Use of Precise point positioning for TAI links

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Link comparisons using geodetic GPS

- An already long history at the BIPM
  - Mostly using P3
  - Petit and Jiang (PTTI'2004, ATF2004)
  - Long-term stability (months) found to be similar for both techniques (< 1 ns)

- Several approaches
  - Network computation using phase + code (IGS analysis centers)
  - Network computation using phase only (R. Dach) for frequency comparisons
  - Precise point positioning

- PPP already in common use
  - Comparisons between different PPP results and IGS clock products in Bruyninx et al. (PTTI'2004)
  - Comparisons between PPP and TW e.g. in Orgiazzi et al. (FCS-PTTI'2005)
  - Multi-technique (PPP, Phase-only, Phase+code, IGS, TW) in Jiang et al (EFTF'2006)

PPP for TAI links

- PPP makes sense for TAI time links
  - It is the natural follower of All-in-view with P3

- BIPM thus started to gain experience with Precise Point Positioning analyses using IGS products.

- Multi-technique comparisons: to quantify the performance of the techniques that presently seem to be the best available for TAI links:
  - Precise Point Positioning (PPP) with dual-frequency geodetic GPS receivers
  - Two Way time transfer:
    - Ku band
    - X band

PPP Software presently used at the BIPM

- GPSPPP software version 2655 (January 2006).
- Developed by NRCan (Kouba and Héroux, GPS Solutions, 2001)

- Features:
  - Uses GPS satellites ephemerides and clocks from the IGS to produce (Station clock – IGS time reference)
  - Uses directly IGS products (e.g. phase center offsets…)
  - Uses up-to-date models for station displacements (tides etc…)
  - Allows to solve for station coordinates, tropospheric delays.

  - Continuous processing of “unlimited” number of days is possible
    => Adapted to monthly TAI computation.

- Several other packages are available

GPSPPP Settings (Nominal)

- IGS Final SP3 orbits and 5-min SV clocks (RINEX format) – fixed
- SV IGS antenna offset values applied
- Antenna PCV values used: from standard IGS file igs_01.pcv
- Ocean loading coefficients from Chalmers Centre for Astrophysics and Space Science: http://www.oso.chalmers.se/~loading/

- *A priori* data weights: 1 m pseudorange, 1 cm phase
- Elevation cut-off: 10°

- Observation sampling & output clocks every 5 minutes
- Tropo delay estimated as 3mm/√hr random walk
- Station coordinates estimated on each 1-month batches

Link comparisons

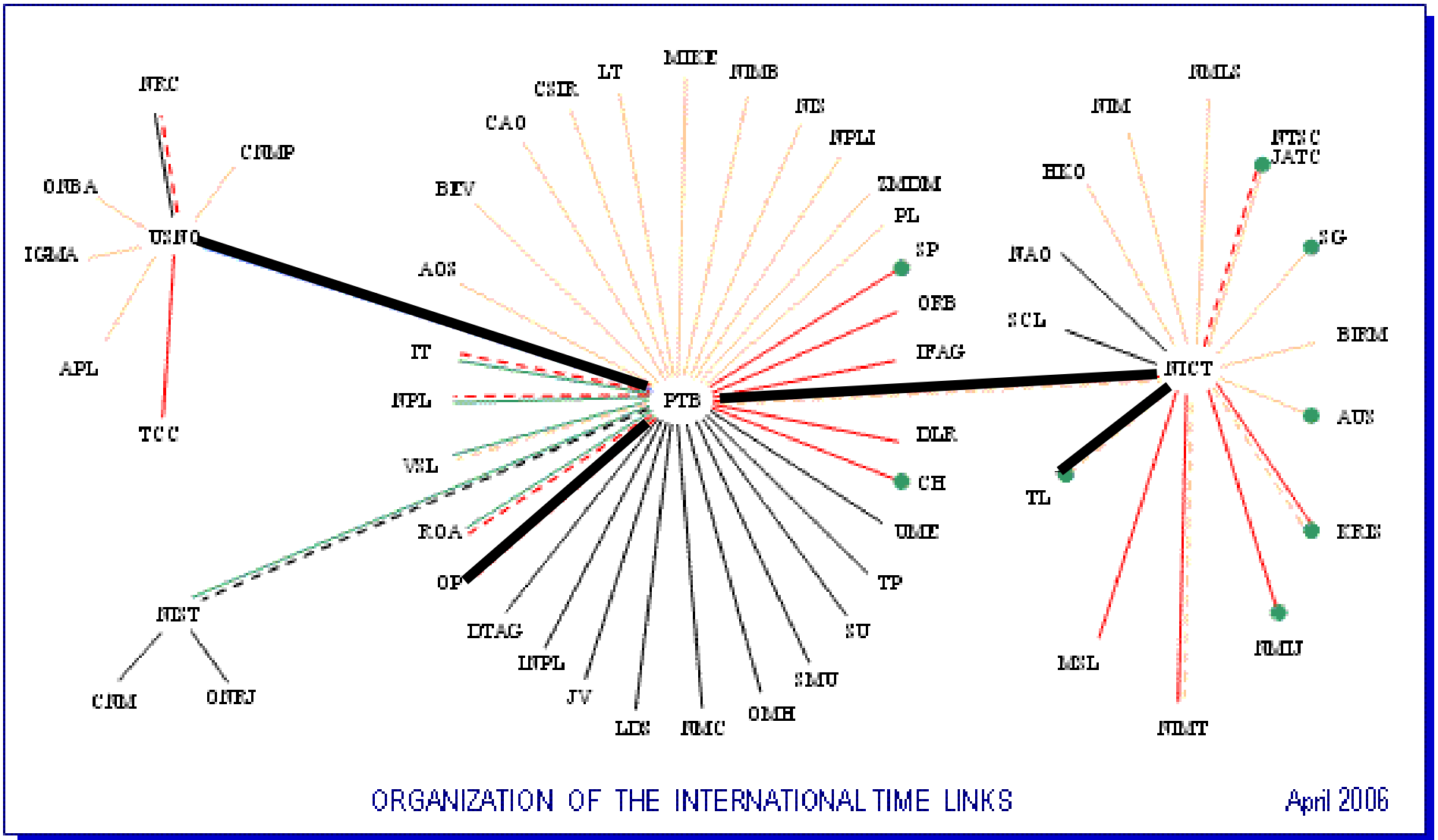
We consider time laboratories with TW and (geodetic receivers + IGS)

- PPP to IGS: Just for checking
  GPSPPP (NRC software) to Atomium (new ORB software)

2. PPP to TW(Ku): Several links in Europe-USA, e.g.
   - USNO-PTB
   - OP-PTB
- Links in Asia-Pacific + link to Europa, e.g.
   - NICT-PTB
   - NICT-TL

3. Comparison of three independent techniques for USNO-PTB
   - TW (Ku) typically 12 or 24 points per day
   - TW (X) typically 24 points per day
   - PPP computed every 5 minutes (288 points per day)
- Three-corner hat computation possible: estimation of the stability of each technique from the three differences.

Links considered



ORGANIZATION OF THE INTERNATIONAL TIME LINKS

April 2006

Laboratory equipped with TWSTFT (not yet used)

TWSTFT by Ku band with X band back-up

TWSTFT link

GPS CV single-channel link

GPS CV single-channel back-up link

GPS CV multi-channel link

GPS CV multi-channel back-up link

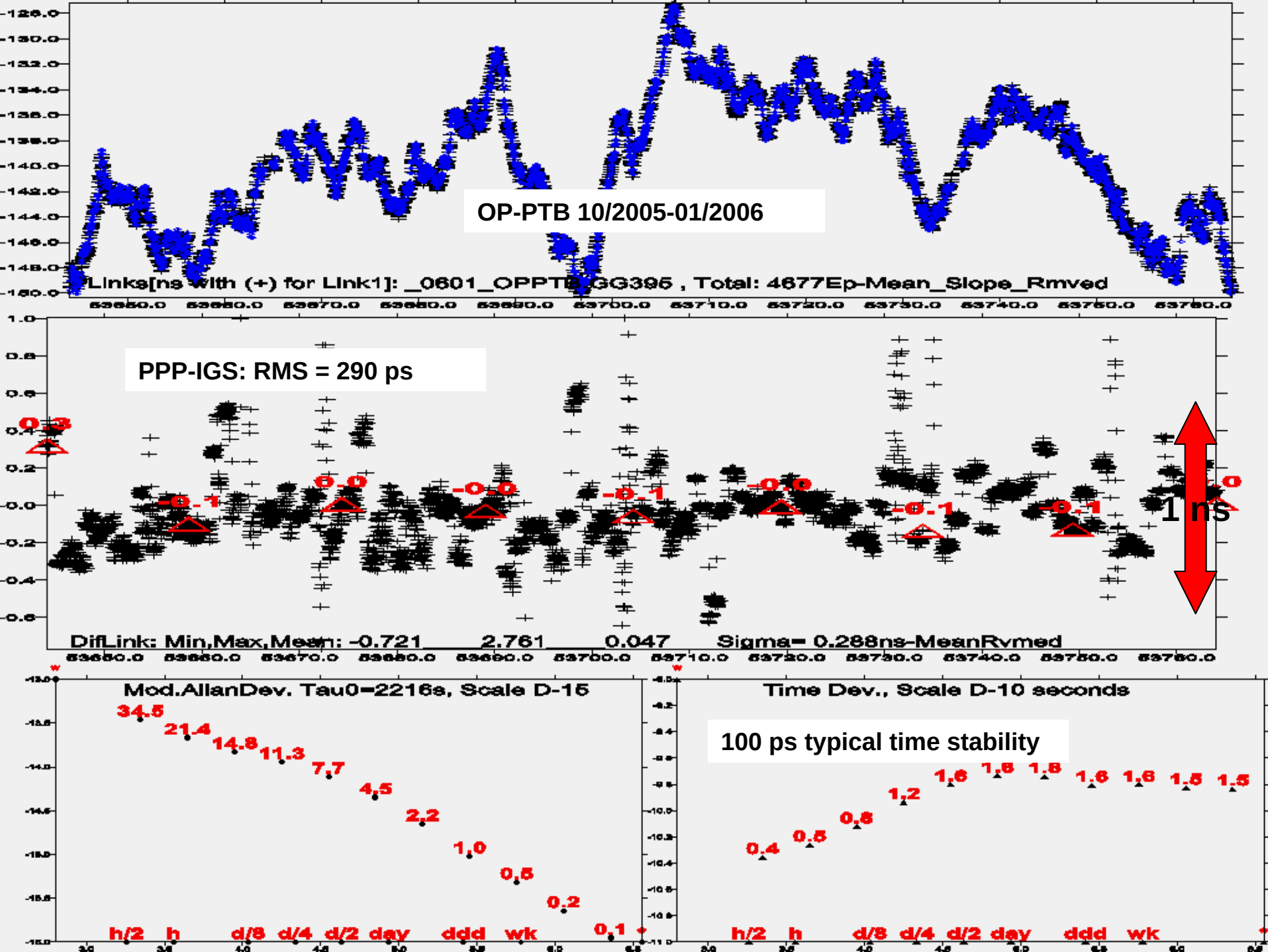
GPS CV dual frequency link

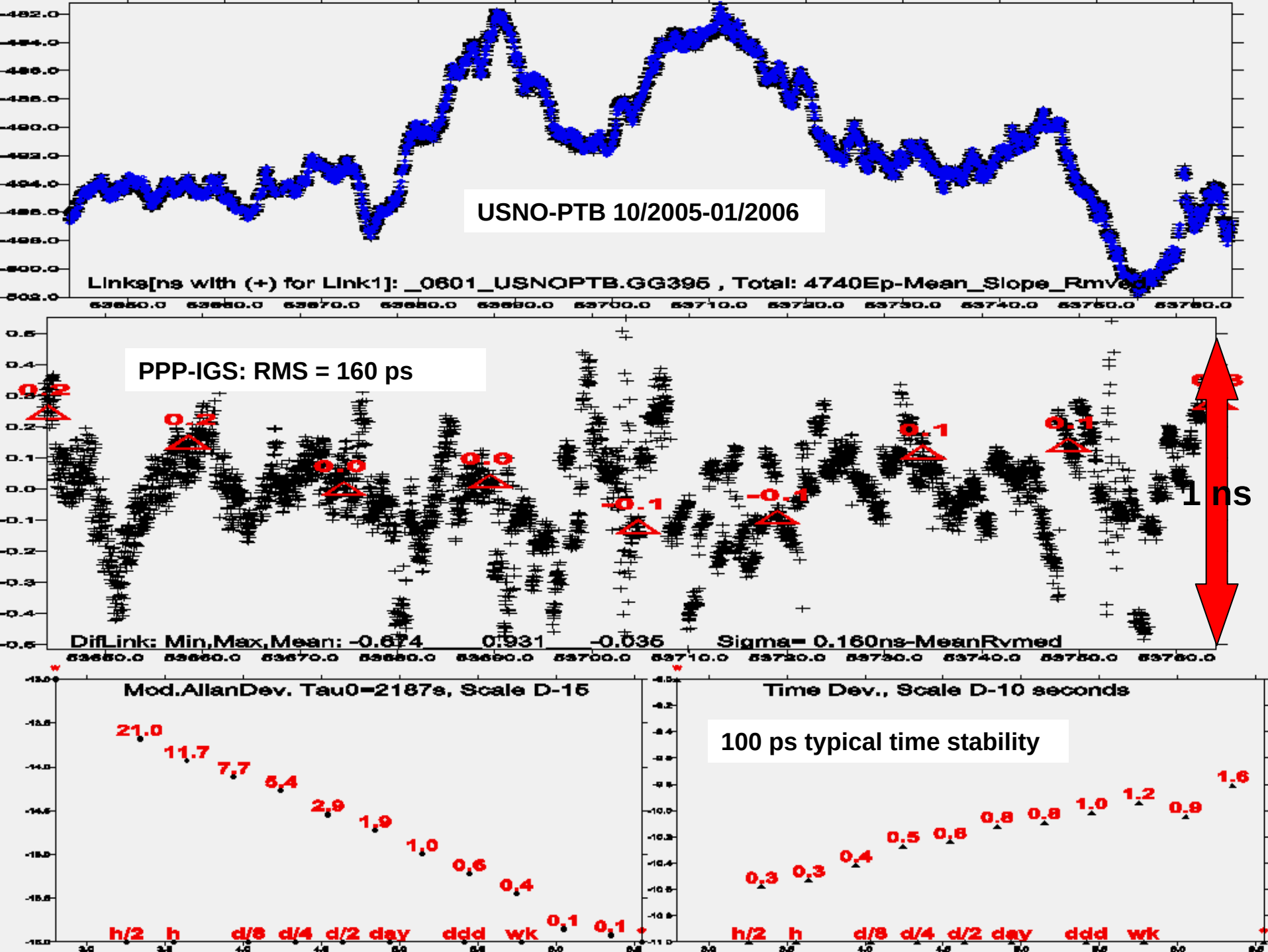
GPS CV dual frequency back-up link

BIPM

PPP – IGS

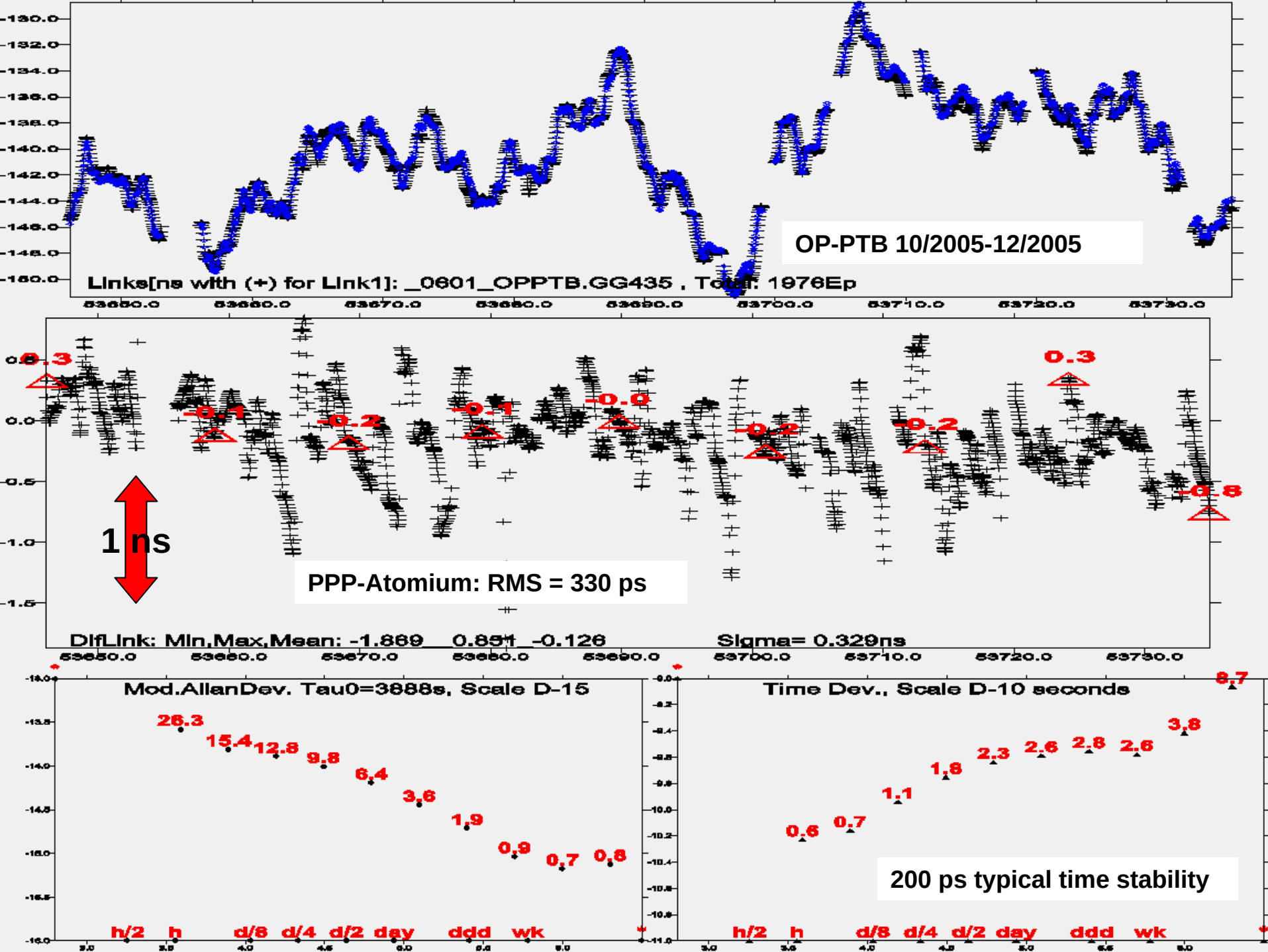
(just to check)

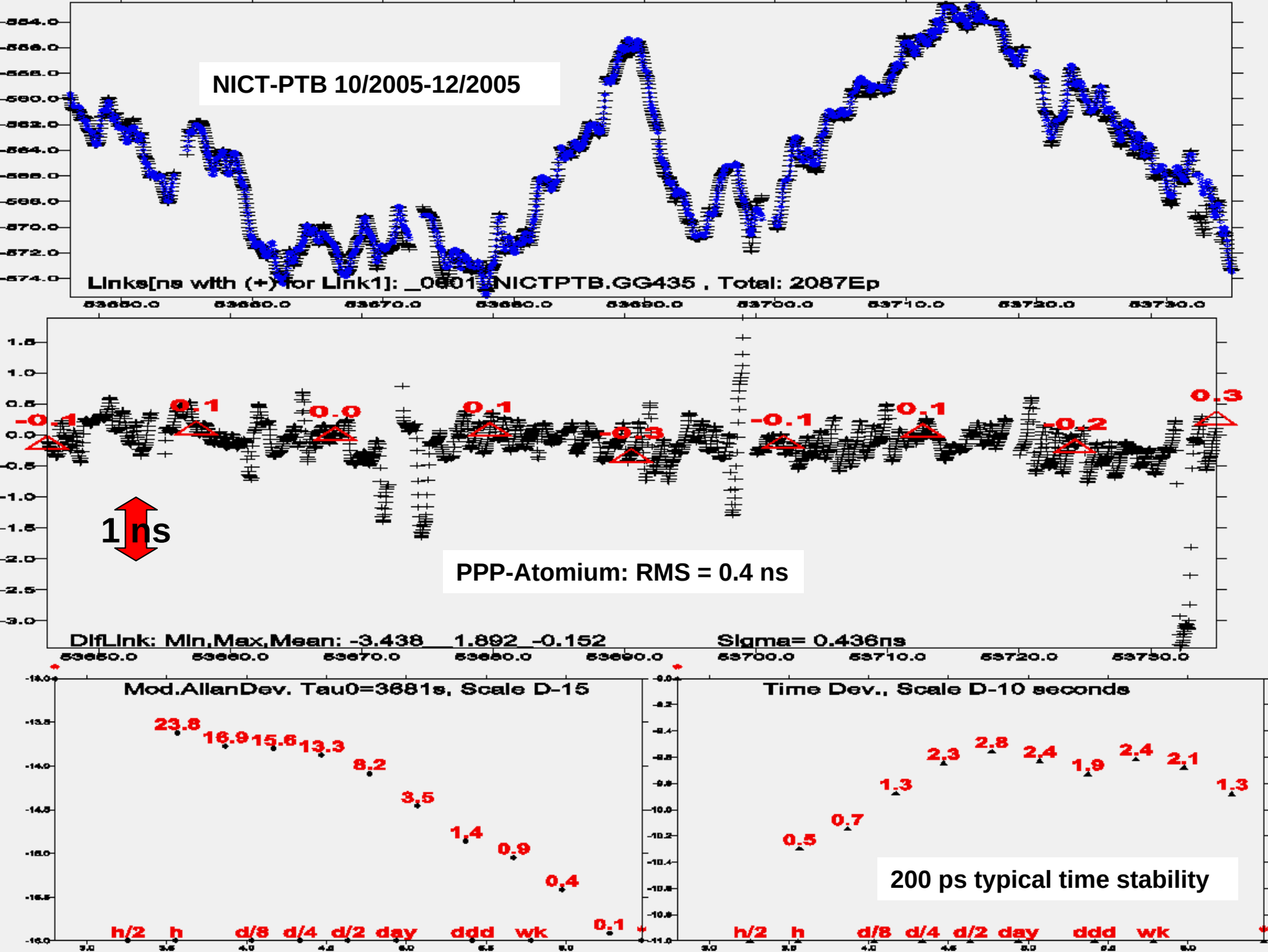

OP-PTB 10/2005-01/2006
PPP-IGS: RMS = 290 ps
1 ns
DifLink: Min,Max,Mean: -0.721 2.761 0.047 Sigma= 0.288ns-MeanRvmed
Mod.AllanDev. Tau0=2216s, Scale D-15
34.5
21.4
14.8
11.3
7.7
4.5
2.2
1.0
0.5
0.2
0.1
h/2 h d/8 d/4 d/2 day ddd wk
Time Dev., Scale D-10 seconds
100 ps typical time stability
0.4
0.5
0.8
1.2
1.6
1.8
1.8
1.6
1.6
1.5
1.5
h/2 h d/8 d/4 d/2 day ddd wk


USNO-PTB 10/2005-01/2006
Links[ns with (+) for Link1]: _0601_USNOPTB.GG395 , Total: 4740Ep-Mean_Slope_Rmved
PPP-IGS: RMS = 160 ps
1 ns
DifLink: Min,Max,Mean: -0.674 0.931 -0.036 Sigma= 0.160ns-MeanRvmed
Mod.AllanDev. Tau0=2187s, Scale D-15
21.0
11.7
7.7
5.4
2.9
1.9
1.0
0.6
0.4
0.1
0.1
h/2 h d/8 d/4 d/2 day ddd wk
Time Dev., Scale D-10 seconds
100 ps typical time stability
0.3
0.3
0.4
0.5
0.8
0.8
0.8
1.0
1.2
0.9
1.6
h/2 h d/8 d/4 d/2 day ddd wk

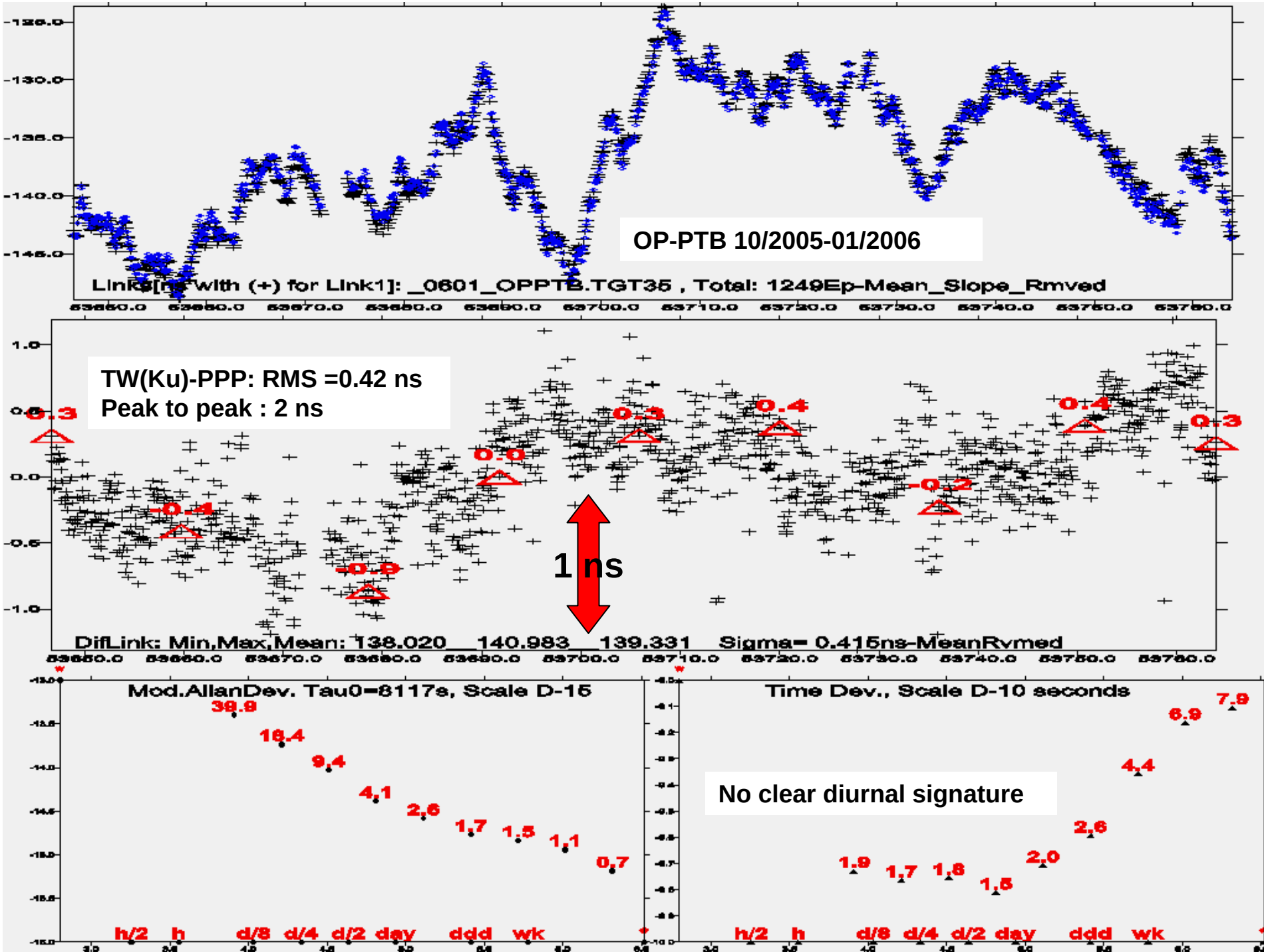
Different PPP softwares: GPSPPP - Atomium

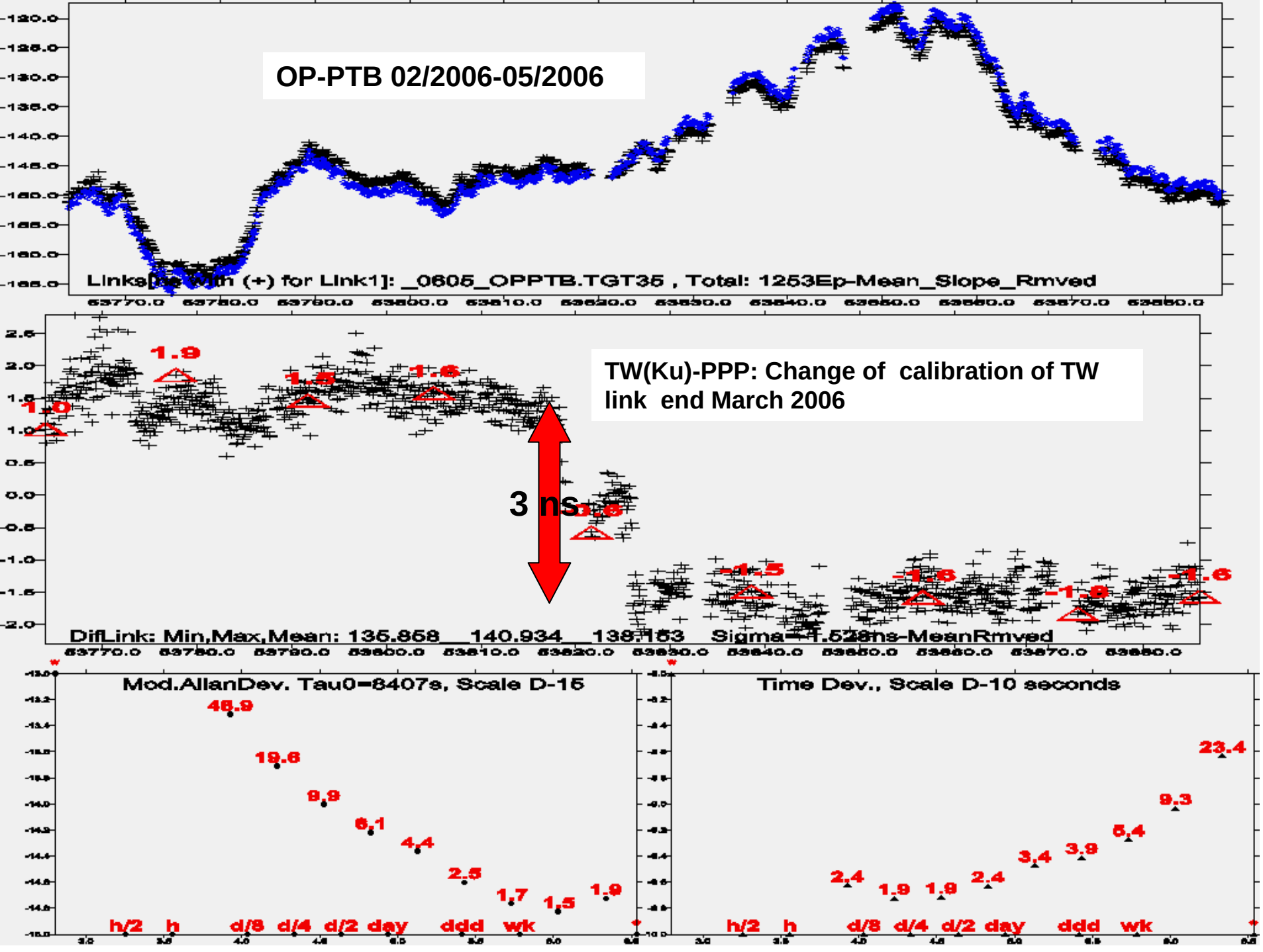
(just to check)

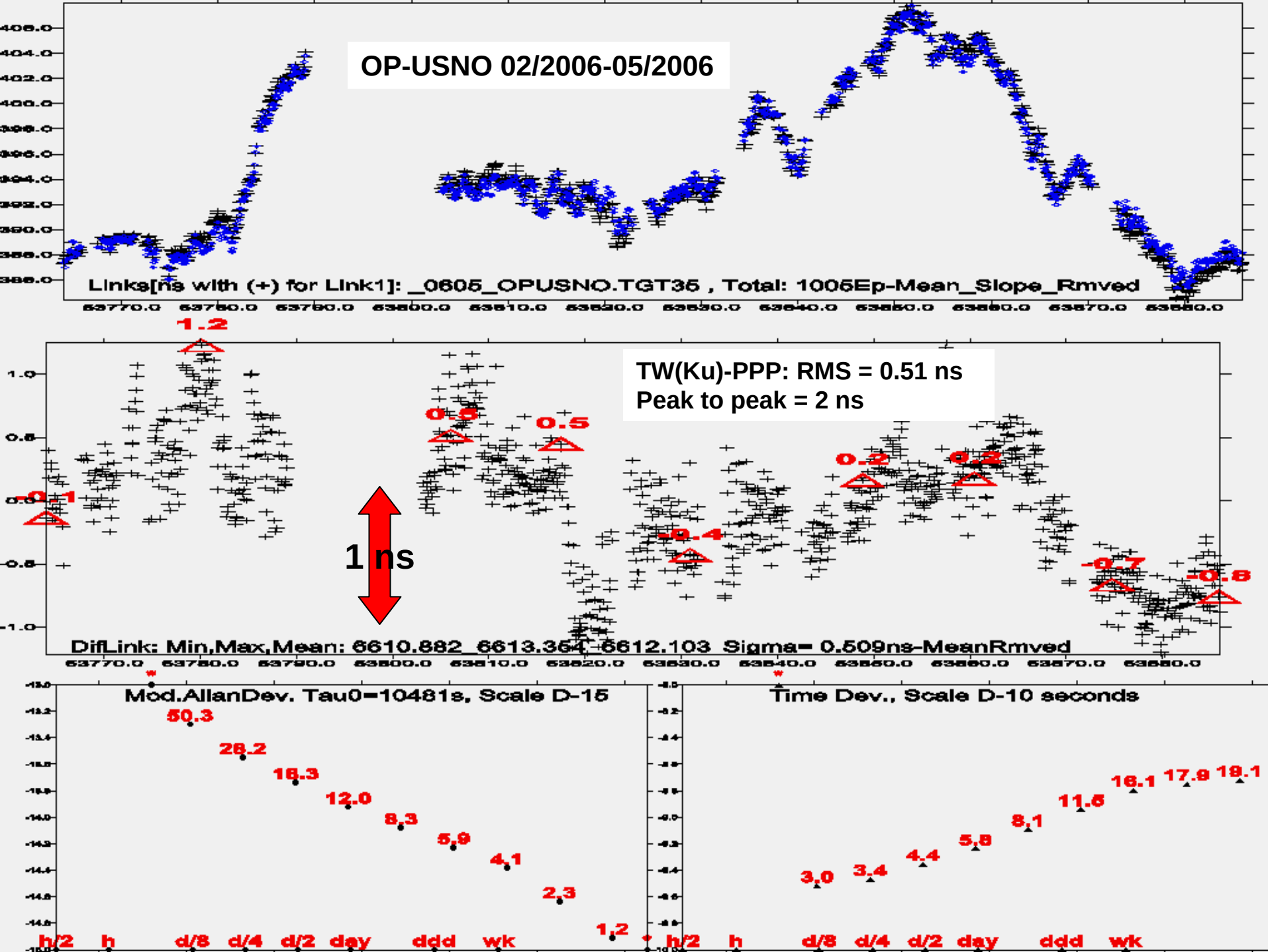

OP-PTB 10/2005-12/2005
Links[ns with (+) for Link1]: _0601_OPPTB.GG435 , Total: 1976Ep
1 ns
PPP-Atomium: RMS = 330 ps
DifLink: Min,Max,Mean: -1.869 0.851 -0.126
Sigma= 0.329ns
Mod.AllanDev. Tau0=3888s, Scale D-15
26.3
15.4
12.8
9.8
6.4
3.6
1.9
0.9
0.7
0.8
h/2 h d/8 d/4 d/2 day ddd wk
Time Dev., Scale D-10 seconds
0.6
0.7
1.1
1.8
2.3
2.6
2.8
2.6
3.8
8.7
h/2 h d/8 d/4 d/2 day ddd wk
200 ps typical time stability

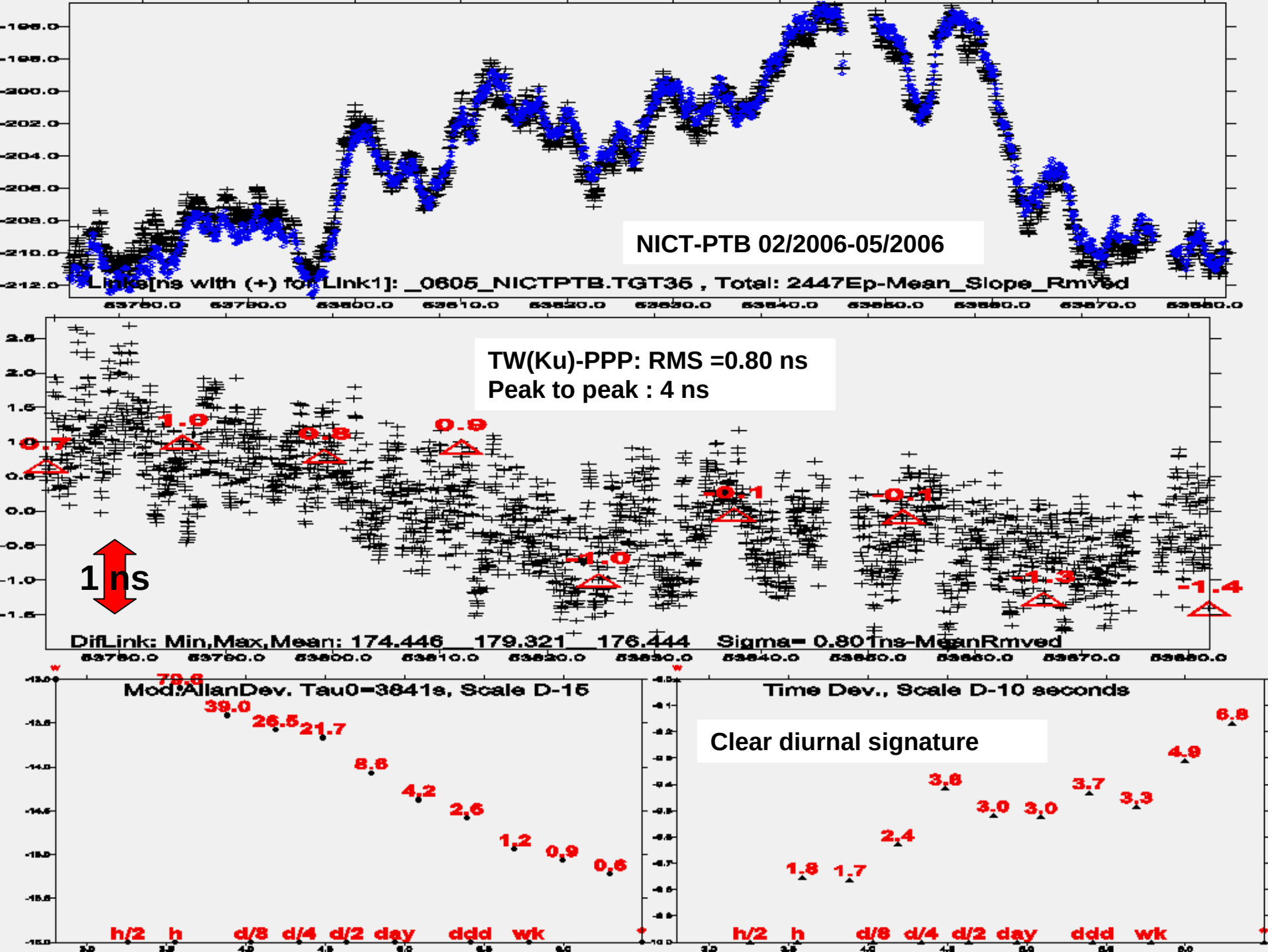

NICT-PTB 10/2005-12/2005
Links[ns with (+) for Link1]: _0601_NICTPTB.GG435 , Total: 2087Ep
53650.0 53660.0 53670.0 53680.0 53690.0 53700.0 53710.0 53720.0 53730.0
-0.1 0.1 0.0 0.1 -0.3 -0.1 0.1 -0.2 0.3
1 ns
PPP-Atomium: RMS = 0.4 ns
DifLink: Min,Max,Mean: -3.438 1.892 -0.152
Sigma= 0.436ns
Mod.AllanDev. Tau0=3681s, Scale D-15
23.8 16.9 15.6 13.3 8.2 3.5 1.4 0.9 0.4 0.1
h/2 h d/8 d/4 d/2 day ddd wk
Time Dev., Scale D-10 seconds
0.5 0.7 1.3 2.3 2.8 2.4 1.9 2.4 2.1 1.3
h/2 h d/8 d/4 d/2 day ddd wk
200 ps typical time stability

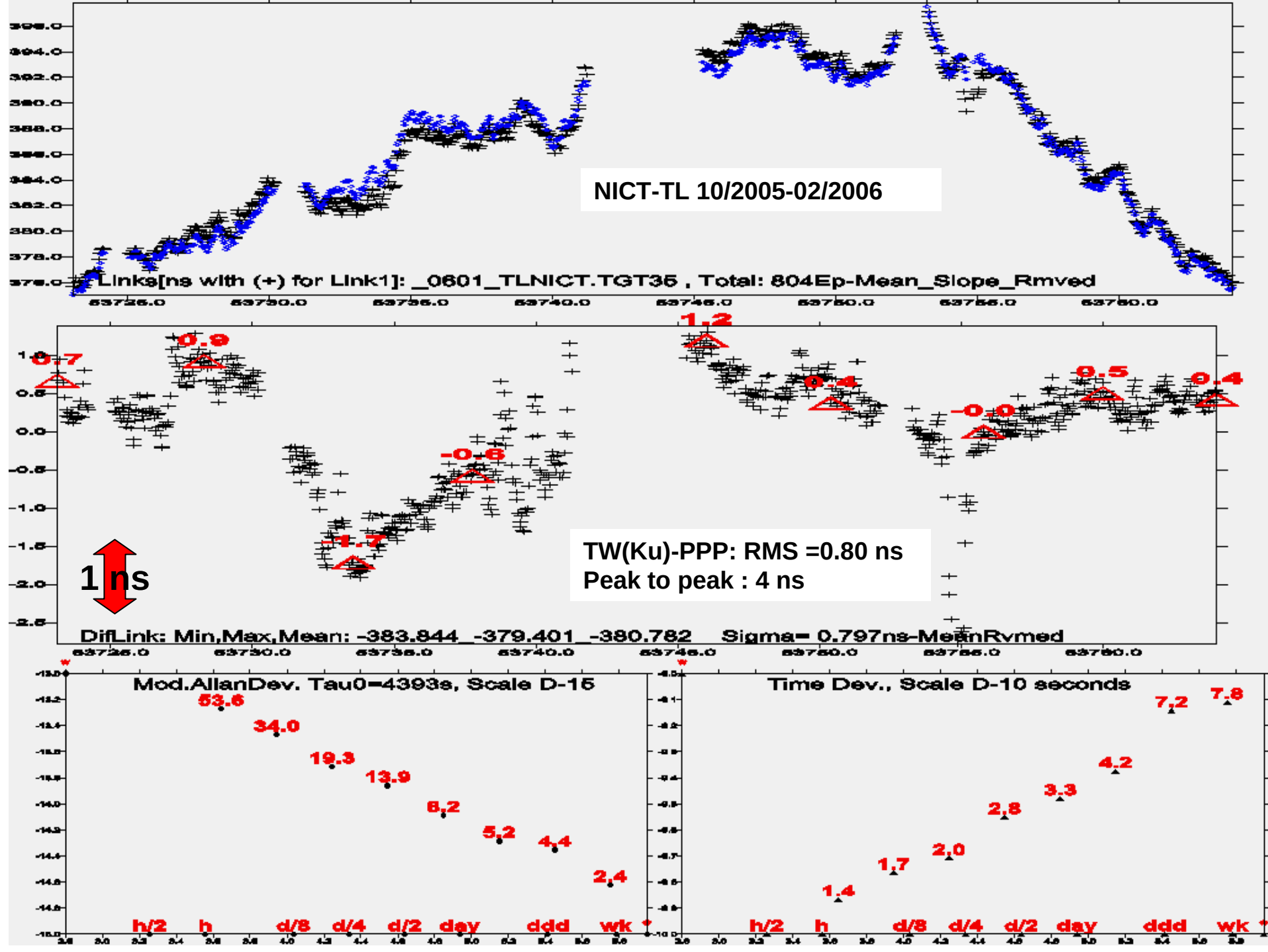
TW(Ku) - PPP


OP-PTB 10/2005-01/2006
Links[ns,with (+) for Link1]: _0601_OPPTB.TGT35 , Total: 1249Ep-Mean_Slope_Rmved
TW(Ku)-PPP: RMS =0.42 ns
Peak to peak : 2 ns
1 ns
DifLink: Min,Max,Mean: 138.020 140.983 139.331 Sigma= 0.415ns-MeanRvmed
Mod.AllanDev. Tau0=8117s, Scale D-15
39.9
18.4
9.4
4.1
2.6
1.7
1.5
1.1
0.7
h/2 h d/8 d/4 d/2 day ddd wk
Time Dev., Scale D-10 seconds
7.9
6.9
4.4
2.6
2.0
1.9
1.7
1.8
1.5
h/2 h d/8 d/4 d/2 day ddd wk
No clear diurnal signature

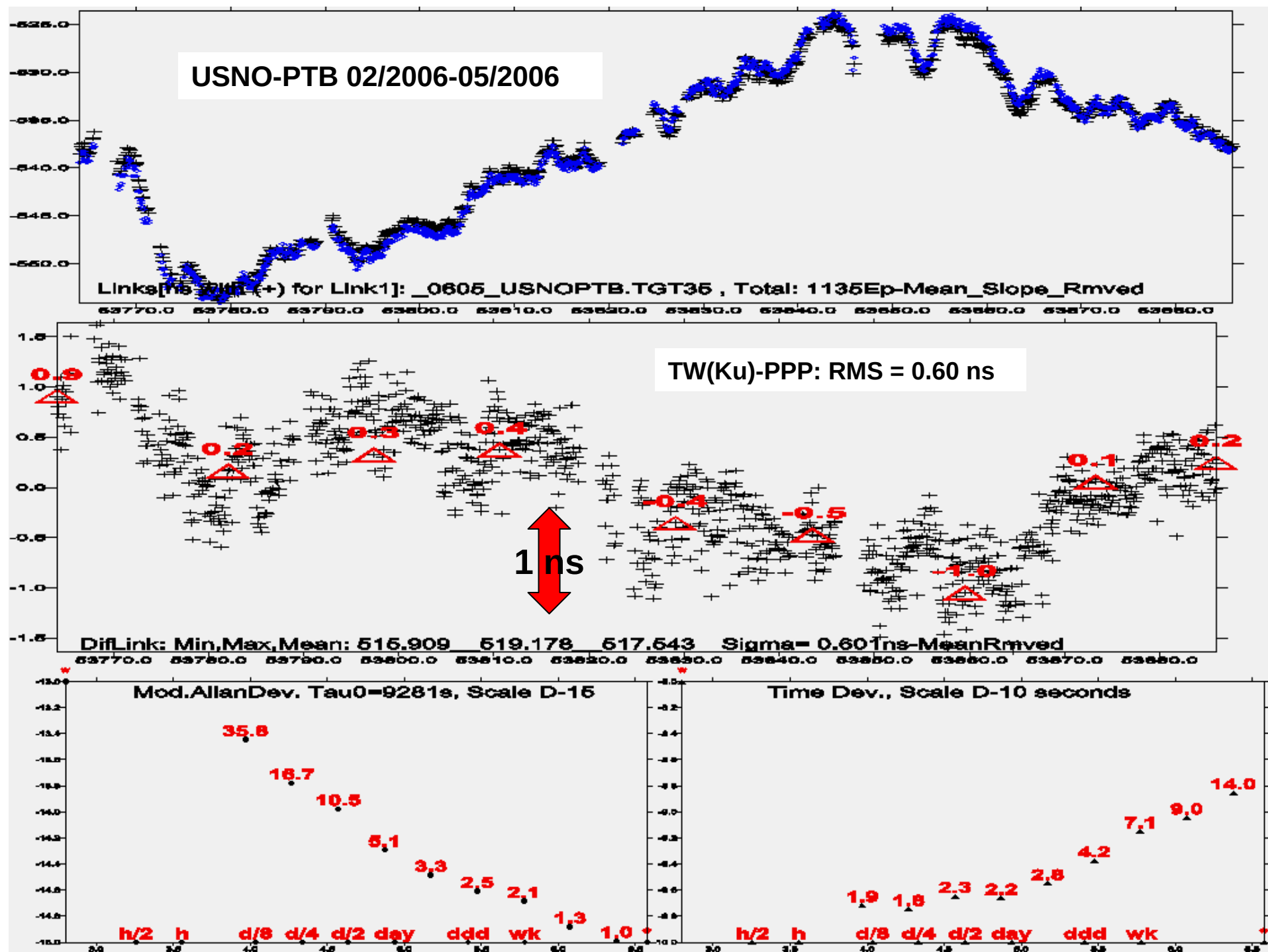

OP-PTB 02/2006-05/2006
Links[ns with (+) for Link1]: _0605_OPPTB.TGT35 , Total: 1253Ep-Mean_Slope_Rmved
TW(Ku)-PPP: Change of calibration of TW link end March 2006
3 ns
DifLink: Min,Max,Mean: 135.868 140.934 138.153 Sigma=1.528ns-MeanRmved
Mod.AllanDev. Tau0=8407s, Scale D-15
48.9
19.6
9.9
6.1
4.4
2.5
1.7
1.5
1.9
h/2 h d/8 d/4 d/2 day ddd wk
Time Dev., Scale D-10 seconds
2.4
1.9
1.9
2.4
3.4
3.9
5.4
9.3
23.4
h/2 h d/8 d/4 d/2 day ddd wk

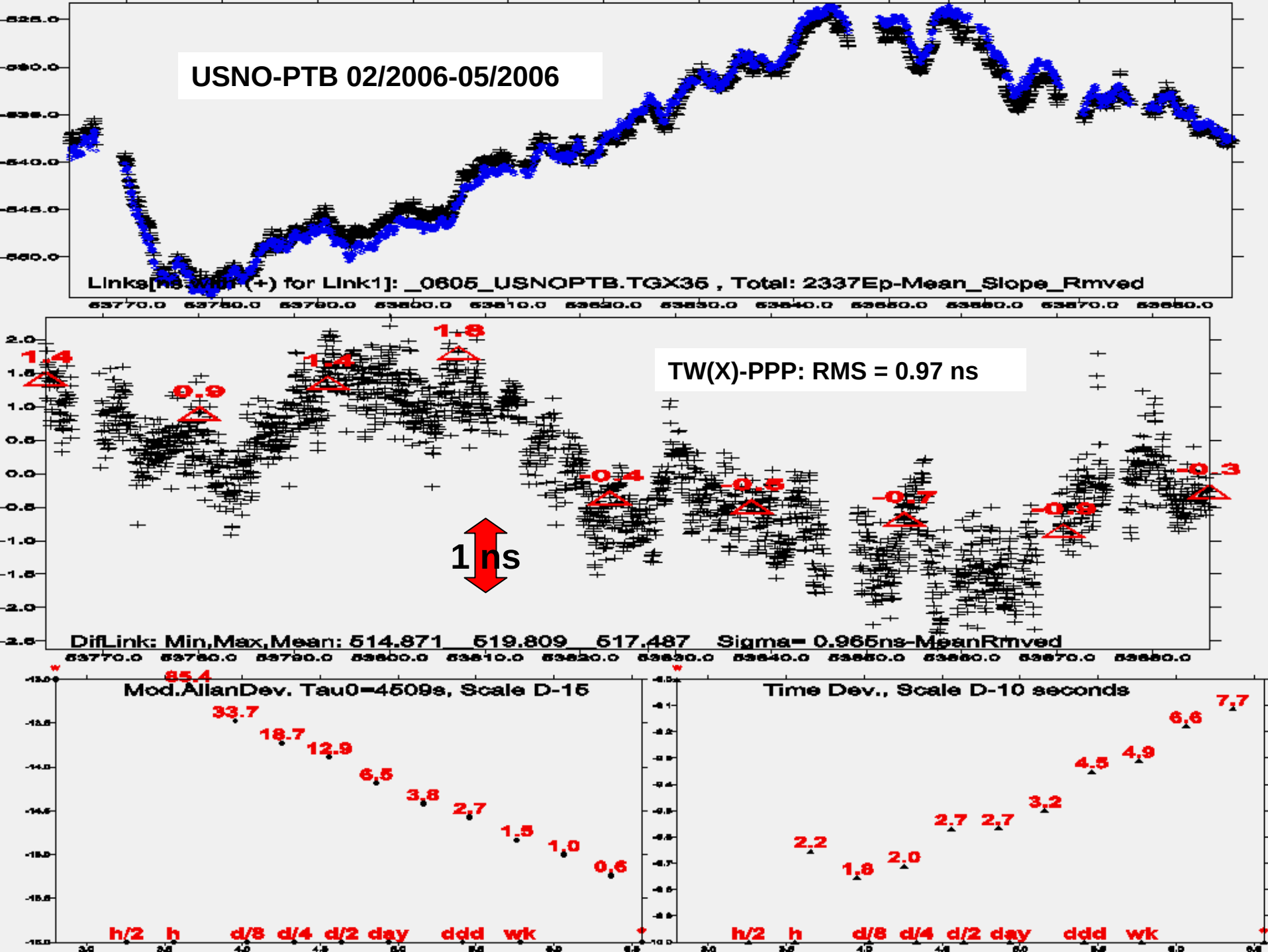

OP-USNO 02/2006-05/2006
Links[ns with (+) for Link1]: _0605_OPUSNO.TGT36 , Total: 1005Ep-Mean_Slope_Rmved
TW(Ku)-PPP: RMS = 0.51 ns
Peak to peak = 2 ns
1 ns
DifLink: Min,Max,Mean: 6610.882_6613.364_6612.103 Sigma= 0.509ns-MeanRmved
Mod.AllanDev. Tau0=10481s, Scale D-15
50.3
28.2
16.3
12.0
8.3
5.9
4.1
2.3
1.2
h/2 h d/8 d/4 d/2 day ddd wk
Time Dev., Scale D-10 seconds
3.0
3.4
4.4
5.8
8.1
11.6
16.1
17.9
19.1
h/2 h d/8 d/4 d/2 day ddd wk

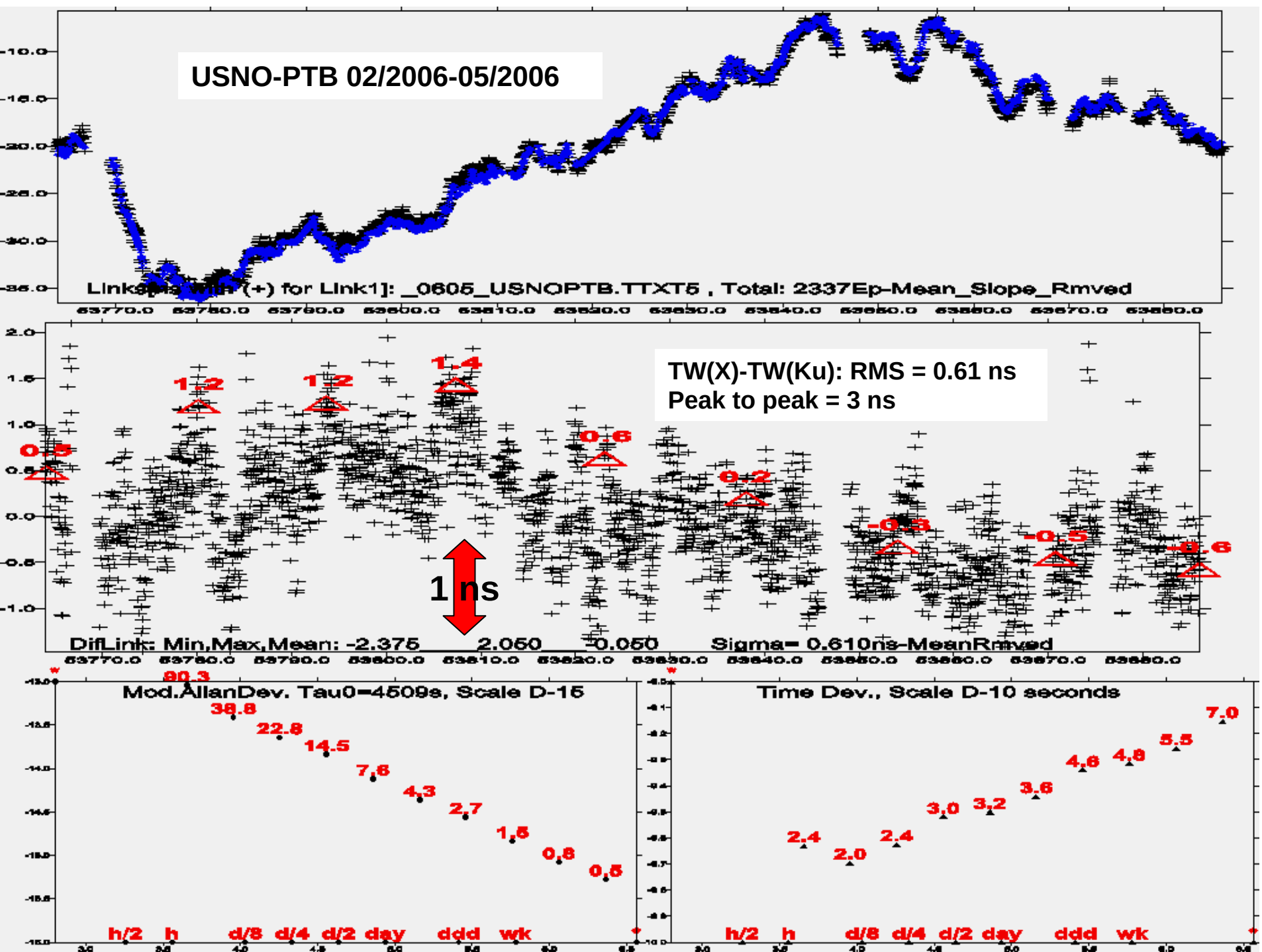

NICT-PTB 02/2006-05/2006
Links[ns with (+) for Link1]: _0605_NICTPTB.TGT35 , Total: 2447Ep-Mean_Slope_Rmved
TW(Ku)-PPP: RMS =0.80 ns
Peak to peak : 4 ns
1 ns
DifLink: Min,Max,Mean: 174.446 179.321 176.444 Sigma= 0.801ns-MeanRmved
Mod.AllanDev. Tau0=3841s, Scale D-15
h/2 h d/8 d/4 d/2 day ddd wk
Time Dev., Scale D-10 seconds
Clear diurnal signature
h/2 h d/8 d/4 d/2 day ddd wk


NICT-TL 10/2005-02/2006
Links[ns with (+) for Link1]: _0601_TLNICT.TGT35 , Total: 804Ep-Mean_Slope_Rmved
TW(Ku)-PPP: RMS =0.80 ns
Peak to peak : 4 ns
1 ns
DifLink: Min,Max,Mean: -383.844_-379.401_-380.782 Sigma= 0.797ns-MeanRvmed
Mod.AllanDev. Tau0=4393s, Scale D-15
53.6
34.0
19.3
13.9
8.2
5.2
4.4
2.4
h/2 h d/8 d/4 d/2 day ddd wk
Time Dev., Scale D-10 seconds
1.4
1.7
2.0
2.8
3.3
4.2
7.2
7.8
h/2 h d/8 d/4 d/2 day ddd wk

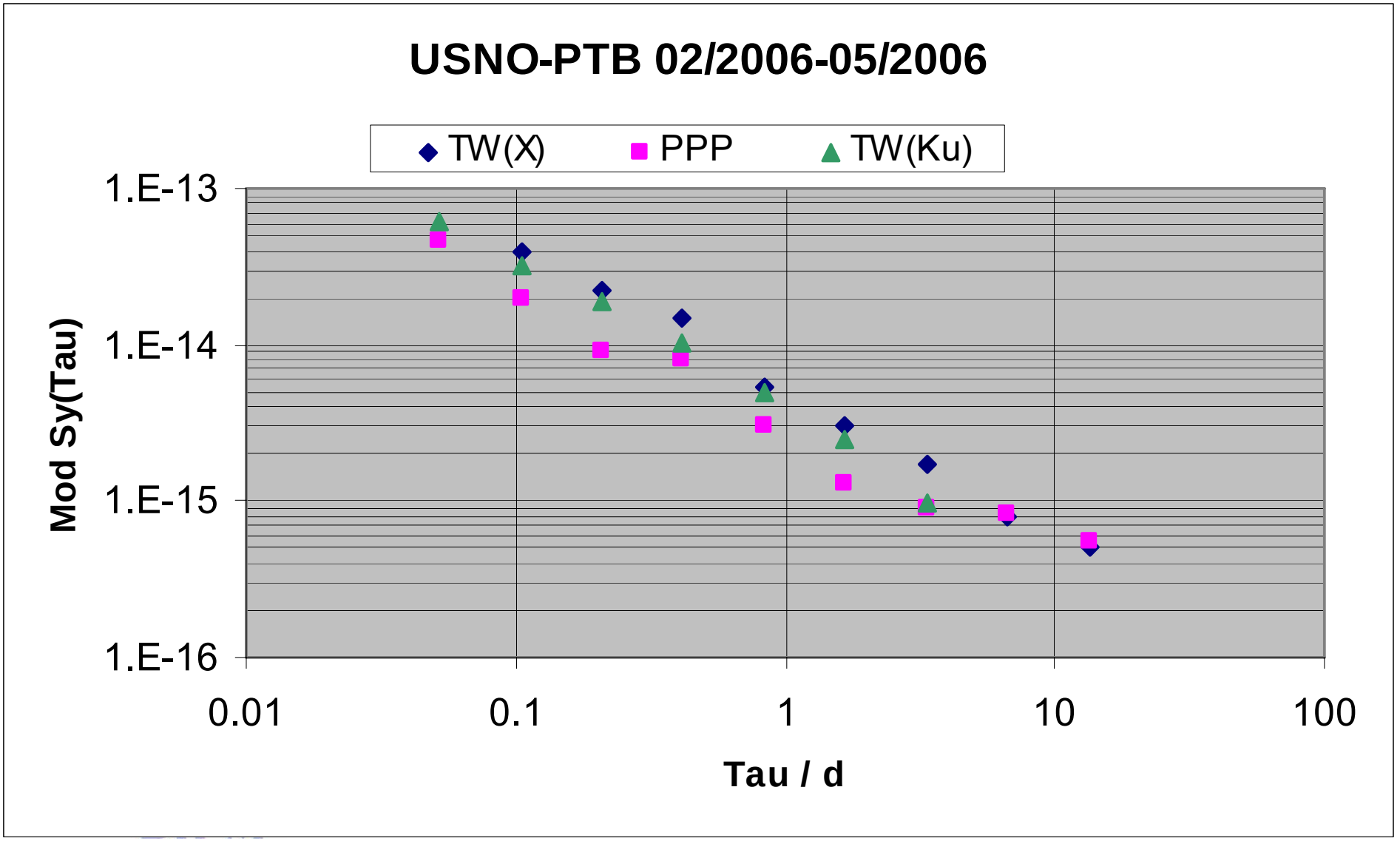
Three-corner hat
TW(X) - TW(Ku) - PPP


USNO-PTB 02/2006-05/2006
Links[ns 2/div (+) for Link1]: _0605_USNOPTB.TGT35 , Total: 1135Ep-Mean_Slope_Rmved
TW(Ku)-PPP: RMS = 0.60 ns
1 ns
DifLink: Min,Max,Mean: 515.909 519.178 517.643 Sigma= 0.601ns-MeanRmved
Mod.AllanDev. Tau0=9281s, Scale D-15
35.8
16.7
10.5
5.1
3.3
2.5
2.1
1.3
1.0
h/2 h d/8 d/4 d/2 day ddd wk
Time Dev., Scale D-10 seconds
1.9
1.8
2.3
2.2
2.8
4.2
7.1
9.0
14.0
h/2 h d/8 d/4 d/2 day ddd wk

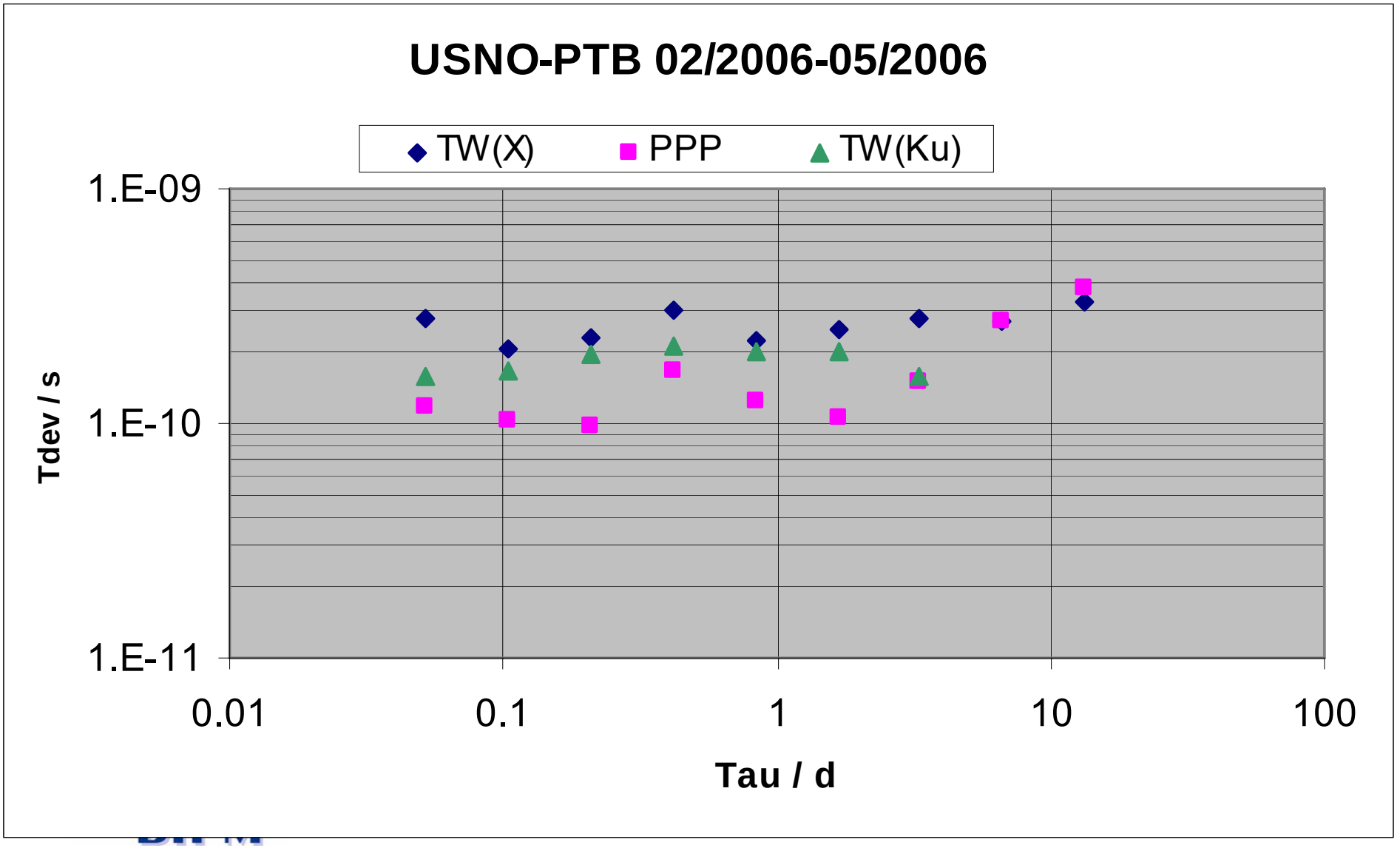

USNO-PTB 02/2006-05/2006
Links[no with (+) for Link1]: _0605_USNOPTB.TGX35 , Total: 2337Ep-Mean_Slope_Rmved
TW(X)-PPP: RMS = 0.97 ns
1 ns
DifLink: Min,Max,Mean: 514.871 519.809 517.487 Sigma= 0.965ns-MeanRmved
Mod.AllanDev. Tau0=4509s, Scale D-15
85.4
33.7
18.7
12.9
6.5
3.8
2.7
1.5
1.0
0.6
h/2 h d/8 d/4 d/2 day ddd wk
Time Dev., Scale D-10 seconds
2.2
1.8
2.0
2.7
2.7
3.2
4.5
4.9
6.6
7.7
h/2 h d/8 d/4 d/2 day ddd wk


USNO-PTB 02/2006-05/2006
TW(X)-TW(Ku): RMS = 0.61 ns
Peak to peak = 3 ns
1 ns
DifLink: Min,Max,Mean: -2.375 2.060 -0.050 Sigma= 0.610ns-MeanRmved
Mod.AllanDev. Tau0=4509s, Scale D-15
90.3
38.8
22.8
14.5
7.6
4.3
2.7
1.5
0.8
0.5
h/2 h d/8 d/4 d/2 day ddd wk
Time Dev., Scale D-10 seconds
2.4
2.0
2.4
3.0
3.2
3.6
4.6
4.8
5.5
7.0
h/2 h d/8 d/4 d/2 day ddd wk

Modified Allan deviation from 3-cornered hat



Time deviation from 3-cornered hat



Conclusions (1): Comparisons results

- PPP clock results generally agree with IGS Final results within ~100-200 ps: The most prominent features are the day-boundary discontinuities.

- PPP-TW(Ku)
  - Over 4 months, RMS of differences between 0.4 ns and 1 ns
  - Diurnal signatures and long-term trends sometimes visible, difficult to attribute

- PPP-TW(Ku)-TW(X) 3-corner comparisons show that
  - PPP generally more stable until 10-day averaging
  - TW(Ku) sometimes noisier than others
  - All techniques stable to 100-300 ps up to 10-day averaging
  - Long-term trend (2 ns over 4 months), possibly in GPS
- These conclusions from one example only!

Conclusions (2): Use of PPP for TAI

- The PPP package used so far is reliable. Other PPP packages are available.
- Some run-time problems eliminated by data editing (currently on a daily basis). Some refinement may be necessary.
- PPP results are satisfactory.

- The routine use of PPP for TAI links looks OK.
- Some changes needed in data transmission / handling:
  - Rinex data necessary.
  - Calibration information should be handled separately or added to Rinex format.

- Manpower needed, specially for the development and tests phase.

Acknowledgements

- Laboratories that operate receivers and provide data for TAI and for the IGS.

- Laboratories that provided data on request, e.g. NICT

- PPP developers (NRCan) specially F. Lahaye.
- ORB