# PRECISE ORBIT DETERMINATION OF THE CHAMP SATELLITE WITH STAND-ALONE GPS

Sunil B. Bisnath and Richard B. Langley

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*Geodetic Research Laboratory • Department of Geodesy and Geomatics Engineering • University of New Brunswick*

# OVERVIEW

- Introduction of single-receiver processing technique.
- Description of UNB technique:
  - Principle.
  - Modelling.
- Spaceborne data processing:
  - Measurement description.
  - Results.
  - Analysis.
- Conclusions and further research.

# SINGLE RECEIVER PROCESSING

- Purpose of research:
  - To develop processing strategy to provide precise positioning of any platform using a single, geodetic-grade GPS receiver.
- Rationale for capability:
  - Rests in desire to remove requirement of reference receiver(s) for high-precision positioning.
- Processing technique possible because:
  - GPS can provide direct, continuous, accurate, 3-dimensional positioning.
  - High-quality GPS data products (orbits and clocks) available.
  - Removal of Selective Availability (SA).
  - Have developed GPS-only technique – make no assumptions regarding platform dynamics – hence platform-independent.

# PROCESSING STRATEGY (1)

- Purely *geometrical* – state-space, GPS-based solution.
- Simultaneously:
  - Utilize *code* data to compute mobile receiver *position,*
  - and *carrier* data to compute mobile receiver *position change,*
  - in a kinematic, sequential, least-squares filter/smoother.
- Inputs (all *readily available* aside from mobile receiver data):
  - Dual-frequency code and carrier measurements from mobile receiver (preferably high-rate).
  - Precise GPS constellation ephemerides.
  - Precise GPS constellation satellite clock offsets from GPST.
- Interpolate GPS-determined positions for mobile receiver state throughout trajectory.

# PROCESSING STRATEGY (2)

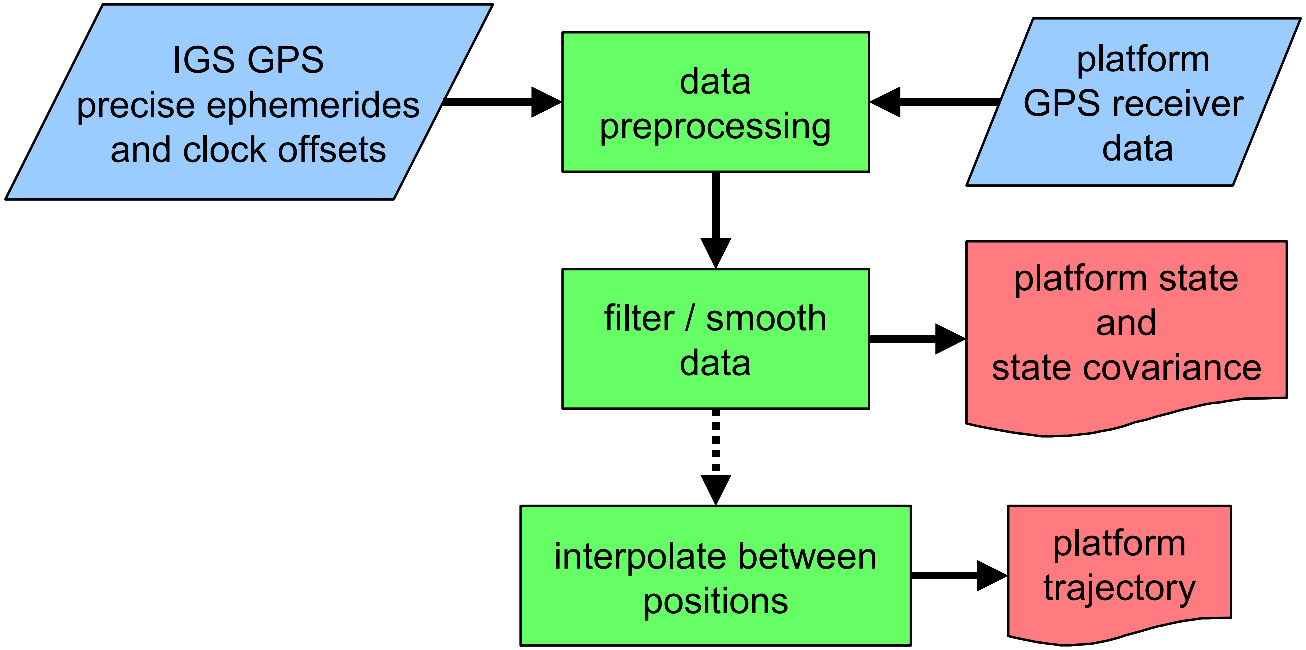
- No need for:
  - Reference receiver or reference receiver network – that information basically provided by IGS data *products*.
  - Assumed dynamic models – time-differenced, carrier-phase observations precisely measure motion.
- Entitled:
  - Carrier-phase-connected, pseudorange point positioning.

# CARRIER-PHASE-CONNECTED, PSEUDORANGE POINT POSITIONING

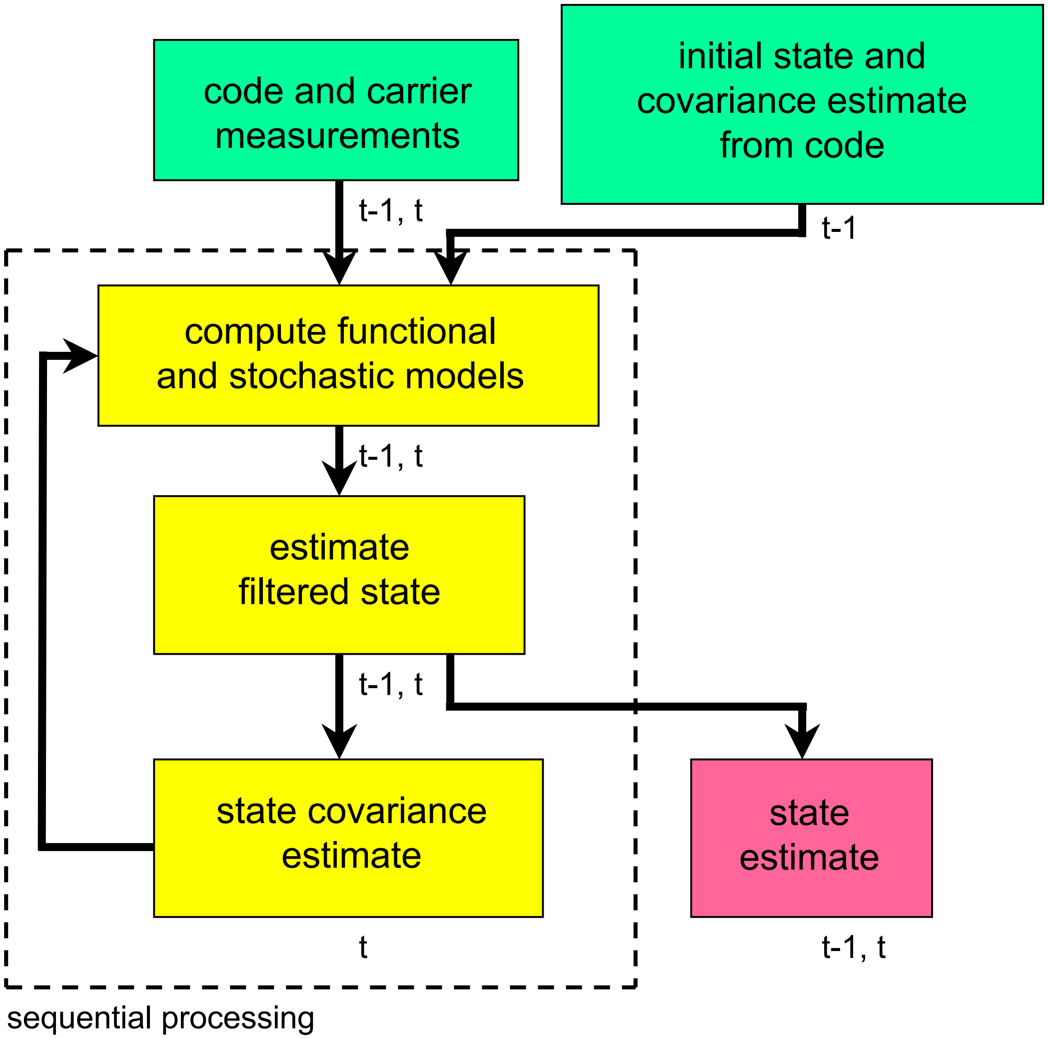
| GPS measurement | low precision (10s of cm), unambiguous *pseudoranges* | high precision (sub-mm), ambiguous *carrier phases* |
|---|---|---|
| **decimetre accuracy** | | |
| measurement constituents which must be estimated or eliminated | • satellite position error × ×<br>• satellite clock × ×<br>• receiver clock × ×<br>• troposphere × ×<br>• ionosphere × ×<br>• multipath ×<br>• receiver noise ×<br>• … | • satellite position error × ×<br>• satellite clock × ×<br>• receiver clock × ×<br>• troposphere × ×<br>• ionosphere × ×<br>• multipath<br>• receiver noise<br>• carrier-phase ambiguity × ×<br>• …<br>• … |

× partially addressed
× × fully addressed

# FLOWCHART OF DATA PROCESSING



# SCHEMATIC OF FILTER PRINCIPLE



# FILTER/SMOOTHER EQUATIONS (1)

Linearized observation equations:

$$\begin{bmatrix} \mathbf{P}_t - \mathbf{P}_t^{\mathbf{0}} \\ \delta\mathbf{\Phi}_t - \delta\mathbf{\Phi}_t^{\mathbf{0}} \end{bmatrix} = \begin{bmatrix} 0 & \mathbf{A}_t \\ -\mathbf{A}_{t-1} & \mathbf{A}_t \end{bmatrix} \begin{bmatrix} \delta\mathbf{x}_{t-1} \\ \delta\mathbf{x}_t \end{bmatrix} + \begin{bmatrix} \mathbf{e}_t \\ \boldsymbol{\varepsilon}_{t-1,t} \end{bmatrix} \qquad \mathbf{C}_{\mathbf{P}_t} \qquad \mathbf{C}_{\delta\mathbf{\Phi}_t}$$

Least-squares solution:

$$\begin{bmatrix} \hat{\mathbf{x}}_{t-1} \\ \hat{\mathbf{x}}_t \end{bmatrix}$$

$$= \begin{bmatrix} \mathbf{x}_{t-1}^0 \\ \mathbf{x}_t^0 \end{bmatrix} - \begin{bmatrix} \mathbf{A}_{t-1}^T \mathbf{C}_{\delta\mathbf{\Phi}_t}^{-1} \mathbf{A}_{t-1} + \mathbf{C}_{\mathbf{x}_{t-1}}^{-1} & -\mathbf{A}_{t-1}^T \mathbf{C}_{\delta\mathbf{\Phi}_t}^{-1} \mathbf{A}_t \\ -\mathbf{A}_t^T \mathbf{C}_{\delta\mathbf{\Phi}_t}^{-1} \mathbf{A}_{t-1} & \mathbf{A}_t^T \left( \mathbf{C}_{\mathbf{p}_t}^{-1} + \mathbf{C}_{\delta\mathbf{\Phi}_t}^{-1} \right) \mathbf{A}_t \end{bmatrix}^{-1}$$

$$\times \begin{bmatrix} -\mathbf{A}_{t-1}^T \mathbf{C}_{\delta\mathbf{\Phi}_t}^{-1} \mathbf{w}_{\delta\mathbf{\Phi}} \\ \mathbf{A}_t^T \mathbf{C}_{\mathbf{P}_t}^{-1} \mathbf{w}_{\mathbf{P}} + \mathbf{A}_t \mathbf{C}_{\delta\mathbf{\Phi}_t}^{-1} \mathbf{w}_{\delta\mathbf{\Phi}} \end{bmatrix}$$

Pseudorange measurement contribution:

$$\mathbf{P}_t - \mathbf{P}_t^{\mathbf{0}} = \mathbf{A}_t \boldsymbol{\delta}\mathbf{x}_t + \mathbf{e}_t; \qquad \mathbf{C}_{\mathbf{P}_t}$$

Carrier-phase measurement contribution:

$$\boldsymbol{\delta\Phi}_t - \boldsymbol{\delta\Phi}_t^{\mathbf{0}} = -\mathbf{A}_{t-1}\boldsymbol{\delta}\mathbf{x}_{t-1} + \mathbf{A}_t \boldsymbol{\delta}\mathbf{x}_t + \boldsymbol{\varepsilon}_{t-1,t}; \qquad \mathbf{C}_{\boldsymbol{\delta\Phi}_t}$$

Optimal smoothed solution:

$$\hat{\mathbf{x}}_{\mathbf{s}_t} = \mathbf{C}_{\mathbf{f}_t}^{-1}\hat{\mathbf{x}}_{\mathbf{f}_t} + \mathbf{C}_{\mathbf{b}_t}^{-1}\hat{\mathbf{x}}_{\mathbf{b}_t}$$

# ADDITIONAL MODELLING

- Observables are ionosphere-free, undifferenced pseudorange and ionosphere-free, time-differenced carrier phase.
- Modelling considerations more acute than for relative positioning:
  - Relativistic GPS SV clock correction (due to orbital eccentricity).
  - GPS SV antenna phase-centre to centre-of-mass offset.
  - GPS SV phase wind-up (especially for large sampling intervals of differenced phase).
  - Model compatibility with IGS products.

# BENEFITS OF SPACEBORNE GPS

- The following capabilities can be realized by placing a GPS receiver modified for spaceflight (a *spaceborne* GPS receiver) aboard a Low Earth Orbiter (LEO) spacecraft:
  - **Orbit determination** (position and velocity).
    - Real-time [few-metre-level].
    - Post-processed [decimetre-level].
  - **Attitude determination** [sub-degree-level].
  - **Timing** [sub-microsecond-level].
  - **Ranging information** between spacecraft and GPS satellites for GPS signals transiting the atmosphere (limb sounding).

# BENEFITS OF GPS-EQUIPPED GEOSCIENCE SPACECRAFT

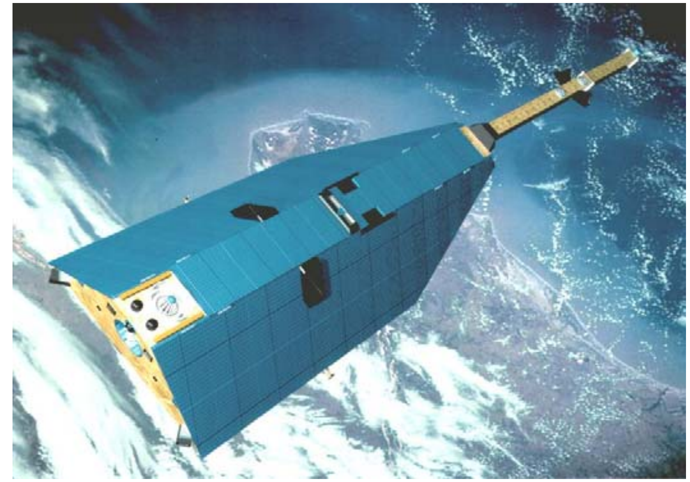
- Gravity field recovery and geoid determination.
- Radar and laser altimetry.
- Interferometric Synthetic Aperture Radar mapping.
- Other remote sensing instrumentation positioning.
- Time-tagging and synchronization of scientific sensor measurements.
- Ionospheric limb sounding.
- Tropospheric limb sounding.
- Sea-surface profiling.

# SPACEBORNE DATA TESTING

- Data description:
  - Orbits of the dual-frequency data from the CHAMP satellite.
  - JPL BlackJack dual-frequency receiver, tracking up to eight SVs.
  - Zenith-mounted POD antenna on choke-ring.
  - January 5$^{th}$ 2002.
  - 10 second data interval.
  - No elevation angle mask, but signal-to-noise mask used.
  - IGS precise GPS satellite orbits and clock offsets.
- Processing:
  - Investigate the geometric strength of measurements.
  - Test practicality and performance of technique against high-quality CHAMP conventional dynamic orbit solutions.

# CHAMP SATELLITE AND SAMPLE GROUNDTRACK

- Near-circular, polar orbit
- Altitude ≈ 450 km
- Orbital Period ≈ 90 minutes



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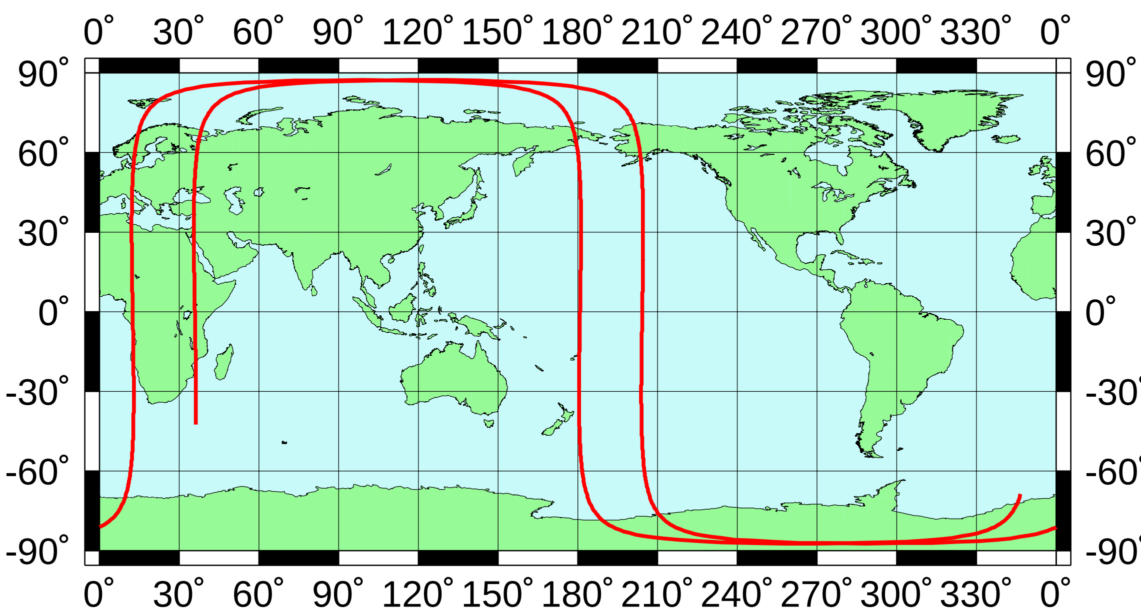


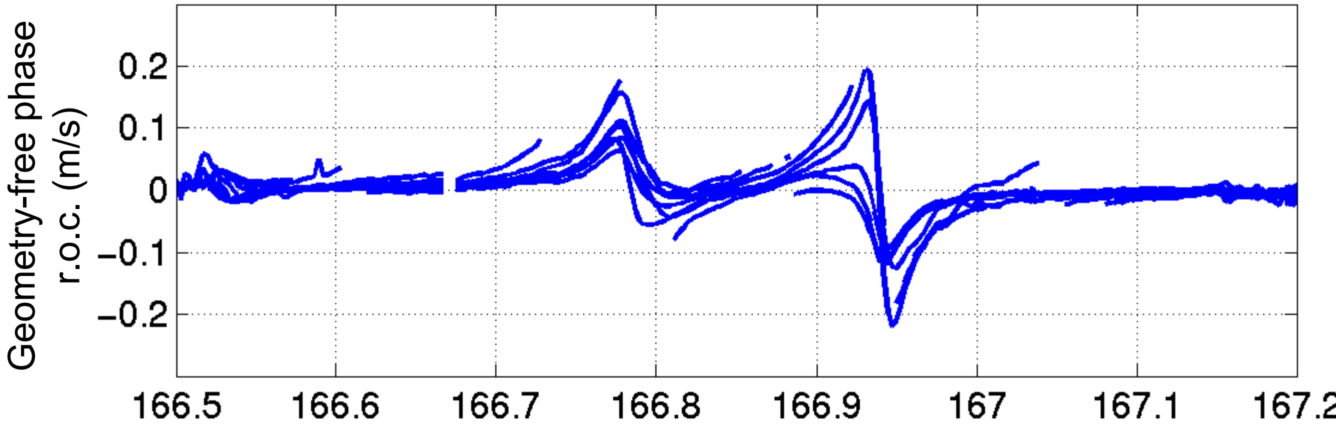
# MEASUREMENT QUALITY ANOMALIES: ISSUES

- Measurement gaps in CHAMP RINEX files.
- Poor quality measurements at low elevation angles – rapid degradation.
- Periods of unexpected behaviour in all tracked carrier-phase observables.
- Entire carrier-phase outlier arcs.
- Individual epochs of single carrier-phase measurement outliers not related to cycle-slips.
- Periods of unexpected behaviour in all tracked pseudorange observables.
- Entire pseudorange outlier arcs.
- Data gaps in IGS precise GPS clock offset estimate files.

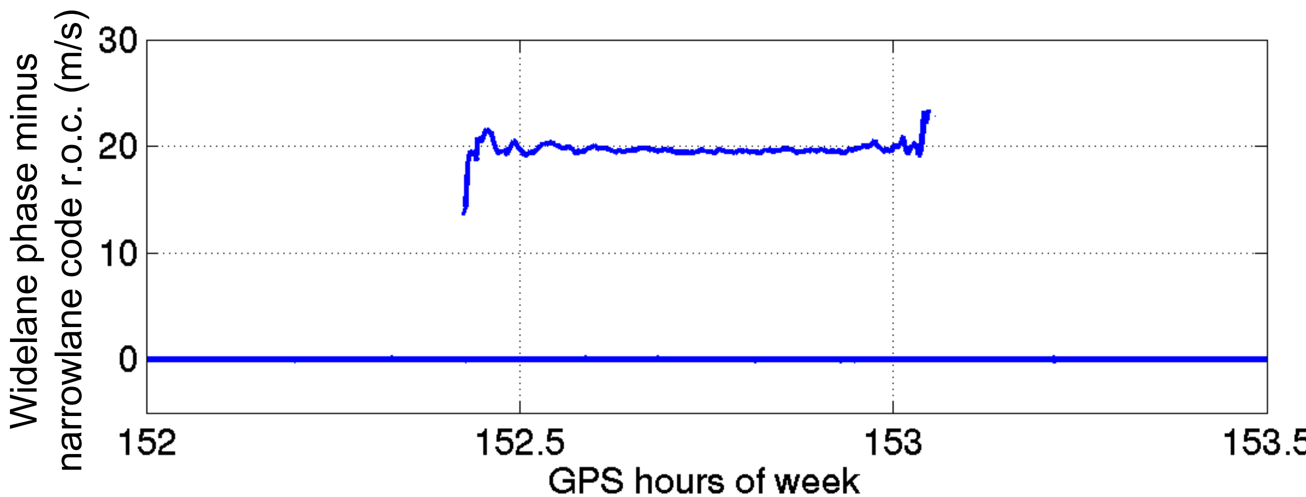
- *Given all of these measurement outliers, a great deal of pre- and post-processing must be carried out.*

# MEASUREMENT QUALITY ANOMALIES: EXAMPLES

UNB




- Periods of unexpected behaviour in all tracked carrier-phase observables




- Entire carrier-phase outlier arcs.
- Entire pseudorange outlier arcs.

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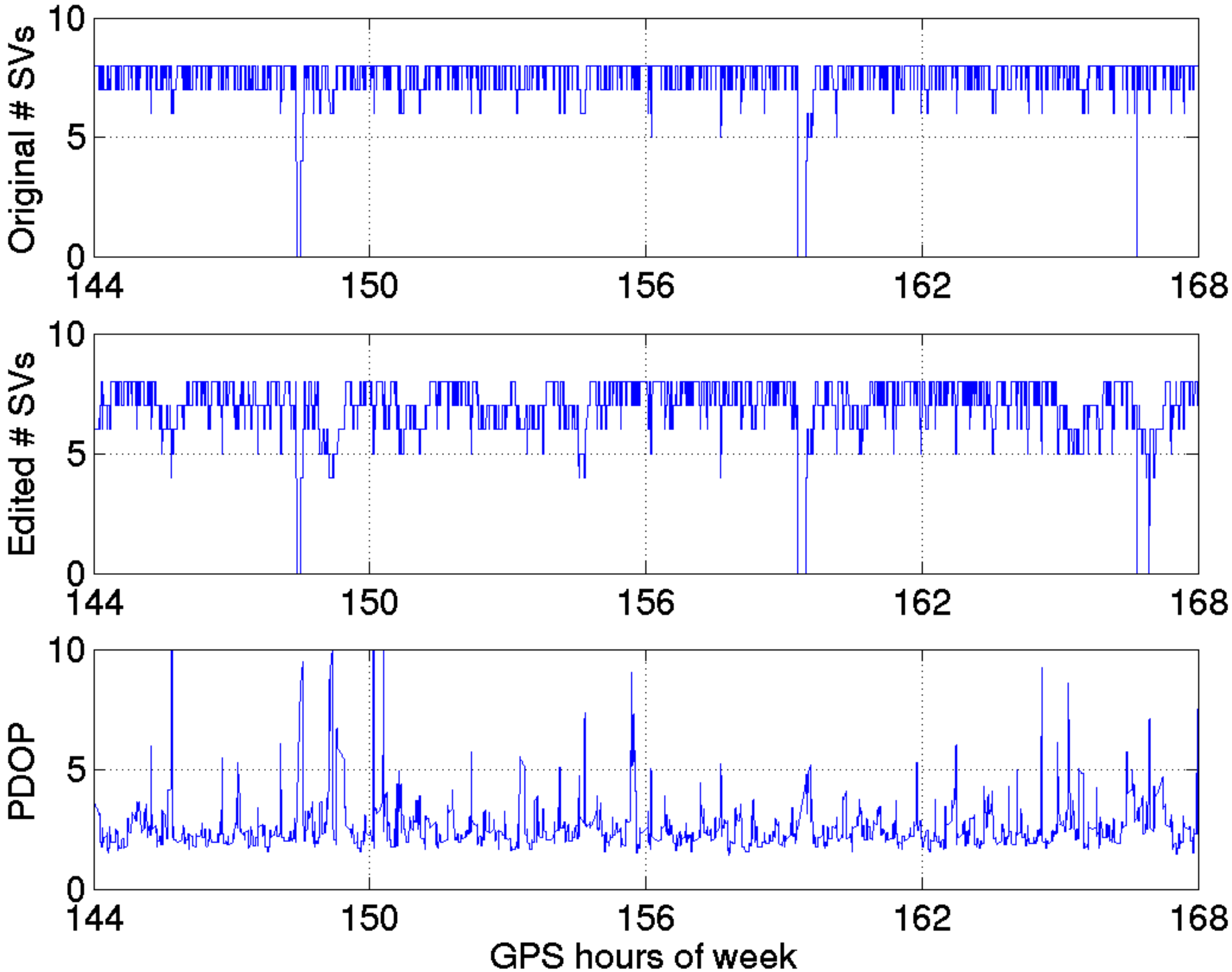
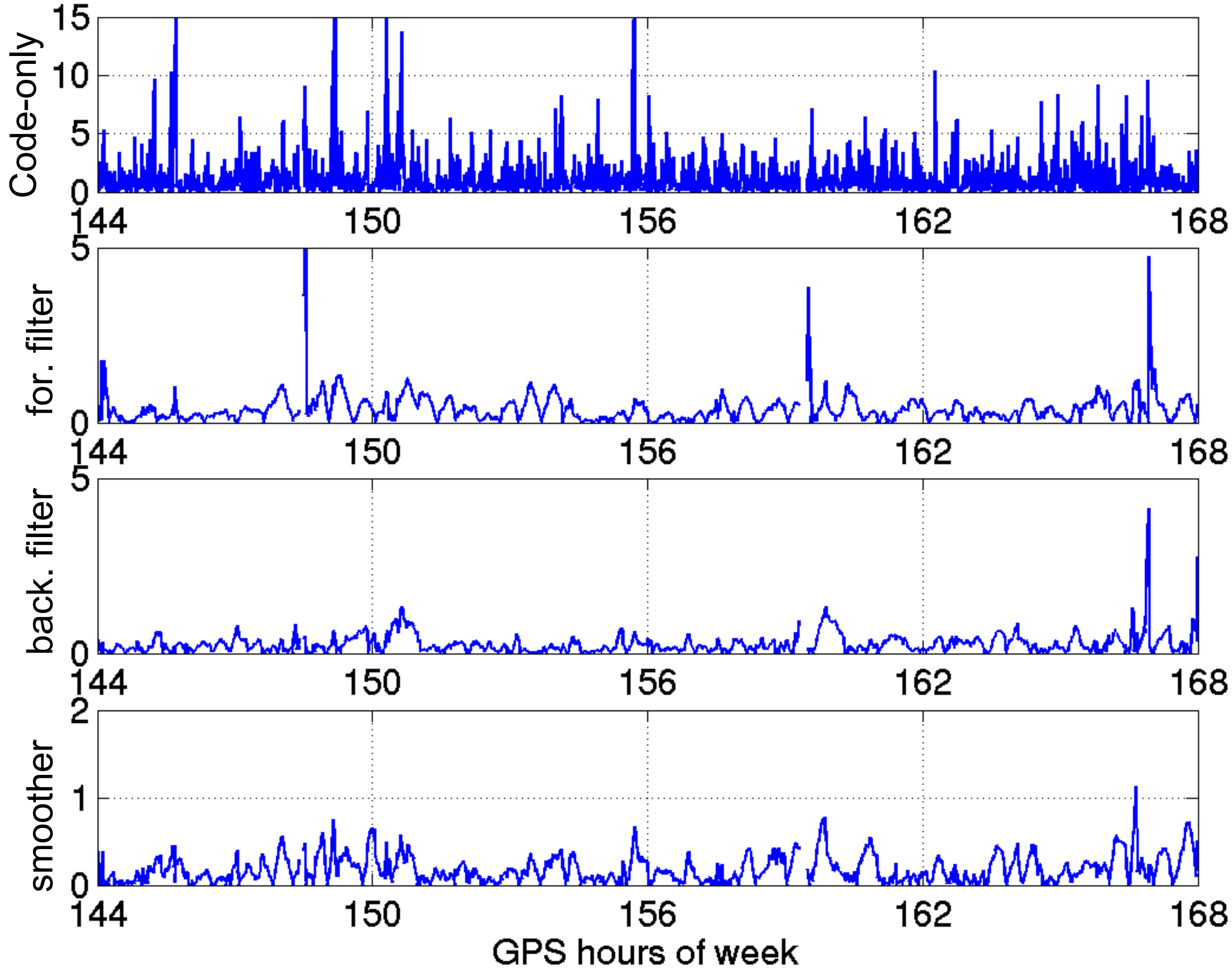
# DATA AVAILABILITY





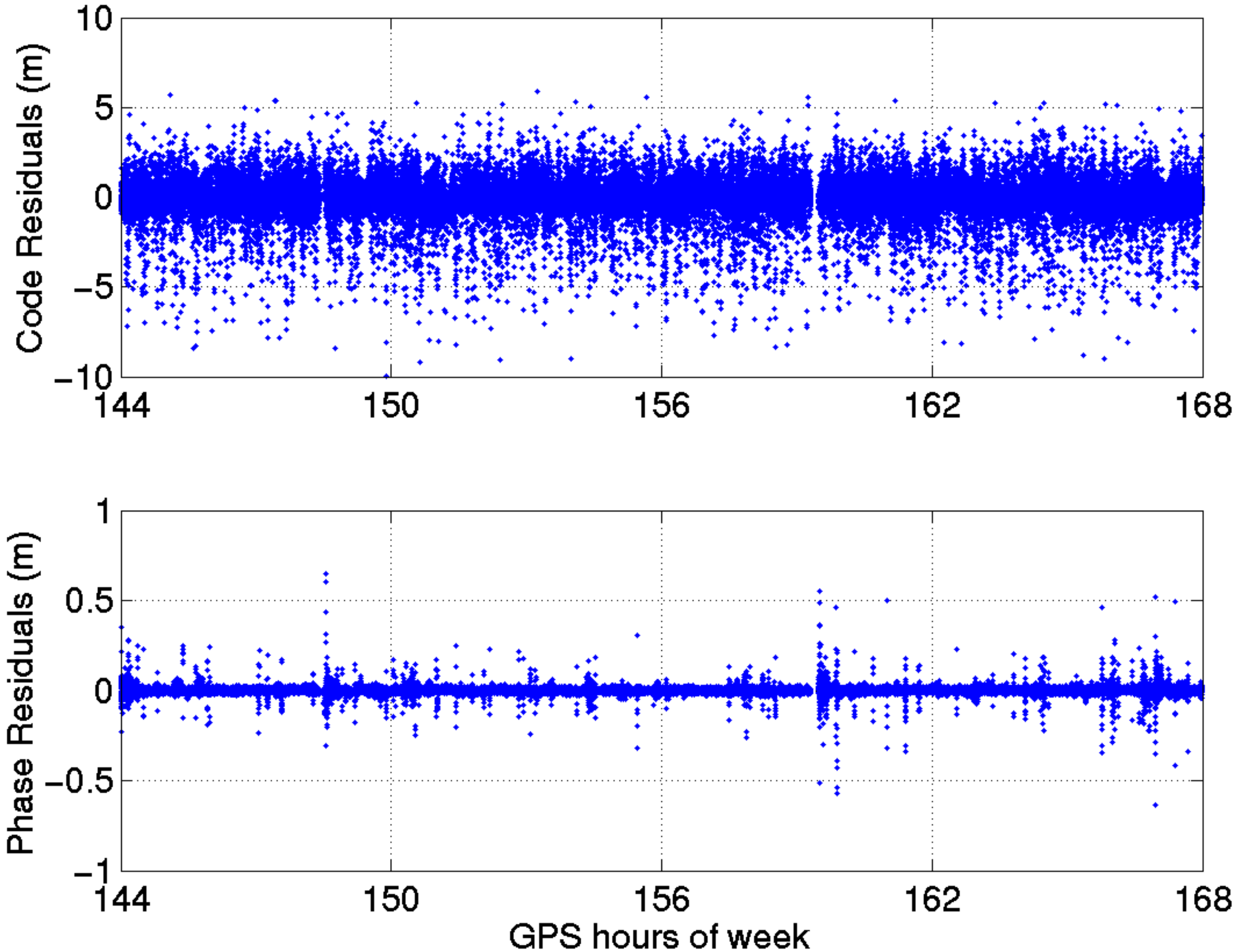

| | mean | std |
|---|---|---|
| original # SVs | 7.6 | 1.0 |
| edited # SVs | 7.0 | 1.2 |
| PDOP | 2.6 | 1.0 |

# PROCESSING SOLUTIONS: CODE-ONLY, FILTERED AND SMOOTHED



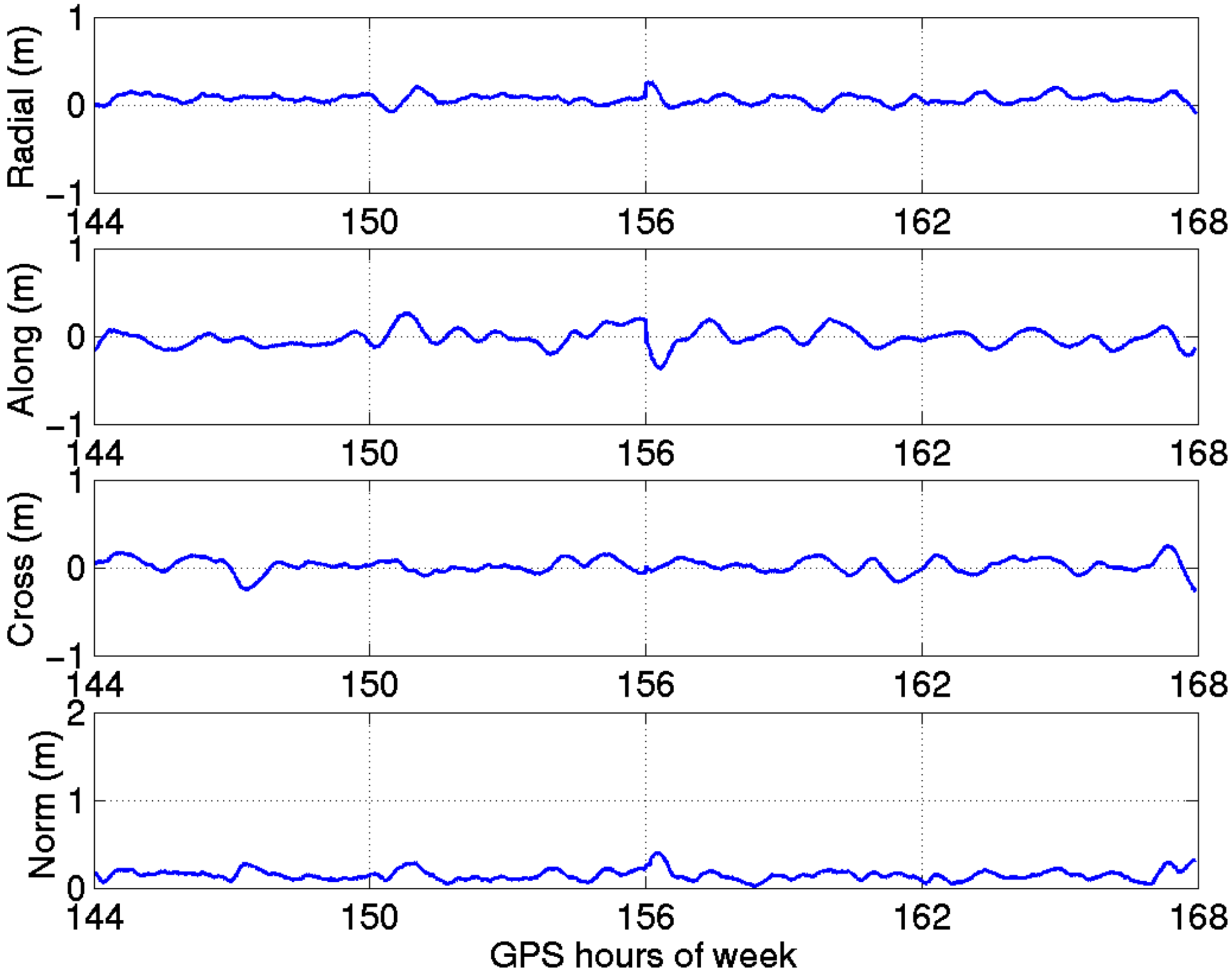

| norm diff. (m) UNB - JPL | max. | r.m.s. |
|---|---|---|
| code-only | 17.6 | 1.9 |
| forward filter | 5.3 | 0.6 |
| backward filter | 4.1 | 0.5 |
| smoother | 1.3 | 0.4 |

# POST-FIT RESIDUALS




| res. (cm) | r.m.s. |
|---|---|
| iono-free pseudorange | 98.1 |
| iono-free phase diff. | 2.1 |

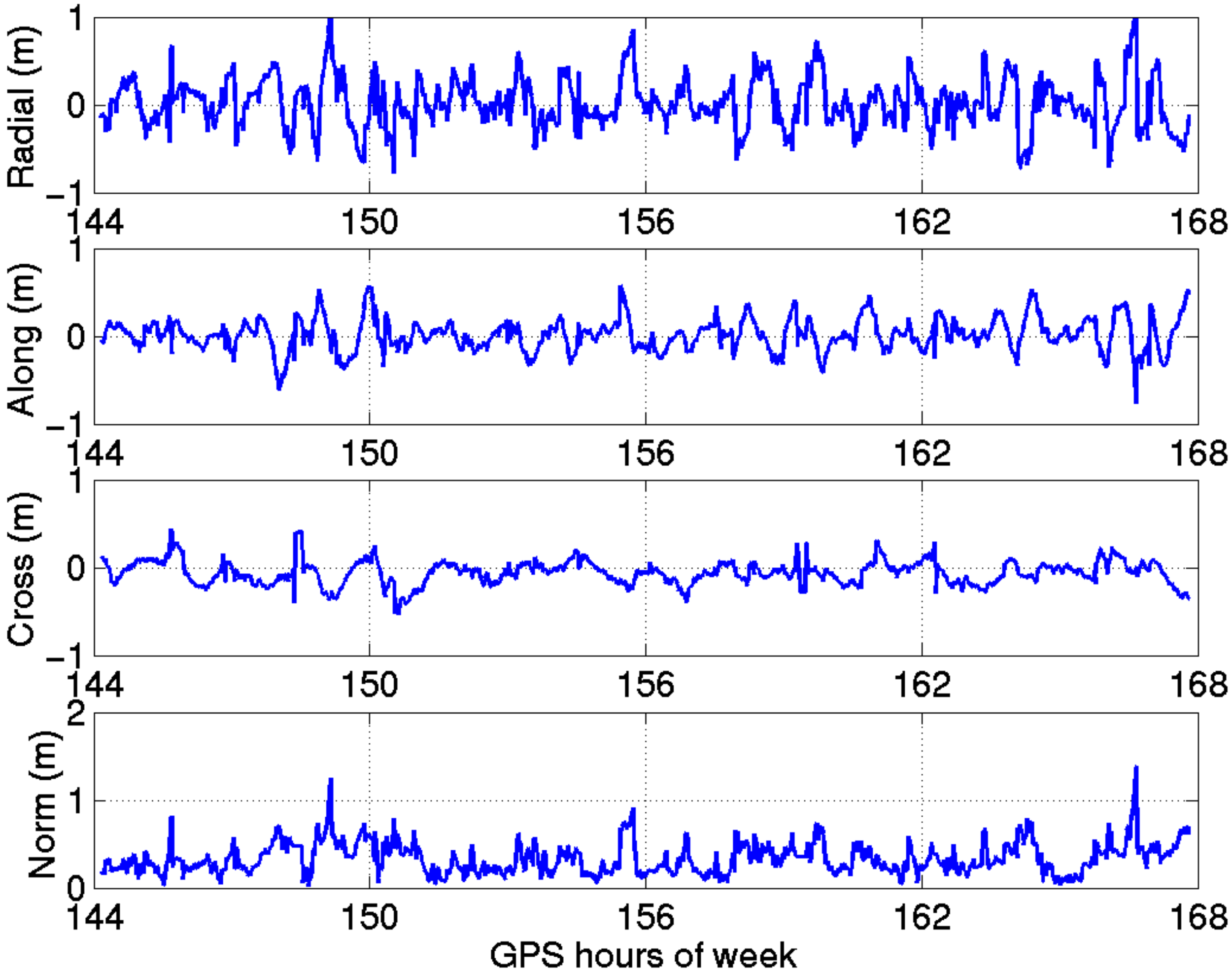
# ORBIT SOLUTION COMPARISON: DYNAMIC JPL AND DYNAMIC GFZ (24 HRS)




| diff. (cm) | max. | bias | r.m.s. |
|---|---|---|---|
| radial | 25.4 | 6.4 | 8.2 |
| along | 37.5 | -2.1 | 10.3 |
| cross | 26.4 | 1.9 | 8.2 |
| norm | 39.5 | 14.4 | 15.6 |

Processing time: hours.

# ORBIT SOLUTION COMPARISON: GEOMETRIC UNB AND DYNAMIC JPL (24 HRS)




| diff. (cm) | max. | bias | r.m.s. |
|---|---|---|---|
| radial | 119.6 | 0.9 | 28.7 |
| along | 76.3 | 1.1 | 18.5 |
| cross | 53.8 | -6.3 | 15.1 |
| norm | 138.9 | 32.9 | 37.3 |

Processing time: *minutes*.

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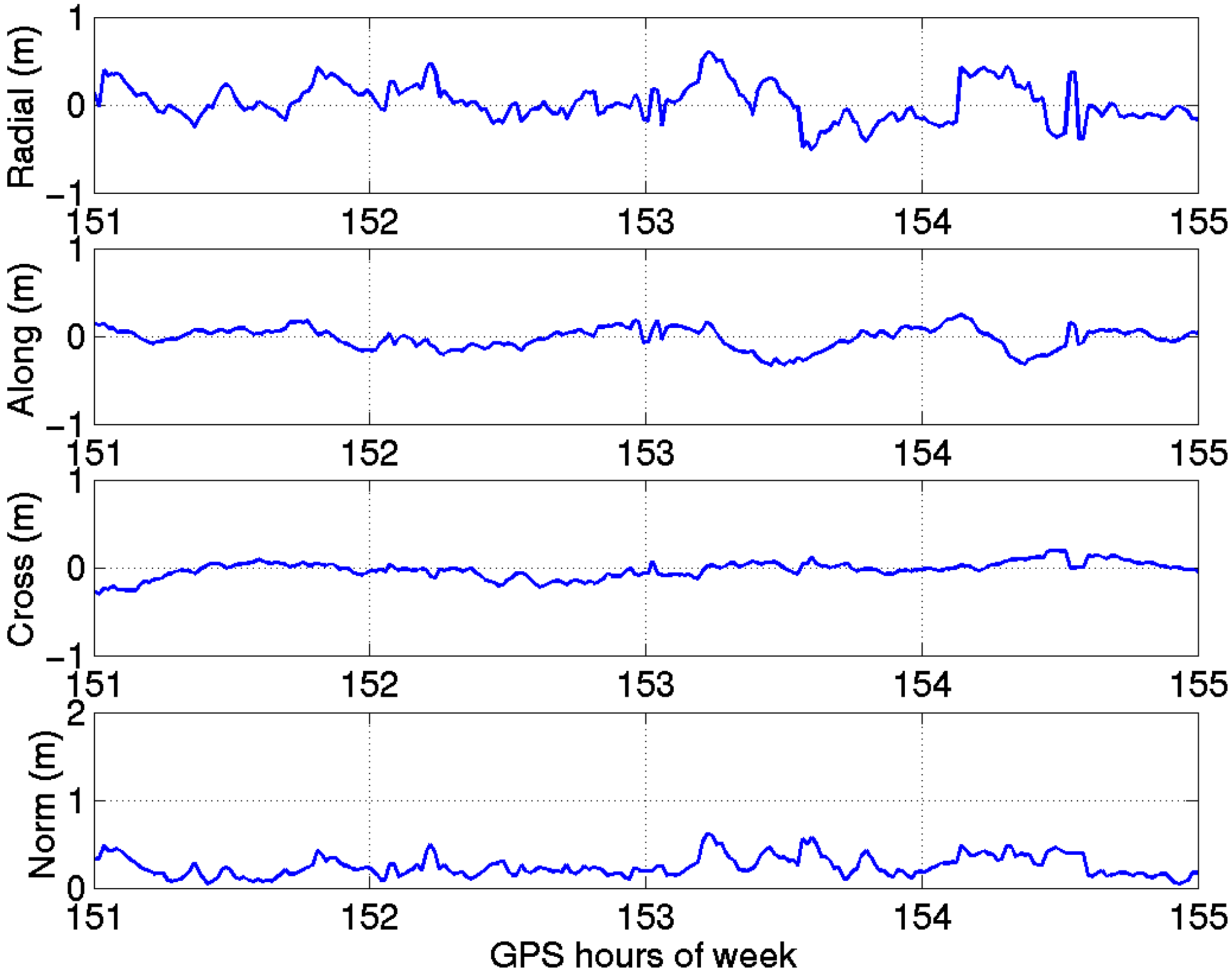
# ORBIT SOLUTION COMPARISON: GEOMETRIC UNB AND DYNAMIC JPL (4 HRS)




| diff. (cm) | max. | bias | r.m.s. |
|---|---|---|---|
| radial | 61.8 | 3.3 | 21.9 |
| along | 34.5 | -1.7 | 12.8 |
| cross | 29.4 | -2.6 | 9.9 |
| norm | 63.8 | 24.3 | 27.2 |

# CONCLUSIONS

- Kinematic, sequential least-squares filter described.
- Dynamics-free nature of filter allows for application to any platform.
- Near-decimetre position component r.m.s difference between UNB geometric solutions and dynamic solutions in the along-track and cross-track components.
- Comparison in radial component at the few-decimetre r.m.s. level.
- Very low processing costs – few minutes of processing time with only CHAMP GPS measurements and RINEX GPS ephemeris and clock data versus hours with conventional dynamic processing.

# FURTHER RESEARCH

- Process additional CHAMP data.
- Improve stochastic models in filter.
- Add some form of residual analysis to remove remaining measurement outliers.
- Simulate real-time processing with IGS predicted GPS ephemeris and clock products.