Improving IGS Timescale Stability and Tracking of UTC

K. Senior, J. Ray
U.S. Naval Research Laboratory (NRL)

2004 IGS Workshop & Symposium
Bern, Switzerland

Status of IGS Clock Products

- Sat clocks+ orbits (Final & Rapid) provide autonomous PPP at few cm level
- Station clock comparisons show accuracies ranging from 120ps to ~ 1ns (*Metrologia 2003*)
- Finals densification much improved (e.g., CODE & GFZ + new MIT)
- Rapids were previously most robust; fragile due to USNO/CODE dropouts
- Estimates referenced to IGS timescales have shown to be useful for diagnosing station problems.

Needed/Expected Improvements in IGS Clock Products

- Continued densification, now particularly with Rapids.
  - H-Masers + timing lab stations critical
- Timescale Improvements
- Station operators could improve local clock performance significantly in almost all cases
  - using clock estimates (referenced to IGS timescales) as diagnostic tool,
  - thermally isolating receiver, phase-stabilized cabling, & other known problems.

Clock “Fiducial” Stations

Primary (Hm or timing lab)

ALGO (HM),	**AMC2*** (HM),	**BOR1*** (Cs),	BREW (HM),	**BRUS*** (HM),
DRAO (HM),	FAIR (HM),	FORT (HM),	GODE (HM),	GODZ (HM),
GOL2 (HM),	HOB2 (HM),	**IENG*** (Cs),	IRKJ (HM),	IRKT (HM),
KGN0* (Cs),	KHAJ (HM),	KOKB (HM),	MAD2 (HM),	MAT1 (HM),
MATE (HM),	**MDVJ*** (HM),	MDVO (HM),	MEDI (HM),	METS (HM),
MIZU* (Cs),	NLIB (HM),	NNOR (HM),	**NPLD*** (HM),	**NRC1*** (HM),
NYA1 (HM),	NYAL (HM),	**OBE2*** (Rb),	ONSA (HM),	**OPMT*** (HM),
PIE1 (HM),	**PTBB*** (Cs),	**SFER*** (Cs),	SPT0 (HM),	STJO (HM),
TID1 (HM),	TID2 (HM),	TIDB (HM),	**TLSE*** (Cs),	**TWTF*** (Cs),
USN1* (HM),	**USNO*** (HM),	USUD (HM),	WES2 (HM),	WSRT (HM),
WTZA* (HM),	**WTZR*** (HM),	YEBE (HM),	YELL (HM)	

Secondary (Cs or Rb not at timing lab)

AREQ (Rb),	BAHR (Cs),	BAN2 (Rb),	CAGZ (Cs),	CHUR (Rb),
DAEJ (Cs),	DARW (Rb),	DWH1 (Cs),	GMAS (Cs),	GRAZ (Rb),
HARB (Cs),	HERS (Rb),	HLFX (Rb),	JOZ2 (Rb),	JOZE (Rb),
JPLM (Rb),	KERG (Cs),	KIRU (Cs),	KOUR (Cs),	LPGS (Rb),
MAR6 (Rb),	MAS1 (Cs),	MCM4 (Rb),	OBET (Cs),	PERT (Cs),
PRDS (Cs),	QAQ1 (Rb),	RIOG (Rb),	SCH2 (Rb),	STR1 (Cs),
SUTM (Rb),	SYOG (Cs),	THTI (Rb),	THU2 (Rb),	THU3 (Rb),
TNML (Rb),	TROM (Rb),	TSKB (Cs),	VILL (Cs),	WHIT (Rb),
WROC (Rb),	WUHN (Cs),	YAKT (Cs),	YAR1 (Cs),	YAR2 (Rb)

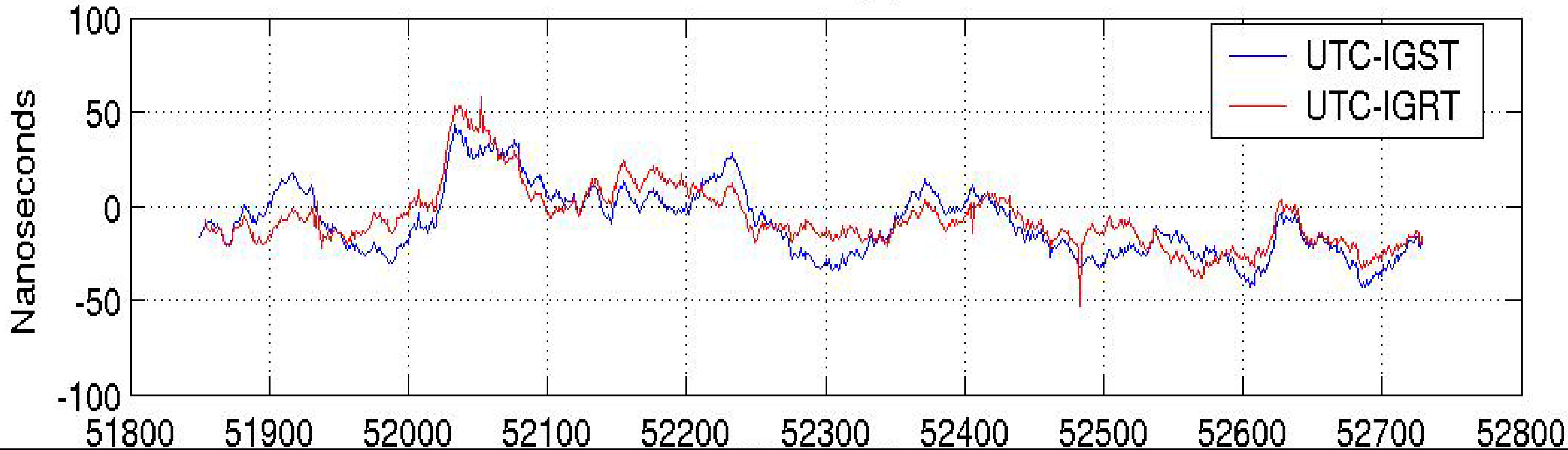
List updated daily at https://timescales.nrl.navy.mil/

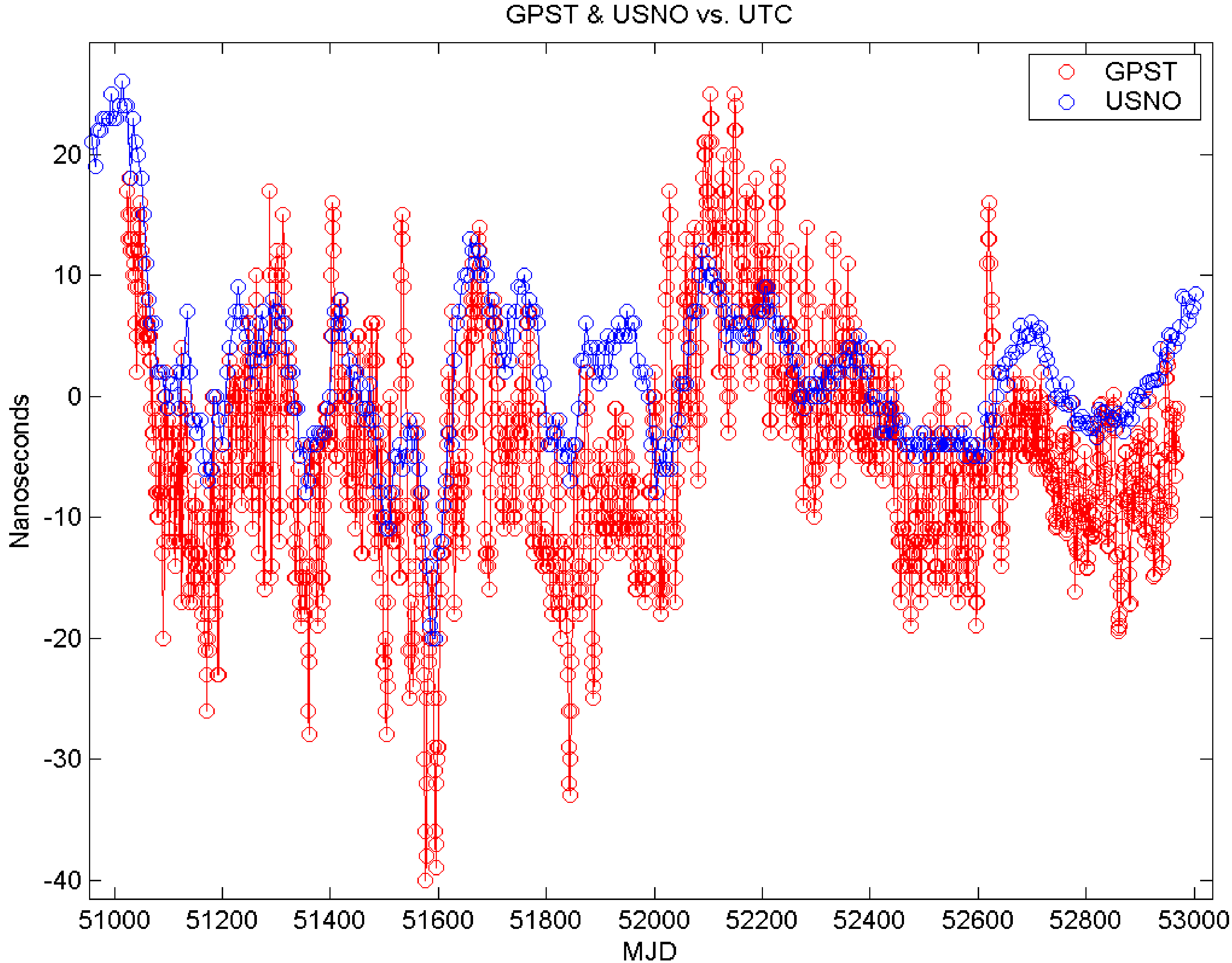
IGS Stations Co-located at Timing Labs

IGS Site	Time Lab	GPS Receiver	Freq. Std.	City
AMC2	AMC *	AOA SNR-12 ACT	H-maser	Colorado Springs, CO, USA
BOR1	AOS	AOA TurboRogue	cesium	Borowiec, Poland
BRUS	ORB	Ashtech Z-XII3T	H-maser	Brussels, Belgium
IENG	IEN	Ashtech Z-XII3T	Cesium	Torino, Italy
KGN0	CRL *	Ashtech Z-XII3	cesium	Koganei, Japan
MDVJ	VNIIM	Trimble 4000SSE	H-maser	Mendeleevo, Russia
MIZU	NAO	AOA Benchmark	cesium	Mizusawa, Japan
NPLD	NPL *	Ashtech Z-XII3T	H-maser	Teddington, UK
NRC1	NRC *	AOA SNR-12 ACT	H-maser	Ottawa, Canada
NRC2	NRC *	AOA SNR-8100 ACT	H-maser	Ottawa, Canada
OBE2	DLR	AOA SNR-8000 ACT	rubidium	Oberpfaffenhofen, Germany
OPMT	OP	Ashtech Z-XII3T	H-maser	Paris, France
PENC	SGO	Trimble 4000SSE	rubidium	Penc, Hungary
PTBB	PTB *	AOA TurboRogue	H-maser	Braunschweig, Germany
SFER	ROA *	Trimble 4000SSI	cesium	San Fernando, Spain
SPT0	SP	JPS Legacy	cesium	Boras, Sweden
TLSE	CNES	AOA TurboRogue	cesium	Toulouse, France
TWTF	TL *	Ashtech Z-XII3T	cesium	Taoyuan, Taiwan
USNO	USNO *	AOA SNR-12 ACT	H-maser	Washington, DC, USA
WTZA	IFAG	Ashtech Z-XII3T	H-maser	Wettzell, Germany
WTZR	IFAG	AOA SNR-8000 ACT	H-maser	Wettzell, Germany

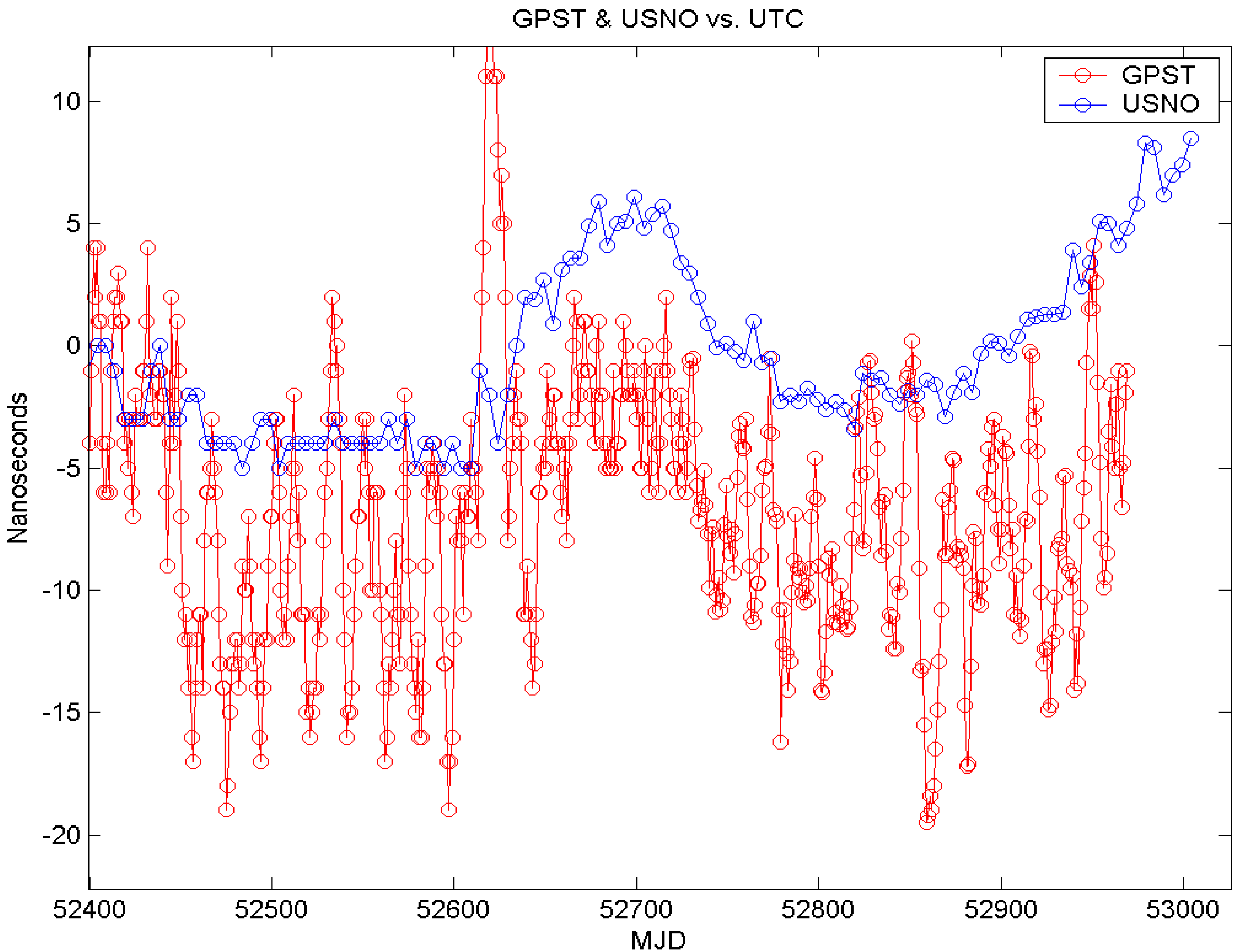
IGS Time Scale

- Internal IGS time scale implemented using a weighted combination of included frequency standards
- 1 d stability improved from ~2 x 10^{-14} (when aligned to GPS time before) to ~1 x 10^{-15} now
- Steered to GPS time in the long term (~30 to 40 d)





GPST & USNO vs. UTC
GPST
USNO
Nanoseconds
MJD
20
10
0
-10
-20
-30
-40
51000
51200
51400
51600
51800
52000
52200
52400
52600
52800
53000


GPST & USNO vs. UTC
GPST
USNO
Nanoseconds
MJD
10
5
0
-5
-10
-15
-20
52400
52500
52600
52700
52800
52900
53000

Station Calibration Bias

To relate IGS time scale to UTC, need to know prediction of $(\mathrm{UTC}_i - \mathrm{UTC})$ and station timing bias:

$$B_i = \mathrm{CLK}_i - \mathrm{UTC}_i$$

CLK_i = GPS geodetic clock estimates at lab i
UTC_i = local realization of UTC for lab i

STATION CALIBRATION BIAS: includes internal GPS receiver/antenna calibration bias & intra-lab offset to UTC_i

From IGS clock products & BIPM Circular T, can compute:

$$\begin{aligned} B_i' &= (\mathrm{CLK}_i - \mathrm{GPST})_{\mathrm{IGS}} - (\mathrm{UTC} - \mathrm{GPST})_{\mathrm{T}} + (\mathrm{UTC} - \mathrm{UTC}_i)_{\mathrm{T}} \\ &= (\mathrm{CLK}_i - \mathrm{UTC}_i) + (\underline{\mathrm{GPST}_{\mathrm{T}} - \mathrm{GPST}_{\mathrm{IGS}}}) \\ &= B_i + \underline{\Delta\mathrm{GPST}} \end{aligned}$$

small corrections due to different methods of observing GPS time

New Steering Reference

Using LQG alg., steer to zero the quanity:

$$(UTC\text{-}IGST_u) = \Sigma w_i(CLK_i - IGST_u) - B_i] + (UTC\text{-}UTC_i)$$

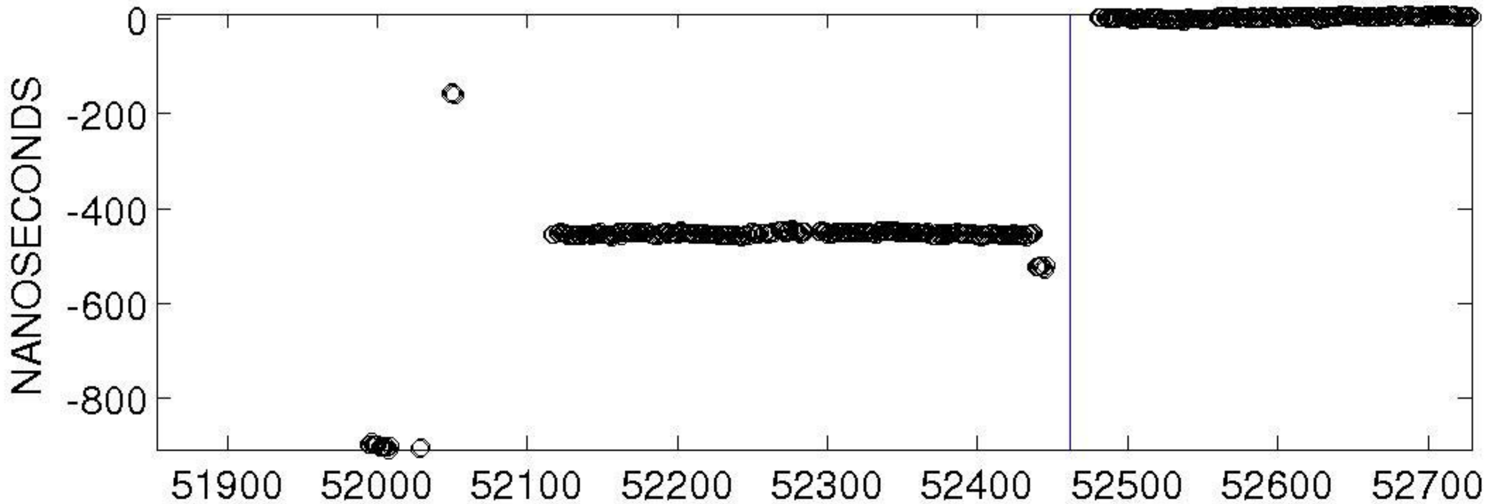
Output of existing timescale algorithm

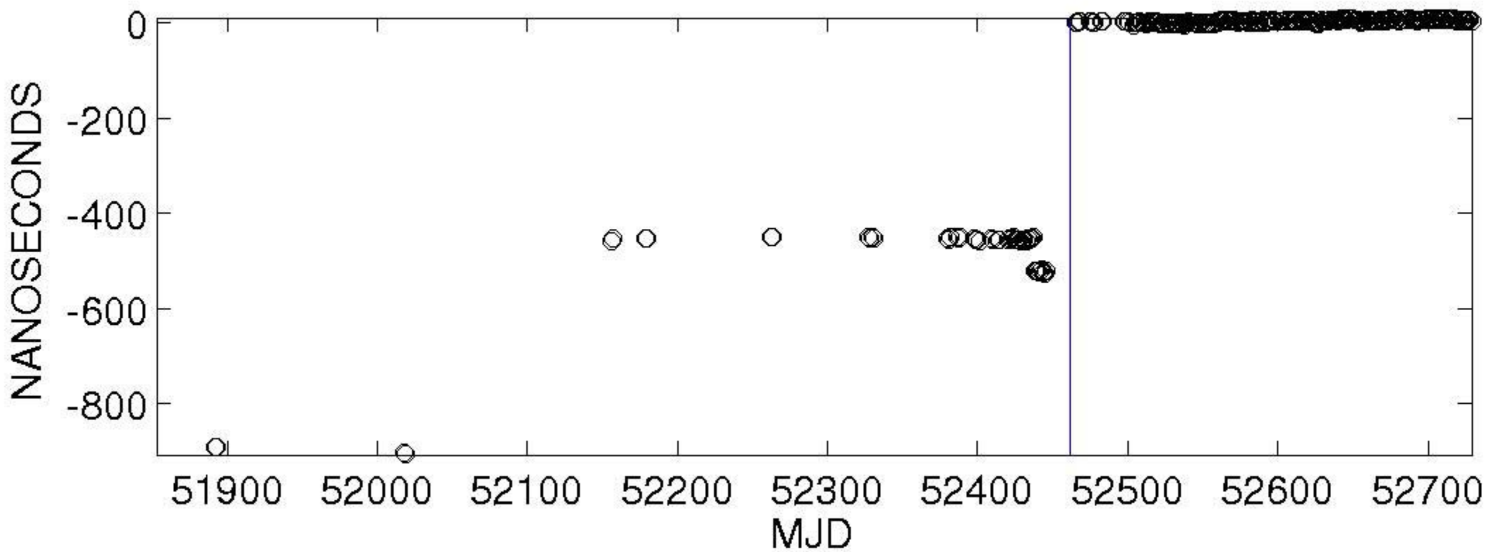
Can be determined provided bias is stable

Must predict

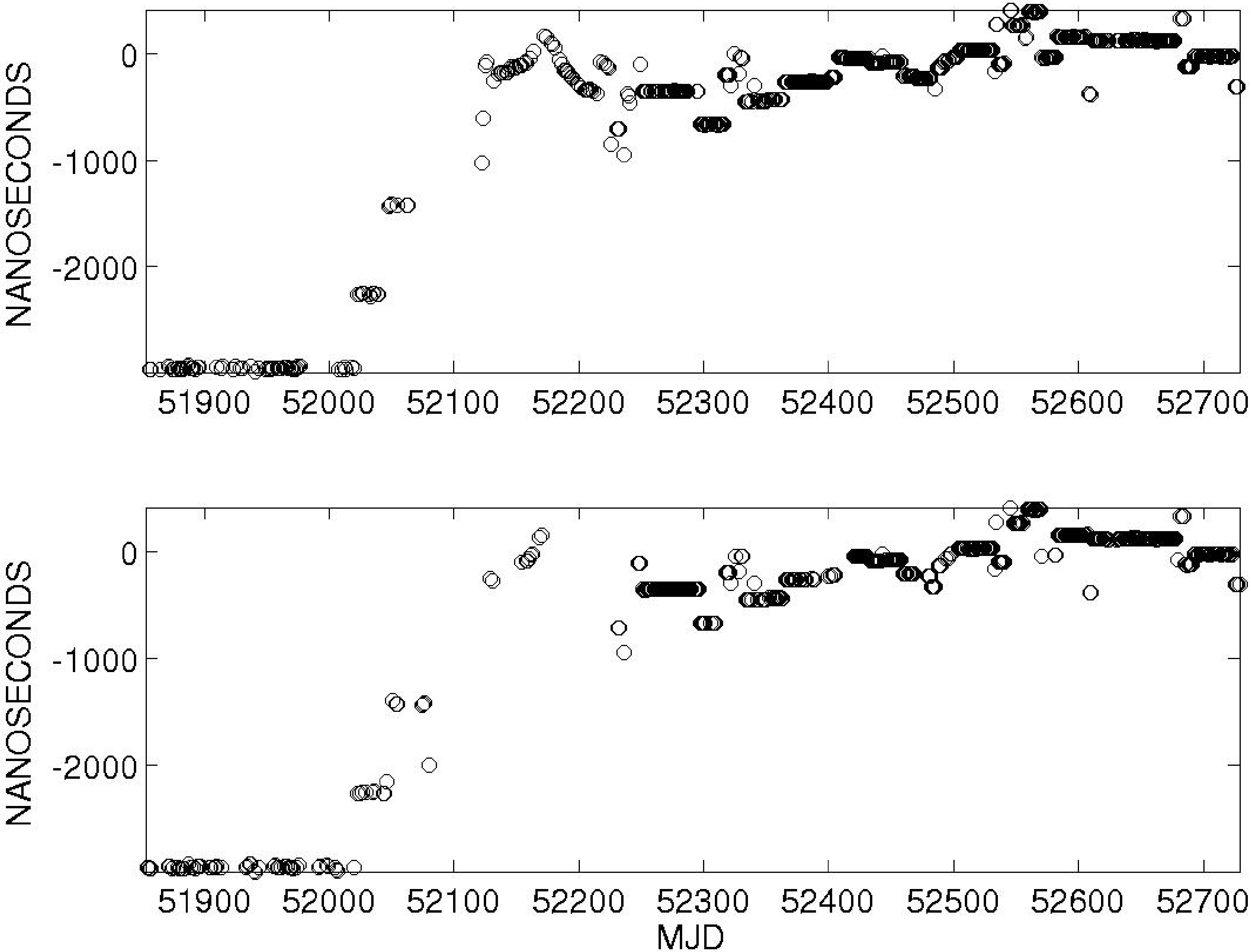
3-state LQG currently used, but 2-state may suffice

$$B'_{\mathrm{AMC2}}(t)$$

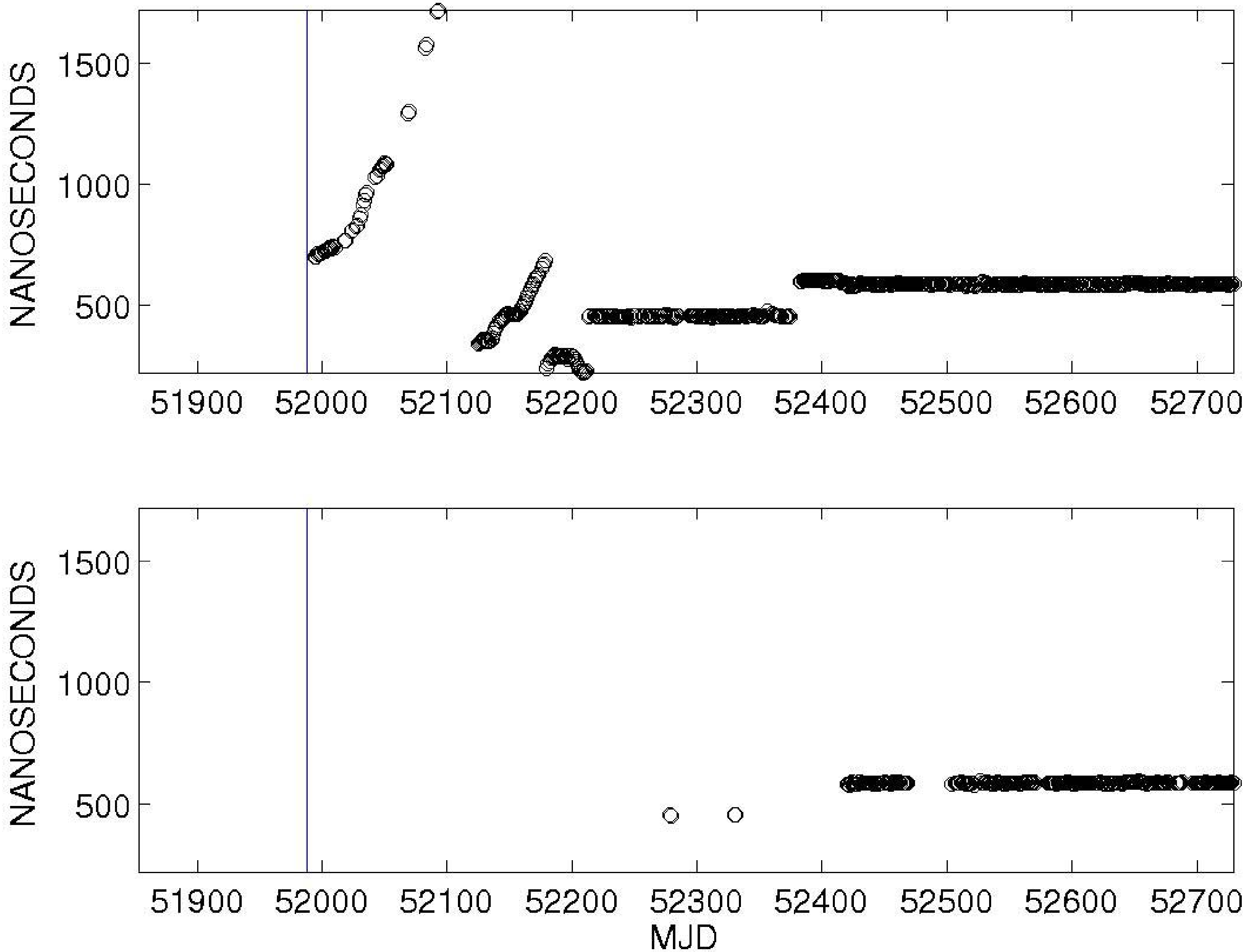




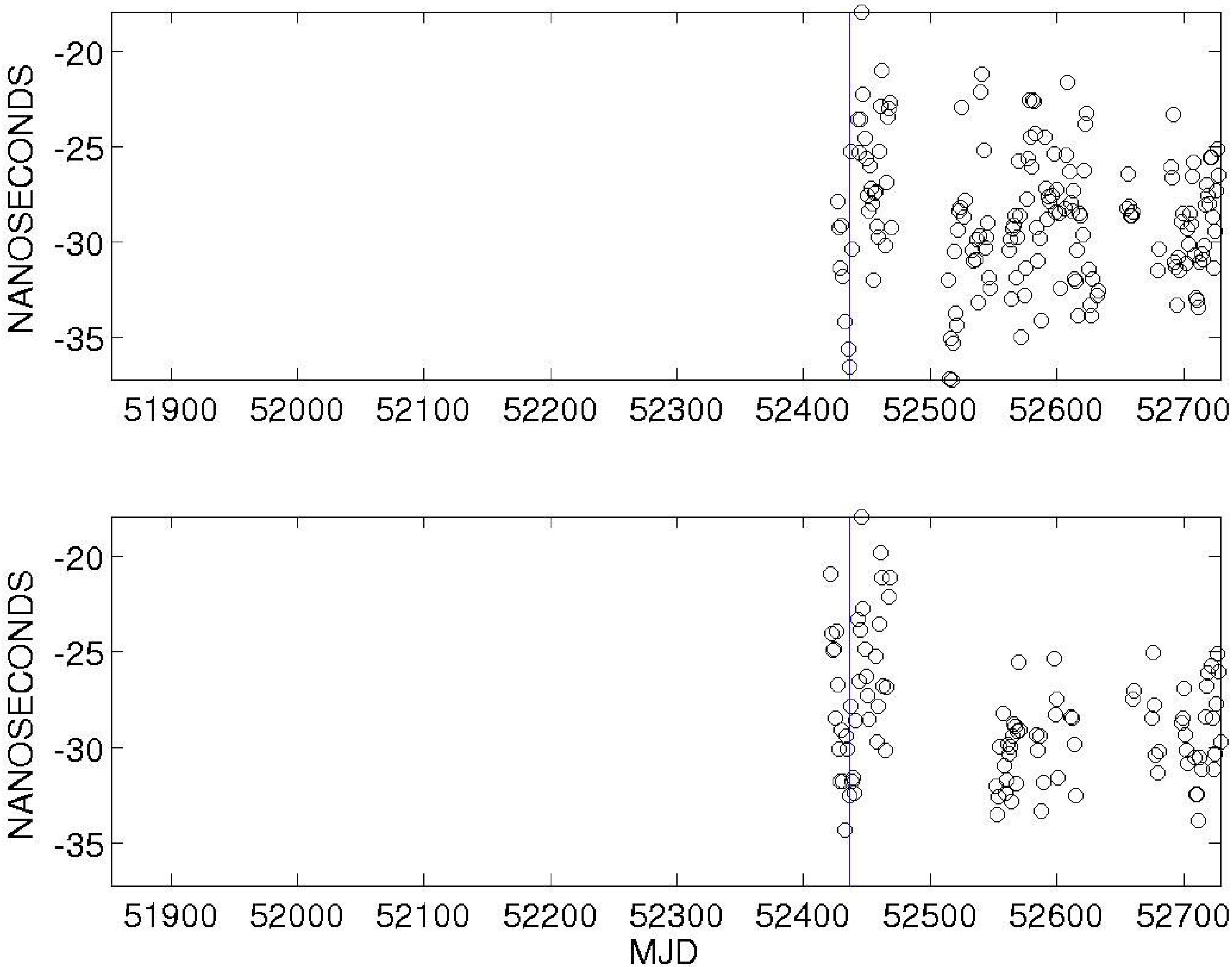
$B'_{\mathrm{BOR1}}(t)$



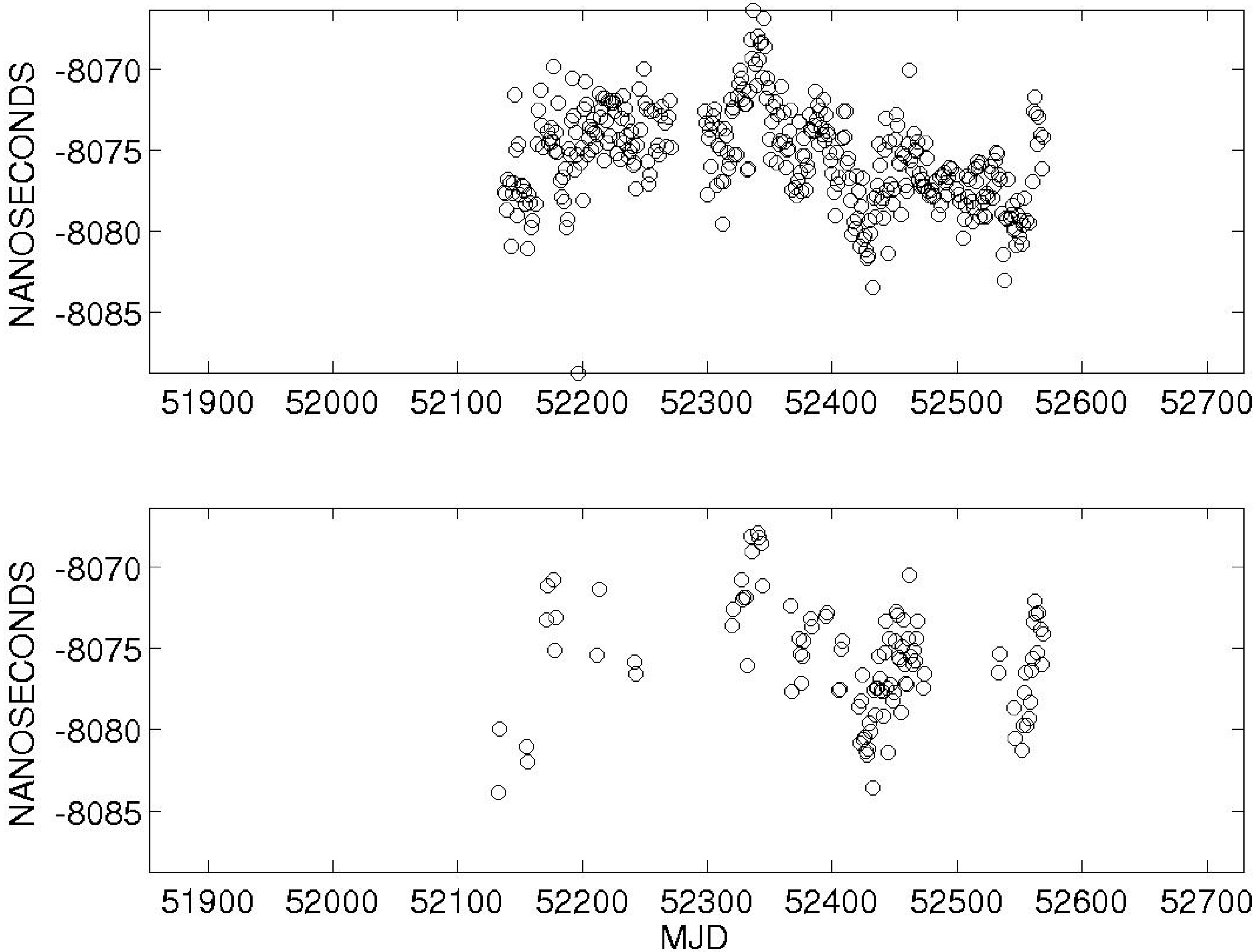
$B'_{\mathrm{BRUS}}(t)$



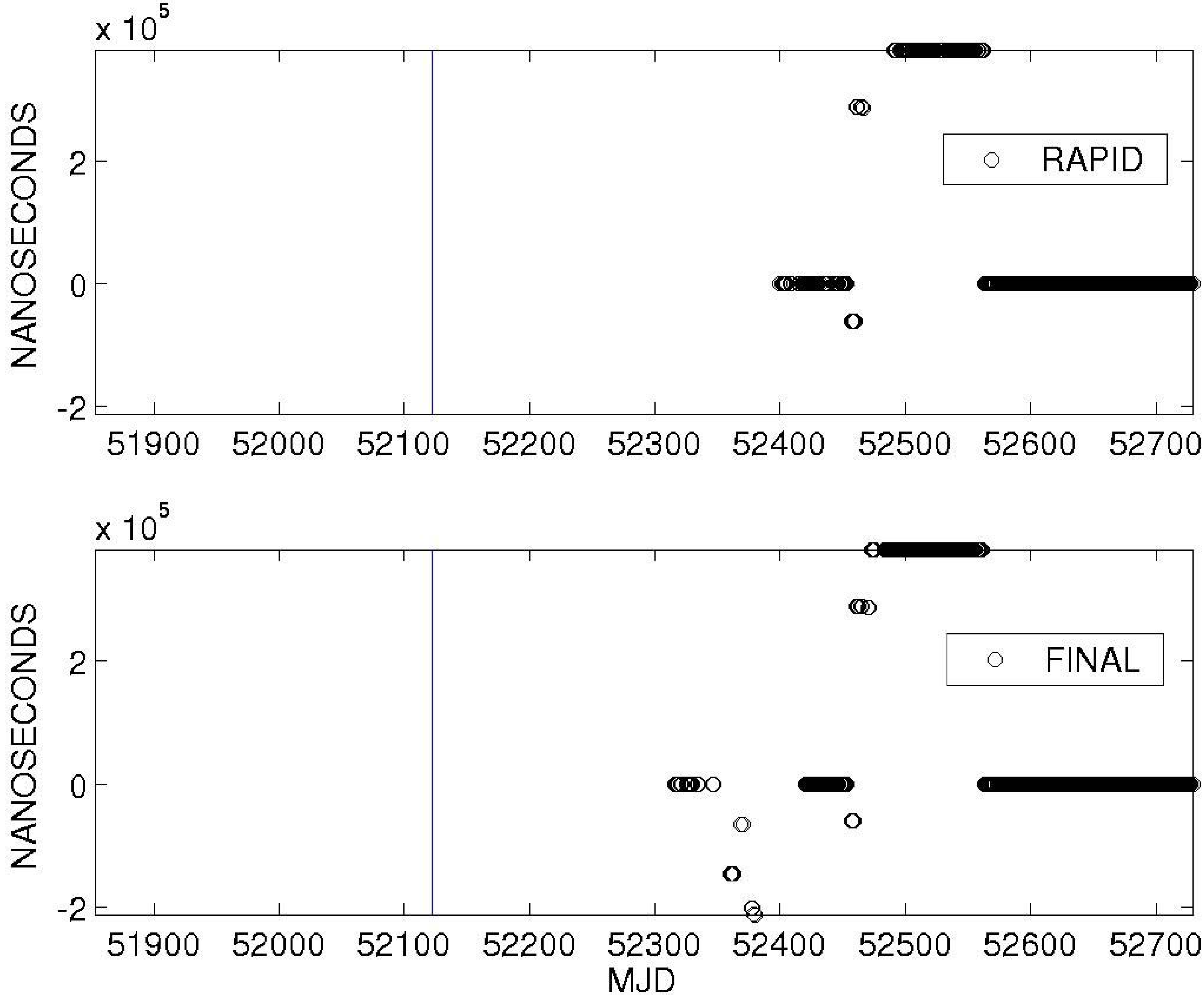
$B'_{\mathrm{KGN0}}(t)$



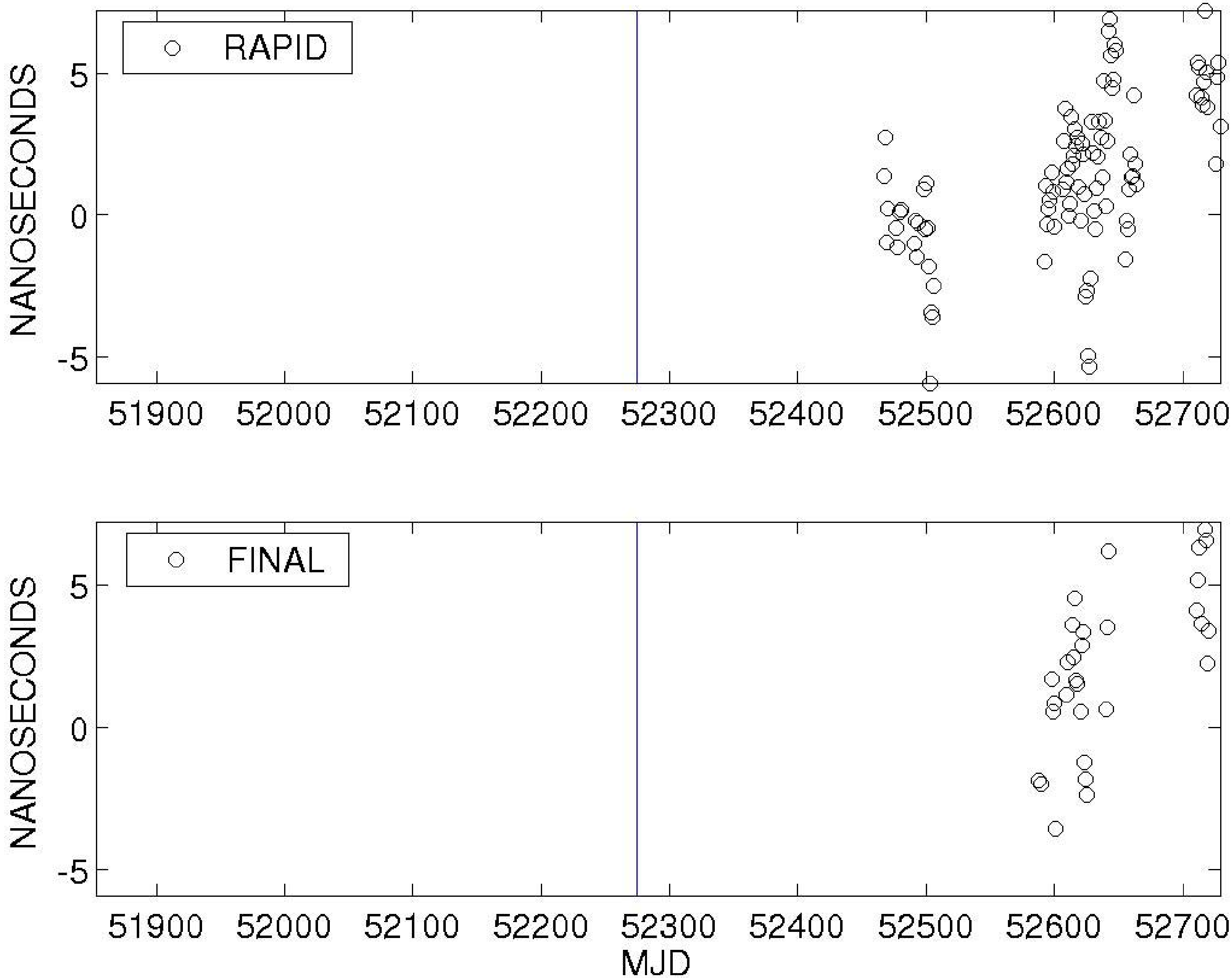
$$B'_{\mathrm{NPLD}}(t)$$

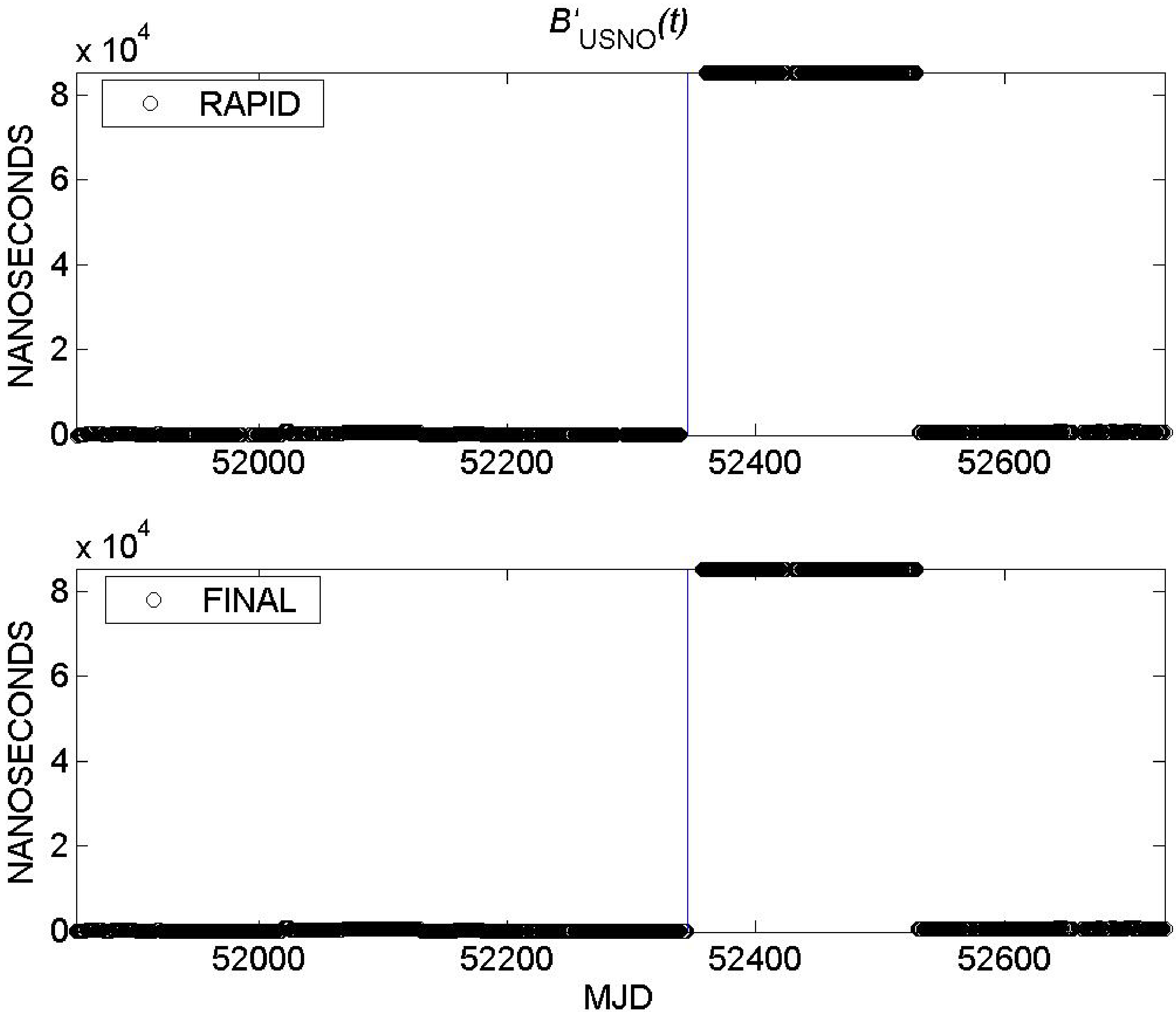


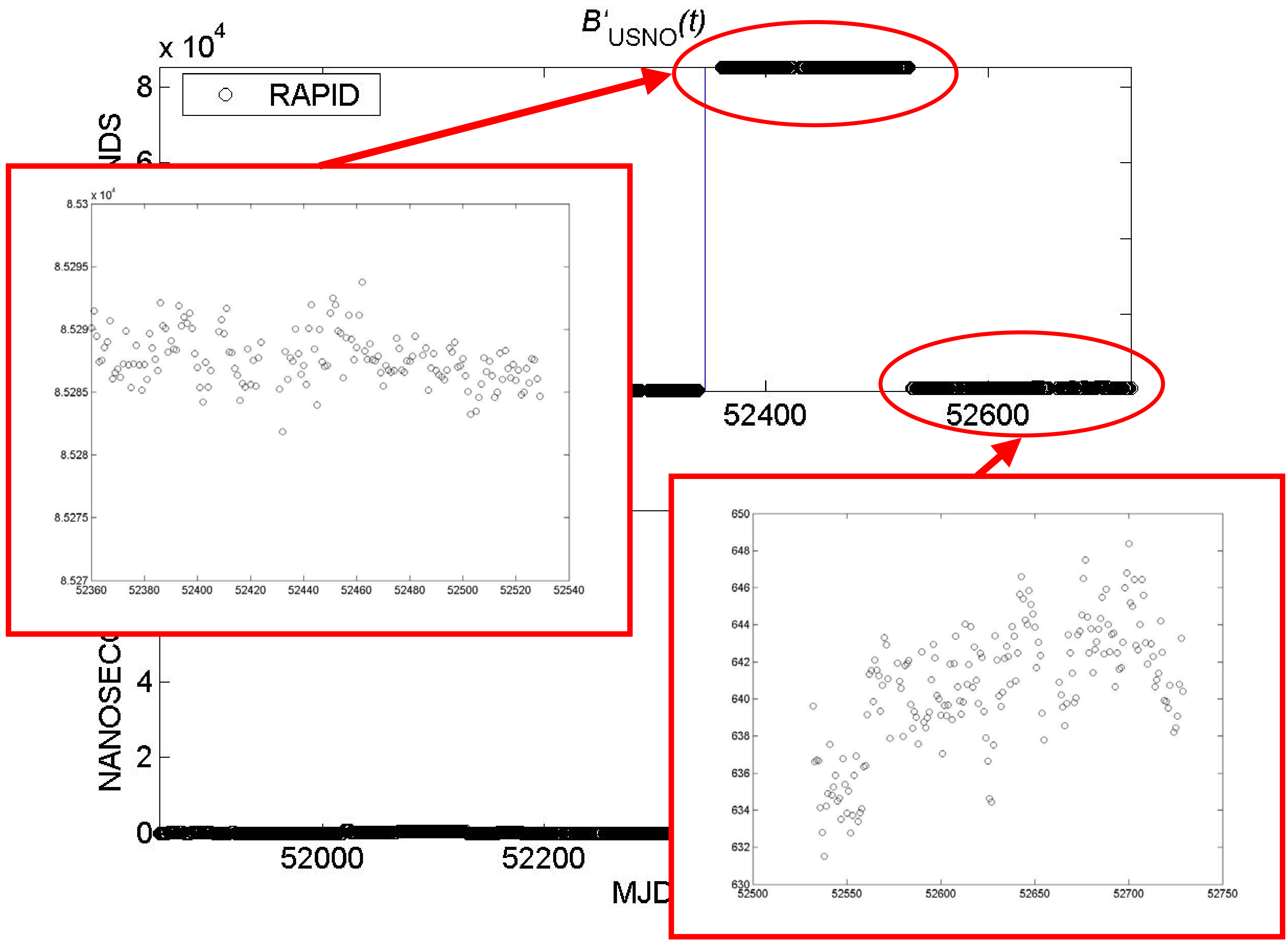
$$B'_{\mathrm{TWTF}}(t)$$



$$B'_{\text{USN1}}(t)$$


RAPID
NANOSECONDS
5
0
-5
51900
52000
52100
52200
52300
52400
52500
52600
52700
FINAL
NANOSECONDS
5
0
-5
51900
52000
52100
52200
52300
52400
52500
52600
52700
MJD


B'USNO(t)
x 10^4
RAPID
NANOSECONDS
0
2
4
6
8
52000
52200
52400
52600
x 10^4
FINAL
NANOSECONDS
0
2
4
6
8
52000
52200
52400
52600
MJD



$B'_{USNO}(t)$
x 10^4
RAPID
NANOSECONDS
MJD
8
6
4
2
0
52000
52200
52400
52600
x 10^4
8.53
8.5295
8.529
8.5285
8.528
8.5275
8.527
52360
52380
52400
52420
52440
52460
52480
52500
52520
52540
650
648
646
644
642
640
638
636
634
632
630
52500
52550
52600
52650
52700
52750

STATION	MJD	# Values		B'_i		B'_i WRMS	
	RANGE	Rapid	Final	Rapid	Final	Rapid	Final
AMC2	**52117-52437**	**299**	**42**	**-451.40**	**-452.38**	**2.87**	**1.47**
	52480-52729	**247**	**230**	**2.71**	**4.26**	**2.69**	**2.60**
BOR1	**51854-52020**	**60**	**54**	**-2955.91**	**-2955.26**	**11.94**	**12.68**
	52251-52296	**34**	**45**	**-353.05**	**-352.91**	**2.75**	**2.02**
	52504-52531	**26**	**28**	**31.72**	**31.15**	**3.31**	**2.62**
	52611-52678	**56**	**60**	**120.79**	**121.23**	**3.98**	**3.51**
	52693-52724	**32**	**31**	**-25.63**	**-25.60**	**2.63**	**2.18**
BRUS	**52213-52374**	**136**	**4**	**454.83**	**452.77**	**3.46**	**0.30**
	52420-52729	**292**	**238**	**585.83**	**586.15**	**2.59**	**2.42**
KGN0	**52421-52729**	**168**	**103**	**-28.95**	**-29.26**	**3.44**	**2.68**
NPLD	**52133-52569**	**376**	**112**	**-8075.90**	**-8075.78**	**2.82**	**3.33**
TWTF	**52316-52347**	**0**	**16**		**294.70**		**7.34**
	52400-52453	**41**	**34**	**298.87**	**298.93**	**4.91**	**6.13**
	52483-52562	**68**	**79**	**381242.55**	**381243.81**	**4.64**	**3.66**
	52563-52729	**160**	**166**	**288.45**	**289.84**	**7.69**	**9.05**
USN1	**52467-52729**	**95**	**30**	**0.76**	**1.65**	**2.24**	**1.89**
USNO	**51922-51986**	**60**	**65**	**-69.71**	**-69.69**	**2.43**	**2.52**
	52069-52129	**61**	**61**	**619.04**	**619.53**	**3.25**	**3.97**
	52131-52158	**26**	**28**	**-157.25**	**-157.72**	**2.27**	**2.36**
	52180-52256	**72**	**73**	**-69.07**	**-68.83**	**2.24**	**1.93**
	52260-52339	**74**	**80**	**5.91**	**5.89**	**1.55**	**1.38**
	52360-52529	**159**	**164**	**85287.15**	**85287.19**	**1.62**	**1.56**
	52532-52729	**185**	**187**	**639.92**	**639.59**	**3.33**	**2.69**

Determining ΔGPST

- Can separate ΔGPST into time-varying & quasi-static components:

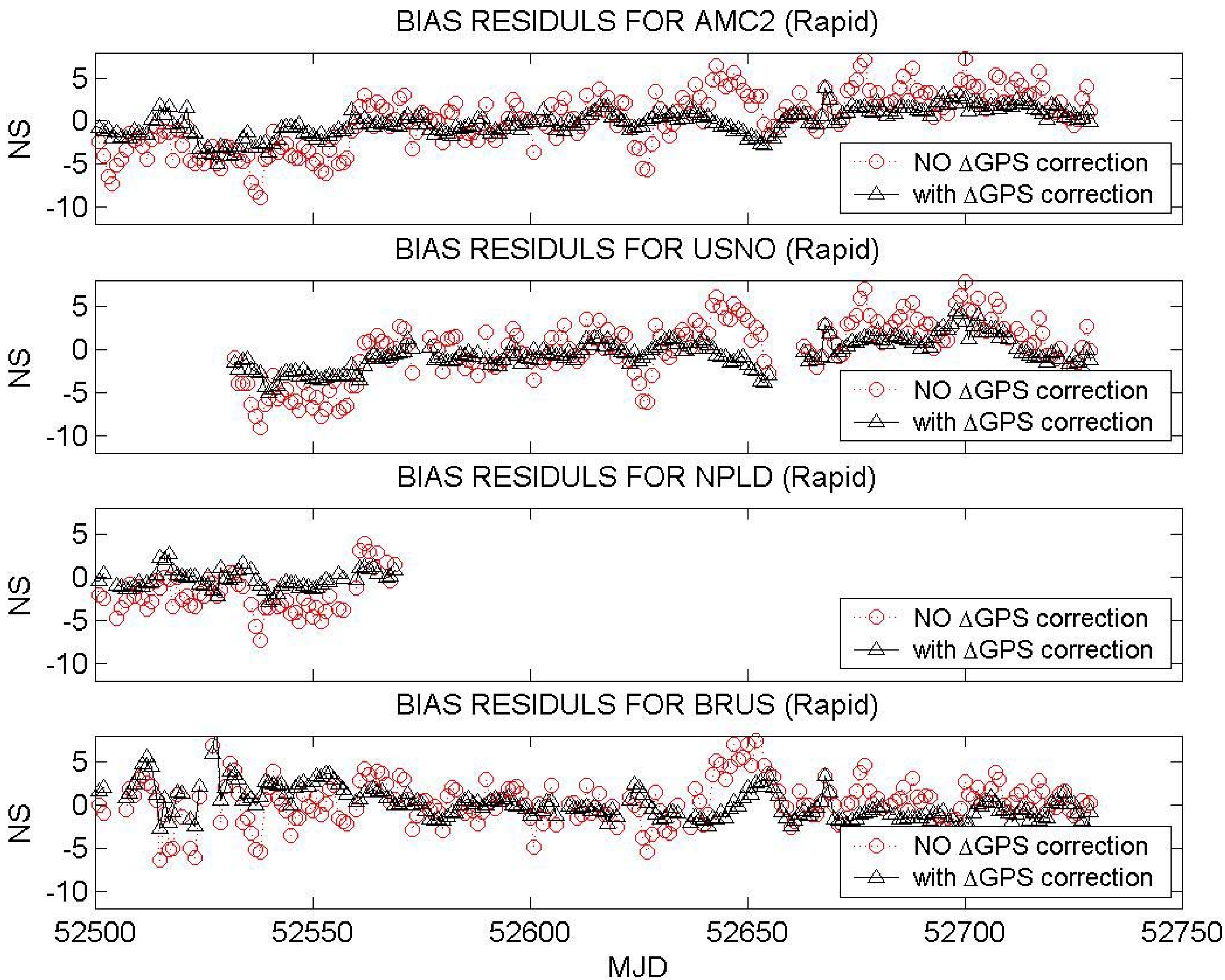
$$B_i = B_i' - \Delta\mathrm{GPST}$$
$$= B_i' - \underline{\Delta\mathrm{GPST}(t)} - \langle \underline{\Delta\mathrm{GPST}} \rangle + \underline{\ldots}$$

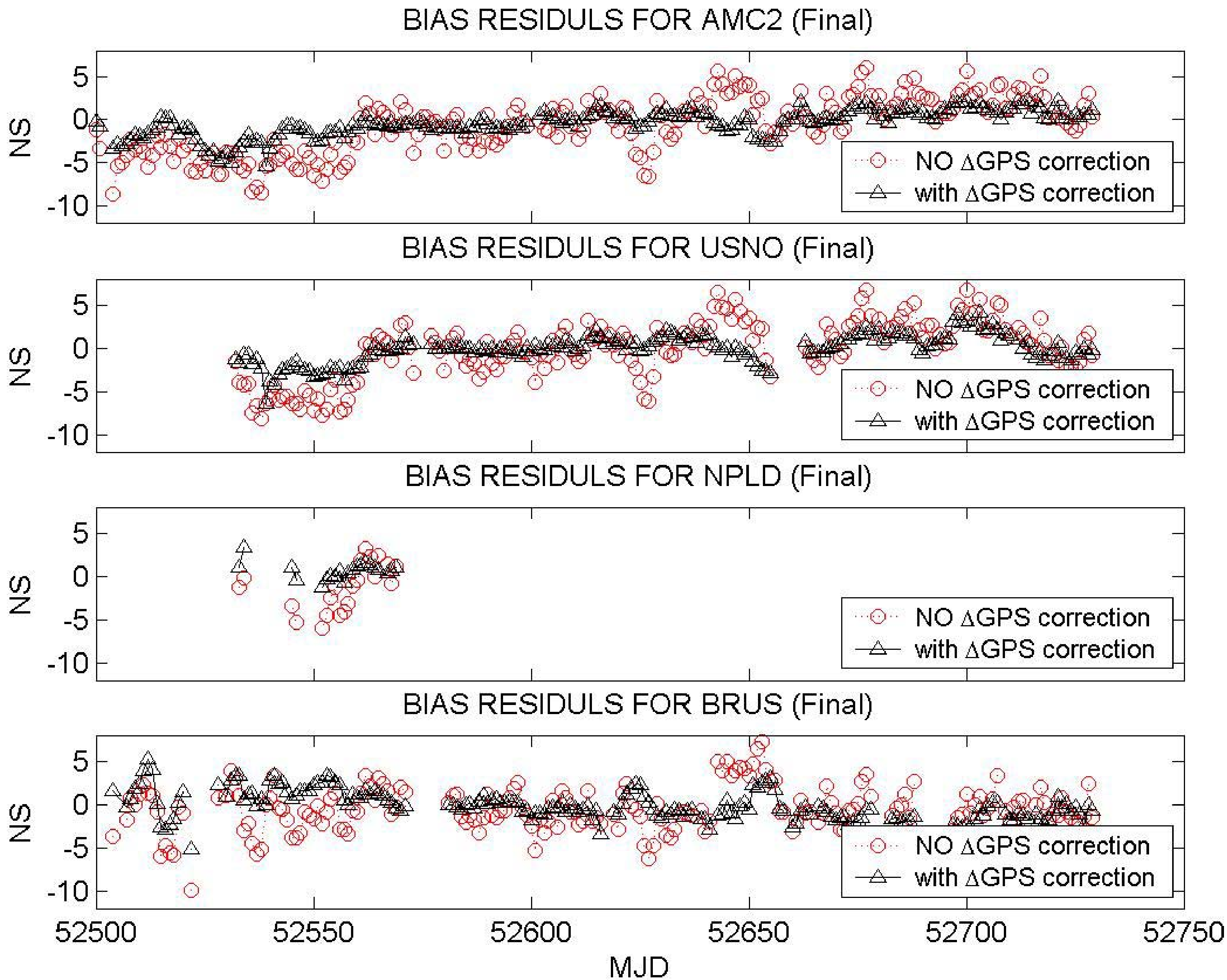
day-to-day variations in IGS clock alignment to GPS time & differences in satellites used by IGS & BIPM each day

average difference in BIPM & IGS measurement of GPS time due to different satellite antenna offset values ~ -1 ns (-0.92 to -1.3 ns over last few years)

lab-specific errors in local calibration & time transfer to BIPM

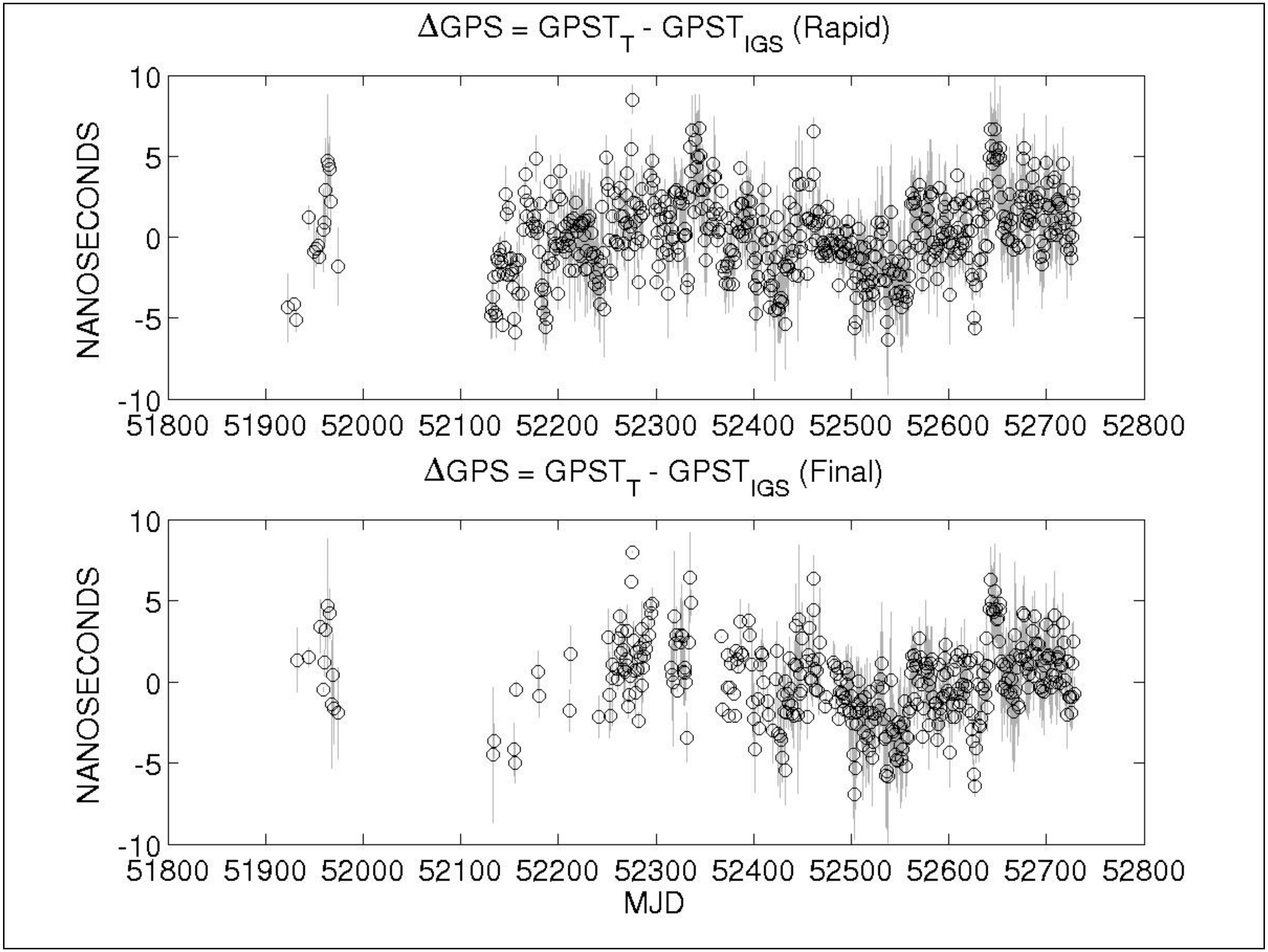
- $\Delta\mathrm{GPST}(t)$ causes common-mode variations in B_i' which can be used to estimate effect when multiple labs are available


BIAS RESIDULS FOR AMC2 (Rapid)
BIAS RESIDULS FOR USNO (Rapid)
BIAS RESIDULS FOR NPLD (Rapid)
BIAS RESIDULS FOR BRUS (Rapid)
NS
NO ΔGPS correction
with ΔGPS correction
5
0
-5
-10
52500
52550
52600
52650
52700
52750
MJD



BIAS RESIDULS FOR AMC2 (Final)
NS
5
0
-5
-10
NO ΔGPS correction
with ΔGPS correction
BIAS RESIDULS FOR USNO (Final)
NS
5
0
-5
-10
NO ΔGPS correction
with ΔGPS correction
BIAS RESIDULS FOR NPLD (Final)
NS
5
0
-5
-10
NO ΔGPS correction
with ΔGPS correction
BIAS RESIDULS FOR BRUS (Final)
NS
5
0
-5
-10
NO ΔGPS correction
with ΔGPS correction
52500
52550
52600
52650
52700
52750
MJD

ΔGPST Adjustments



STATION	MJD	# Values		B'_i		B'_i WRMS		B_i		B_i WRMS	
	RANGE	Rapid	Final	Rapid	Final	Rapid	Final				
AMC2	**52117-52437**	**299**	**42**	**-451.40**	**-452.38**	**2.87**	**1.47**	**-450.72**	**-452.02**	**1.93**	**0.75**
	52480-52729	**247**	**230**	**2.71**	**4.26**	**2.69**	**2.60**	**4.19**	**5.10**	**1.39**	**1.41**
BOR1	**51854-52020**	**60**	**54**	**-2955.91**	**-2955.26**	**11.94**	**12.68**	**-2955.00**	**-2954.49**	**11.77**	**12.59**
	52251-52296	**34**	**45**	**-353.05**	**-352.91**	**2.75**	**2.02**	**-353.19**	**-353.19**	**1.49**	**0.98**
	52504-52531	**26**	**28**	**31.72**	**31.15**	**3.31**	**2.62**	**34.40**	**33.77**	**2.88**	**2.33**
	52611-52678	**56**	**60**	**120.79**	**121.23**	**3.98**	**3.51**	**120.32**	**121.26**	**1.92**	**1.72**
	52693-52724	**32**	**31**	**-25.63**	**-25.60**	**2.63**	**2.18**	**-25.69**	**-25.73**	**1.55**	**1.77**
BRUS	**52213-52374**	**136**	**4**	**454.83**	**452.77**	**3.46**	**0.30**	**454.42**	**453.68**	**1.31**	**0.06**
	52420-52729	**292**	**238**	**585.83**	**586.15**	**2.59**	**2.42**	**585.81**	**586.89**	**1.24**	**1.43**
KGN0	**52421-52729**	**168**	**103**	**-28.95**	**-29.26**	**3.44**	**2.68**	**-27.92**	**-28.31**	**2.64**	**2.44**
NPLD	**52133-52569**	**376**	**112**	**-8075.90**	**-8075.78**	**2.82**	**3.33**	**-8074.74**	**-8074.25**	**1.35**	**2.33**
TWTF	**52316-52347**	**0**	**16**		**294.70**		**7.34**		**294.60**		**7.11**
	52400-52453	**41**	**34**	**298.87**	**298.93**	**4.91**	**6.13**	**301.34**	**301.33**	**4.91**	**5.35**
	52483-52562	**68**	**79**	**381242.55**	**381243.81**	**4.64**	**3.66**	**381245.16**	**381246.48**	**4.15**	**3.47**
	52563-52729	**160**	**166**	**288.45**	**289.84**	**7.69**	**9.05**	**288.27**	**290.12**	**7.42**	**8.60**
USN1	**52467-52729**	**95**	**30**	**0.76**	**1.65**	**2.24**	**1.89**	**1.40**	**3.04**	**0.76**	**1.03**
USNO	**51922-51986**	**60**	**65**	**-69.71**	**-69.69**	**2.43**	**2.52**	**-68.78**	**-68.85**	**2.15**	**2.39**
	52069-52129	**61**	**61**	**619.04**	**619.53**	**3.25**	**3.97**	**620.04**	**620.53**	**3.25**	**3.97**
	52131-52158	**26**	**28**	**-157.25**	**-157.72**	**2.27**	**2.36**	**-155.08**	**-156.46**	**0.30**	**2.24**
	52180-52256	**72**	**73**	**-69.07**	**-68.83**	**2.24**	**1.93**	**-68.30**	**-67.80**	**0.91**	**1.62**
	52260-52339	**74**	**80**	**5.91**	**5.89**	**1.55**	**1.38**	**7.24**	**6.75**	**0.45**	**1.01**
	52360-52529	**159**	**164**	**85287.15**	**85287.19**	**1.62**	**1.56**	**85288.65**	**85288.68**	**0.83**	**1.39**
	52532-52729	**185**	**187**	**639.92**	**639.59**	**3.33**	**2.69**	**641.59**	**641.72**	**2.01**	**1.22**

Conclusions

- Demonstrated an *in situ* method to transfer lab calibration to co-located IGS geodetic receiver system
  - Requires no cable, connector, or configuration changes
  - Precision (RMS) good to ~1 ns
  - IGS Rapid & Final results consistent to <~1 ns

- Accuracy compared to absolute instrumental calibration:
  - AMC2 differences -- +4.2 ns (Rapids), +5.1 ns (Finals)
  - USN1 differences -- +1.4 ns (Rapids), +3.0 ns (Finals)

- Technique can be applied to continuously monitor intra-lab calibration stability

- Being used to improve steering of IGS time scales w.r.t. UTC (~EFTF April, 2004)