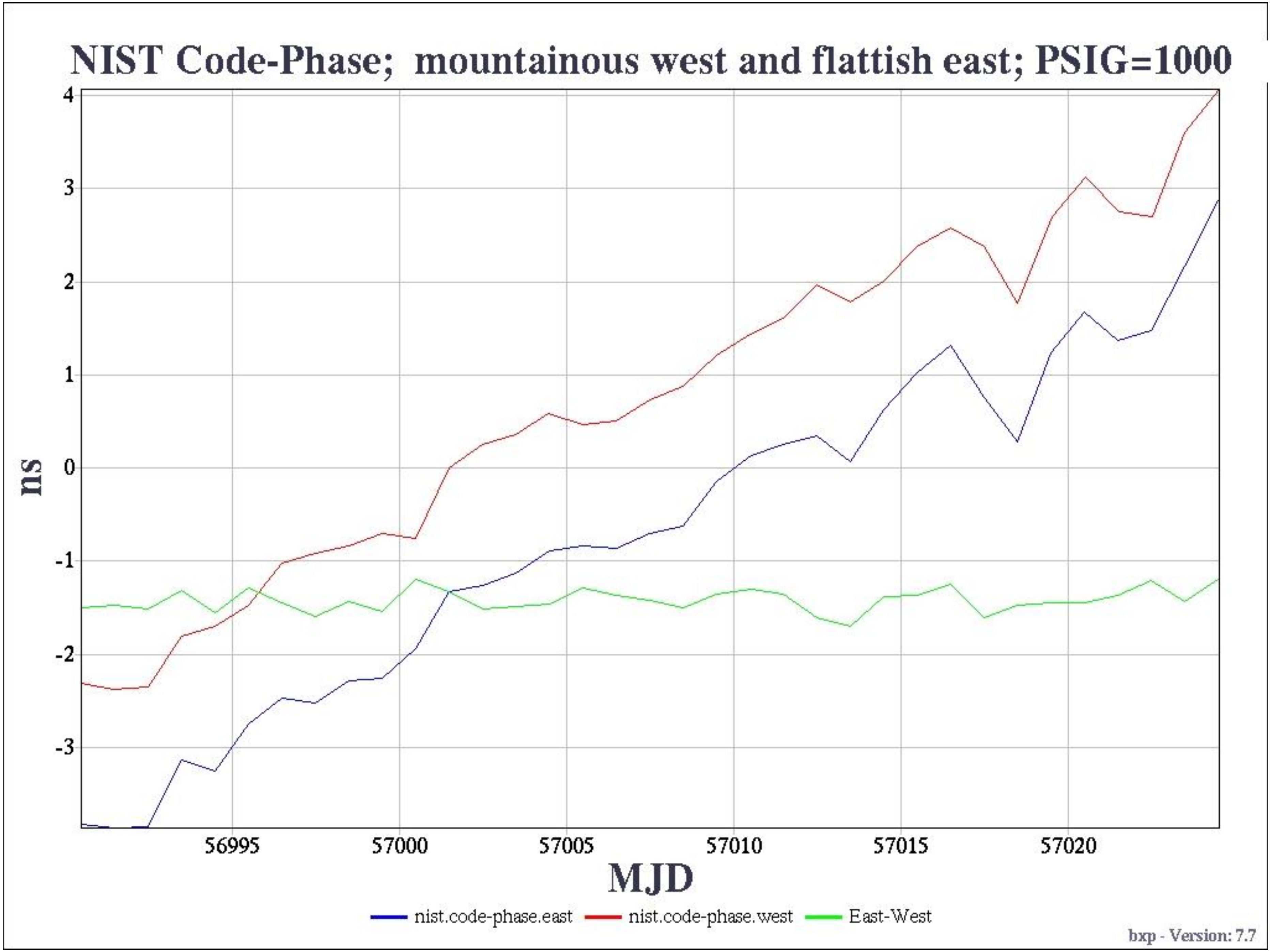


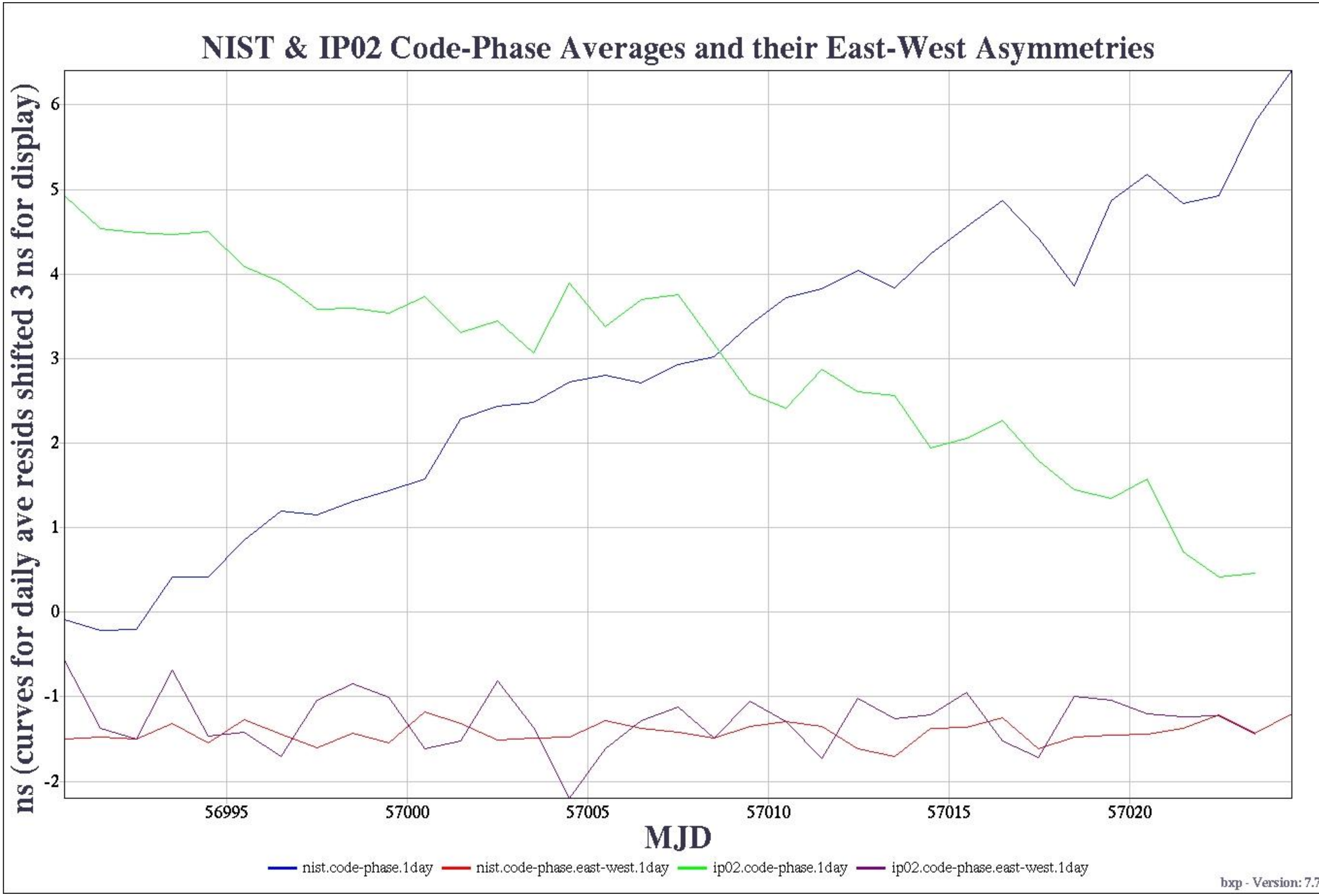


Double Difference: IGST-Lab(k) , Low Weight Code - Lower Weight Code
ns
20
15
10
5
0
-5
56990
56995
57000
57005
57010
57015
57020
MJD
mbro.clk.bak.difsig
migt.clk.bak.difsig
mn__.clk.bak.difsig
nc02.clk.bak.difsig
nist.clk.bak.difsig
nm0c.clk.bak.difsig
np11.clk.bak.difsig

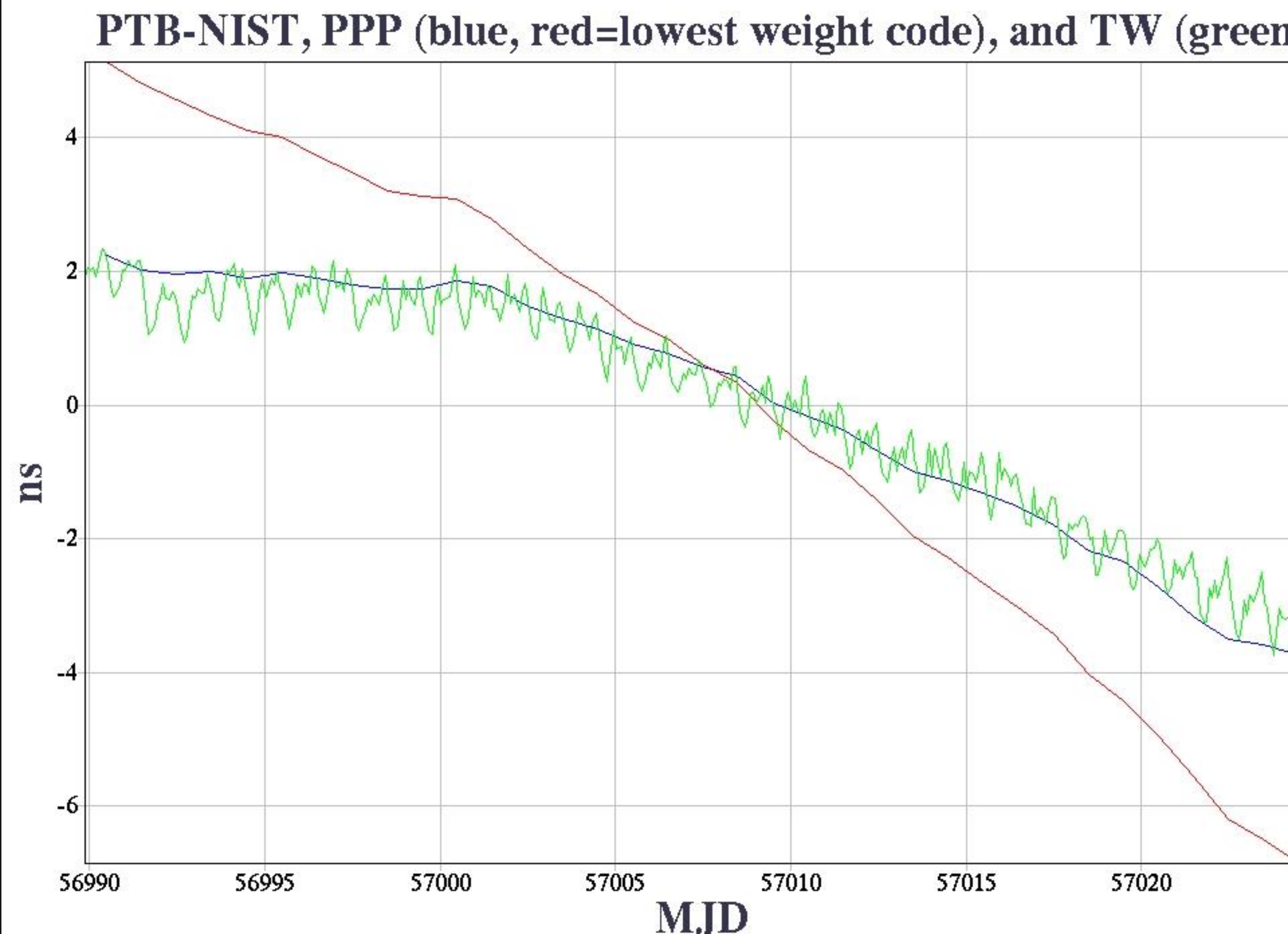
PTB-USNO via PPP (blue, red=lowest wt code), and TW (green




NIST Code-Phase; mountainous west and flattish east; PSIG=1000
ns
4
3
2
1
0
-1
-2
-3
56995
57000
57005
57010
57015
57020
MJD
nist.code-phase.east
nist.code-phase.west
East-West
bxp - Version: 7.7



NIST & IP02 Code-Phase Averages and their East-West Asymmetries
ns (curves for daily ave resids shifted 3 ns for display)
6
5
4
3
2
1
0
-1
-2
56995
57000
57005
57010
57015
57020
MJD
nist.code-phase.1day
nist.code-phase.east-west.1day
ip02.code-phase.1day
ip02.code-phase.east-west.1day
bxp - Version: 7.7


PTB-NIST, PPP (blue, red=lowest weight code), and TW (green
ns
4
2
0
-2
-4
-6
56990
56995
57000
57005
57010
57015
57020
MJD