GNSS Orbit and Clock Determination for (Near-)Real-time Occultation Data Processing

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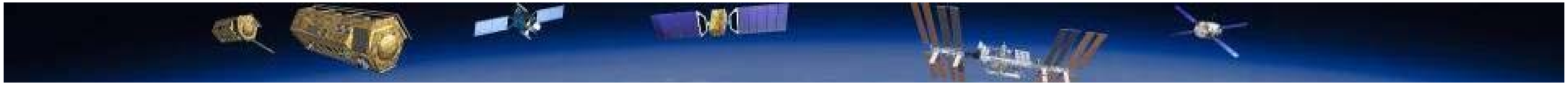
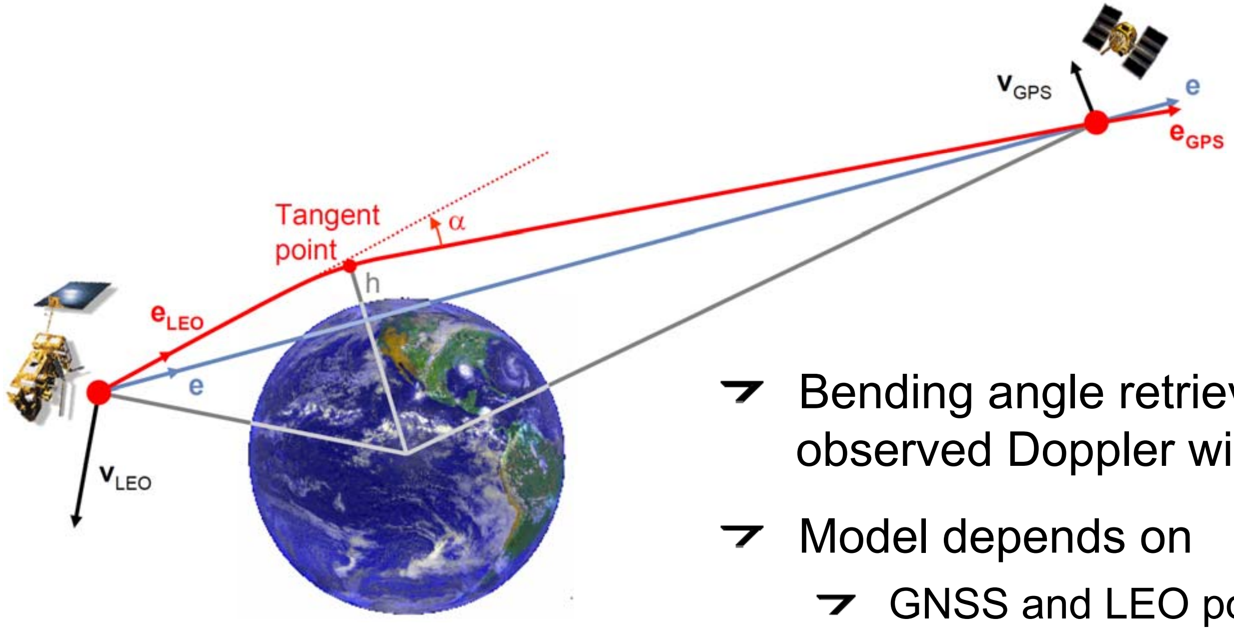


Motivation



- Bending angle retrieved from comparison of observed Doppler with staight-line model
- Model depends on
  - GNSS and LEO position
  - GNSS and LEO velocity
  - GNSS and LEO clock (frequency)
- GNSS and LEO POD

Requirements

- Timeliness
  - Near-real time („as fast as possible“)
  - Metop: Bending angle delivery 2¼ h after RO event
- Accuracy
  - Kursinki et al. (1997): 0.05 mm/s along-track velocity uncertainty introduces a negligible error (<0.2% at 50–60 km altitude) into atmospheric parameters
  - Adopted as 2σ threshold for Metop
  - Corresponds roughly to 10 cm POD accuracy

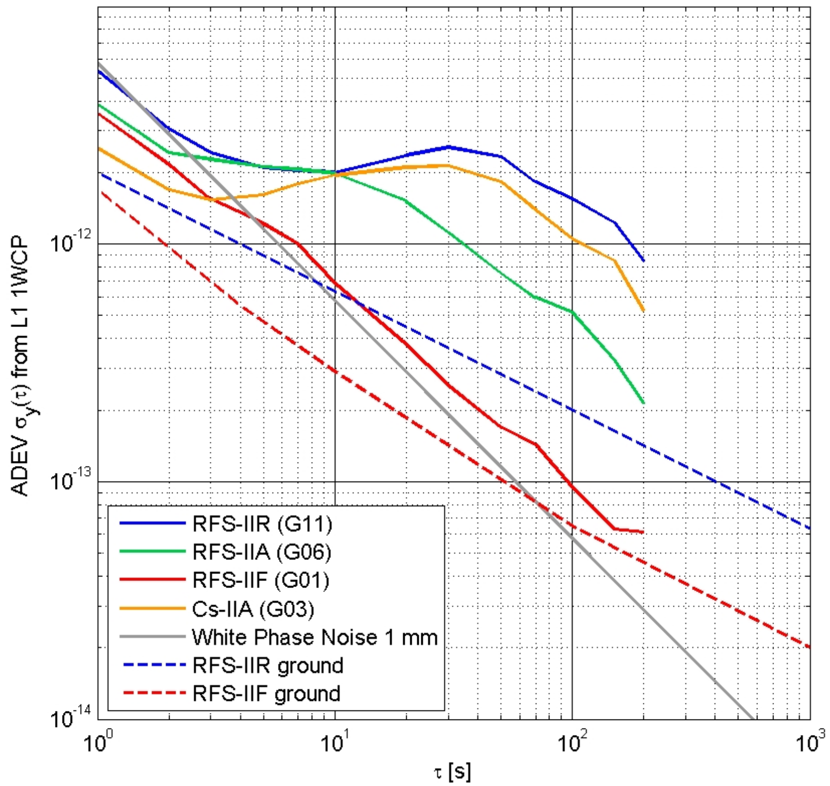
Kursinski ER, Hajj GA, Schofield JT, Linfield RP, Hardy KR (1997)
„Observing Earth’s atmosphere with radio occultation measurements using the Global Positioning System“.
J Geophys Res 102(D19):23429–23465. doi:10.1029/97JD01569

Notes on Accuracy Requirement

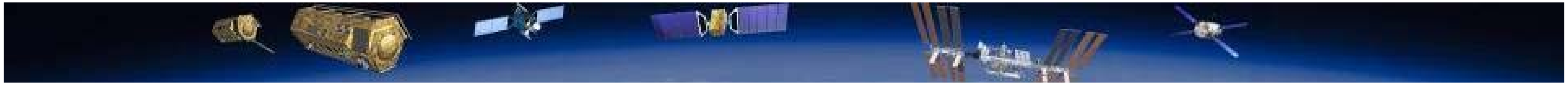
- Commonly accepted, frequently copied but rarely re-assessed
- 0.05 mm/s reflects the assessed POD accuracy at the time,
  not necessarily the actual needs
- Relative bending angle error is most pronounced at high altitudes,
  but current use in NRT data assimilation is typically limited to 40 km altitude
- 0.05 mm/s corresponds to 2e-13 relative frequency stability,
  but GNSS clock variance at short intervals is typically much higher

GNSS Clock Characterization

- Allen deviation $\sigma_y(\tau)$ measures variance of average frequency over given time interval
- Determines error of interpolated clock solutions
- Depends on frequency standard (Cesium, Rubidium, H-maser) and clock generation (Hauschild et al. 2013)
- Typically $>10^{-12}$ at $\tau<10$s
- Analysis at short τ affected by receiver noise (see also Griggs et al. 2013)

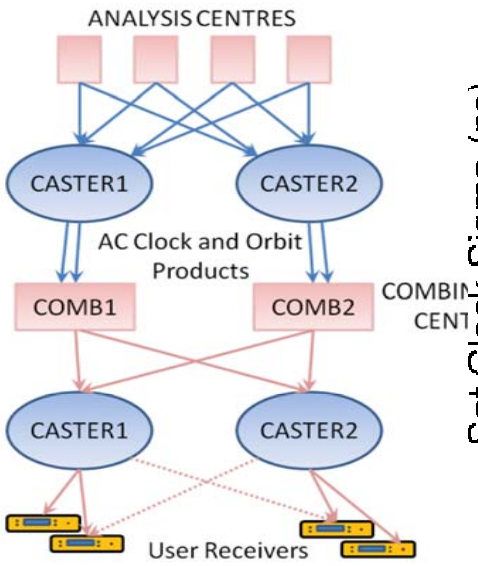


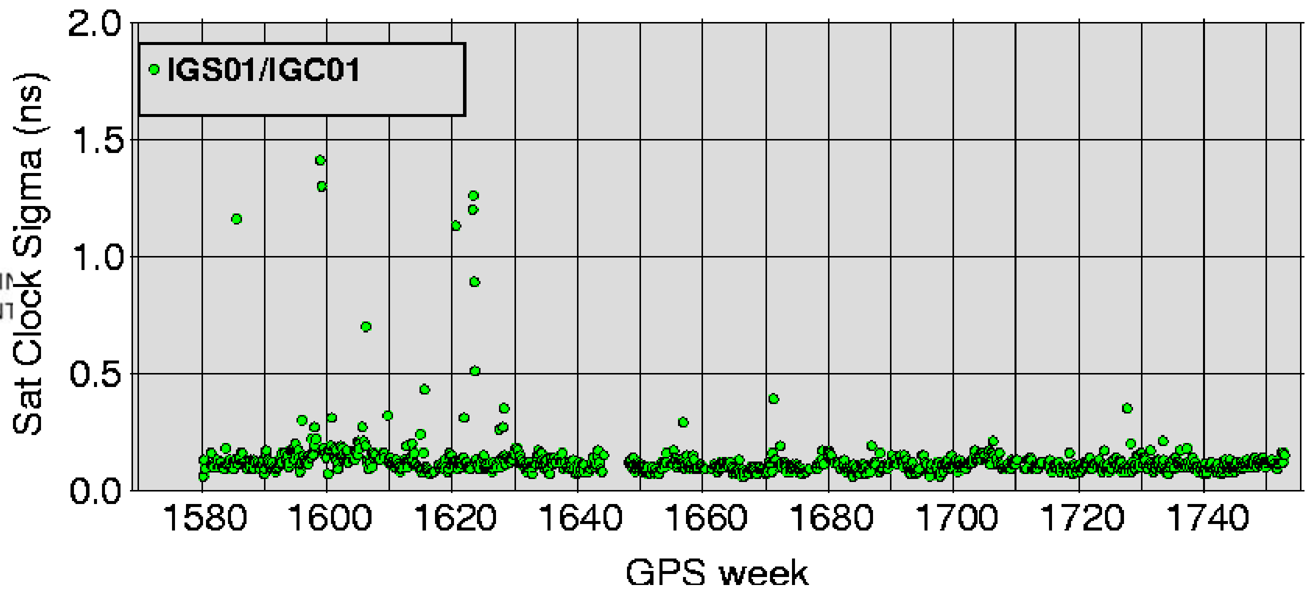
Hauschild A., Montenbruck O., Steigenberger P. (2013) "Short-term analysis of GNSS clocks." GPS Solutions 17(3):295-307
Griggs E., Kursinski E.R., Akos D. (2013); An Investigation of GNSS Atomic Clock Behavior at Short Time Intervals; OPAC-IROWG 2013, Seggau, Sep 5-11, 2013.

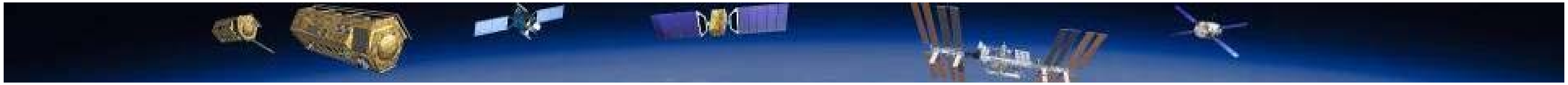


GNSS Orbit and Clock Products – IGS

- International GNSS Service (IGS) is key provider of GPS data products
- Global network, numerous analysis centers; various offline products
- New Real-Time Service (RTS; http://rts.igs.org)
- Combined R/Trpoduct: orbit RMS ~ 3cm, clock std.dev ~0.10-0.15 ns

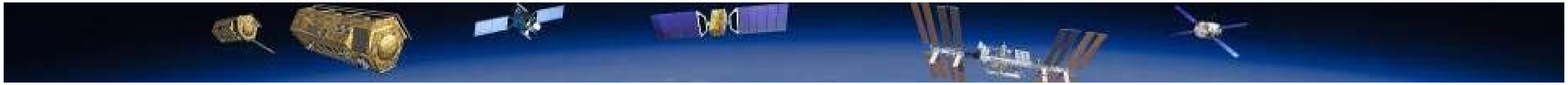






GNSS Orbit and Clock Products – Other Providers

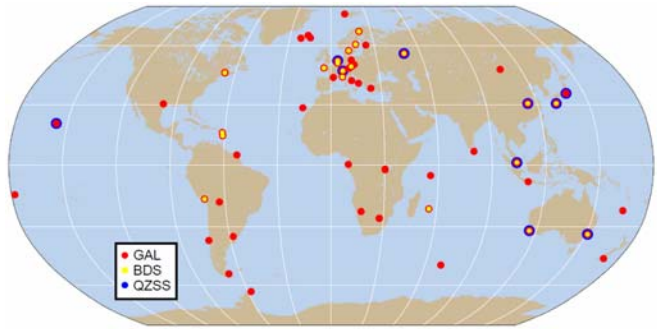
- JPL Global Differential GPS (GDGPS) http://www.gdgps.net/
  - Very large network
  - GPS+GLO real-time product
  - <10 cm position, sub-ns clocks
  - TDRSS Augmentation Service (TASS)
- ESA/ESOC Ground Support Network (GSN) http://dgn7.esoc.esa.int/projects/gras-ground-support-network/
  - Originally built up for GRAS/Metop support
  - High performance near-real-time product
- Industrial PPP service providers
  - FUGRO G2
  - Trimble RTX
  - …



Towards a Multi-GNSS Service

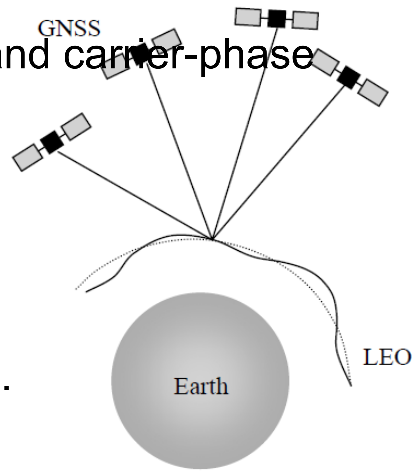
- Various new and emerging constellations
  - BeiDou, Galileo, IRNSS, QZSS
  - Open signals on multiple (up to 3) frequencies
  - Prospects for real-time orbit and clock corrections (QZSS LEX, Galileo CS?)

- IGS Multi-GNSS Experiment (MGEX)
  http://igs.org/mgex/
  - Global multi-GNSS network (~85 stations, ~65 R/T)
  - Initial Galileo and QZSS orbit & clock products
  - Real-time Galileo orbit & clock product in preparation (DLR, BKG, others)



GNSS Based Precise Orbit Determination of LEO Satellites

- Concepts
  - Undifferenced, PPP-style processing of dual-frequency code and carrier-phase
  - Use of known GNSS orbit and clock products
  - Auxiliary spacecraft data (attitude, etc.)
  - High-fidelity dynamical and observation models
  - Empirical accelerations (reduced dynamics approach)
  - Estimation of dynamical params, epoch wise clocks, biases, …

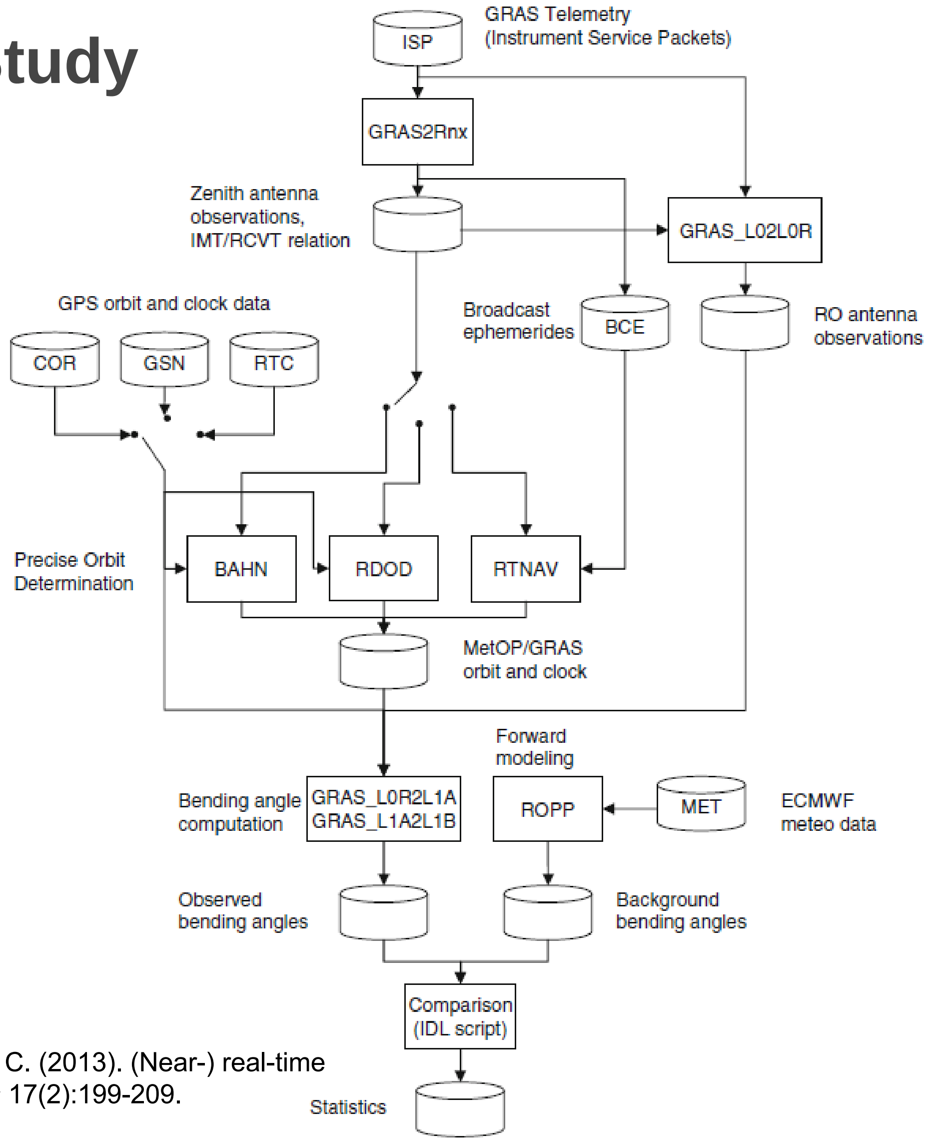


- Tools
  - Numerous GNSS processing and POD S/W packages (BERNESE, EPOS, GEODYN, GIPSY-OASIS, GHOST, NAPEOS, ZOOM, …)
  - High consistency (e.g. 5 cm 3D rms in Metop POD study, Montenbruck et al. 2009)
  - Adequate processing speed (~5 min/day) for near-real-time execution

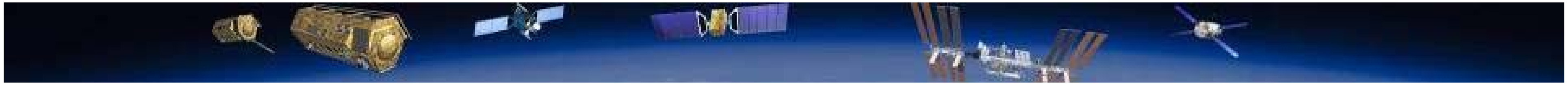
Montenbruck, O., Andres, Y., Bock, H., van Helleputte, T., van den Ijssel, J., Loiselet, M., ... & Yoon, Y. (2008). Tracking and orbit determination performance of the GRAS instrument on MetOp-A. *GPS Solutions*, *12*(4), 289-299.

DLR/EUMETSAT NRT POD Study

- 1 month of GRAS observations (POD and RO)
- Two POD s/w packages (NAPEOS, GHOST)
- Three GPS orbit & clock products (CODE rapid, GSN NRT, RETICLE R/T)
- NRT-style processing
- Complementary R/T Navigation Filter with broadcast ephemerides
- Bending angle computation for RO events based on POD and RTNAV solutions



Montenbruck, O., Hauschild, A., Andres, Y., von Engeln, A., & Marquardt, C. (2013). (Near-) real-time orbit determination for GNSS radio occultation processing. *GPS Solutions* 17(2):199-209.



Near-Real-Time POD Results

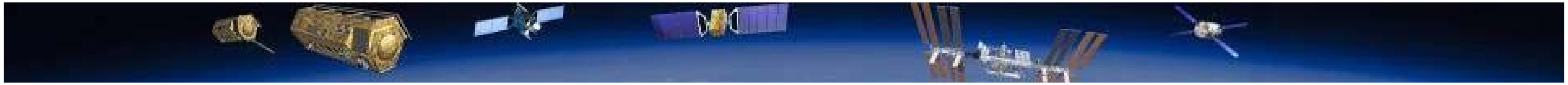
Solution	Radial [mm]	Along-track [mm]	Cross-track [mm]	Position (3D rms, [mm])
OFF_COR_N	-6 ± 16	-2 ± 40	+23 ± 13	51
NRT_RTC_N	-7 ± 19	+1 ± 39	+23 ± 16	52
NRT_RTC_G	+1 ± 18	-3 ± 36	-1 ± 14	43
NRT_GSN	-6 ± 18	-2 ± 39	+23 ± 15	51
Solution	**Radial [mm/s]**	**Along-track [mm/s]**	**Cross-track [mm/s]**	**Velocity (3D rms, [mm/s])**
OFF_COR_N	+0.00 ± 0.03	-0.01 ± 0.03	+0.00 ± 0.02	0.05
NRT_RTC_N	+0.00 ± 0.03	-0.01 ± 0.03	+0.00 ± 0.02	0.05
NRT_RTC_G	+0.00 ± 0.03	+0.00 ± 0.02	+0.00 ± 0.01	0.04
NRT_GSN	+0.00 ± 0.03	-0.01 ± 0.03	+0.00 ± 0.02	0.05

All results referred to OFF_COR_G solution

Type: OFF=Offline, NRT=Near-Real-Time
GPS product: COR=CODE rapid, RTC=RETICLE, GSN=Ground Support Network
Softwware: N=NAPEOS, G=GHOST

Near-Real-Time POD Results (cntd.)

- Highly consistent results obtained with different s/w package
  - 5 cm / 0.05 mm/s (3D rms) agreement in accord with earlier studies
  - Small biases due to different modelling differences (radial and cross-track acceleration)
- Highly consistent results obtained with different (near-)real-time GPS orbit and clock products
- NRT POD products have essentially the same quality as final products
  - Benefit of batch least-squares estimation scheme

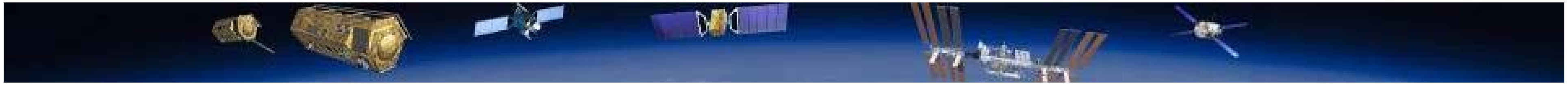


Real-Time Orbit Determination

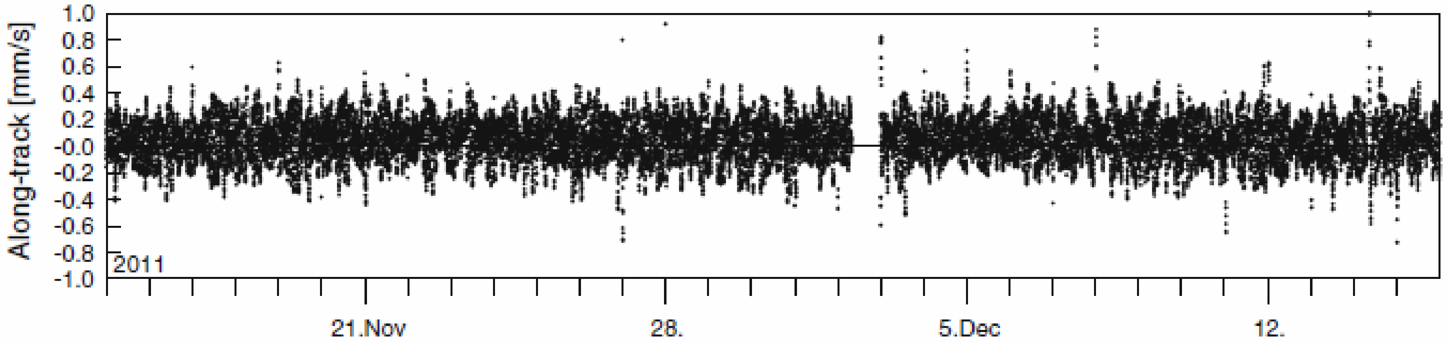
- Real-time navigation filter
  - RTNAV software for playback data processing on ground
  - Replicates Phoenix-XNS software (PROBA-2, GRAPHIC version)
  - Flight code compatible with common onboard CPU (32-bit 30 MHz)
- Employed Models
  - 40x40 gravity field, luni-solar perturbations, drag & SRP, empirical accelerations
  - Weekly Earth orientation parameter updates
  - Dual-frequency pseudorange and phase observations (at 30s intervals)
  - GPS broadcast ephemerides

Montenbruck O, Ramos-Bosch P (2008) "Precision Real-Time Navigation of LEO Satellites using Global Positioning System Measurements", *GPS Solutions* 12(3):187-198. DOI 10.1007/s10291-007-0080-x

Montenbruck O., P. Swatschina, M. Markgraf, S. Santandrea, J. Naudet, E. Tilmans (2012) „Precision Spacecraft Navigation Using a Low-cost GPS Receiver", *GPS Solutions* 16(4):519 – 529



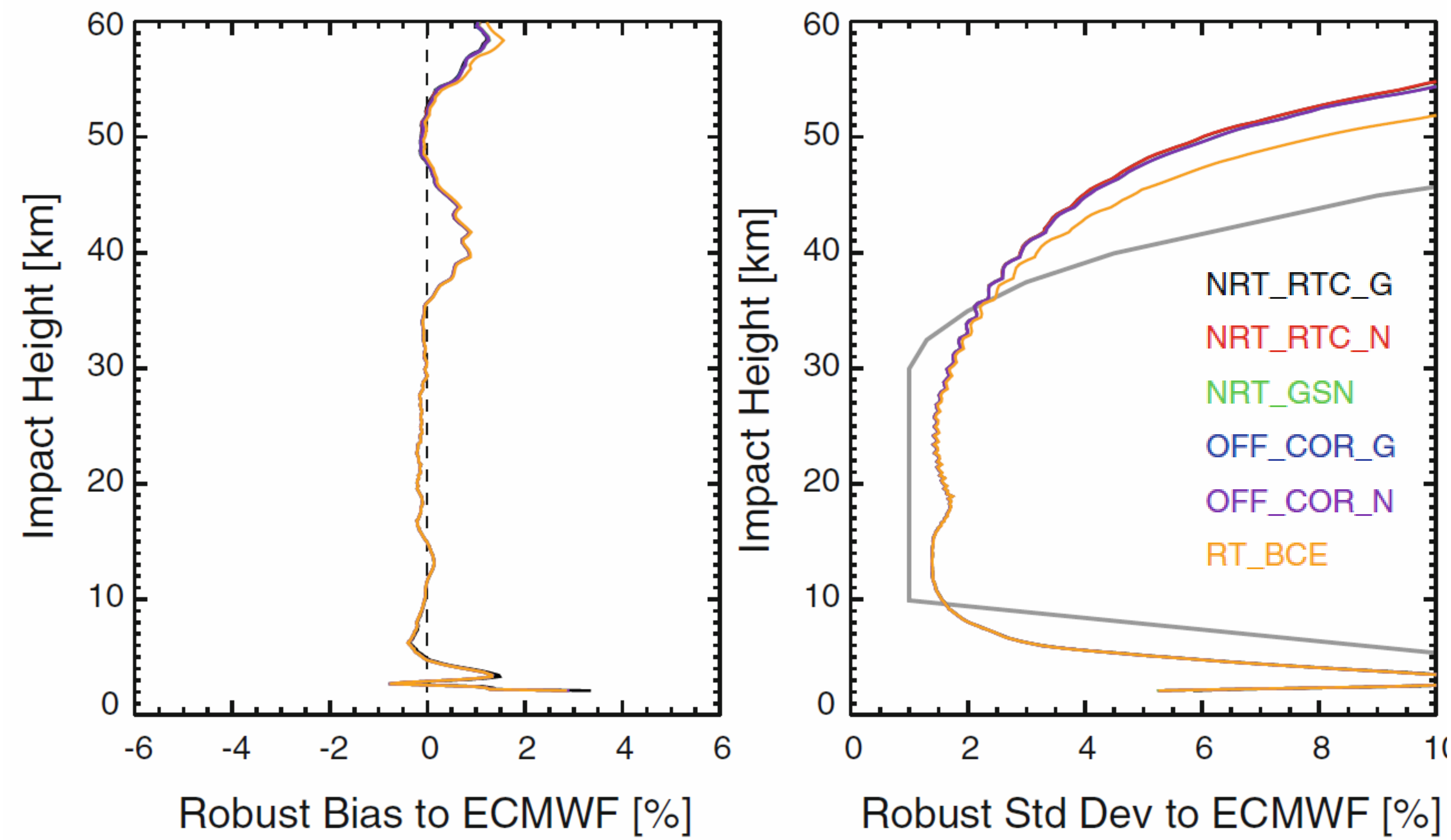
Real-Time Orbit Determination Results



- Ten times lower performance than ground-based POD
- Still ~ 0.2 mm/s along-track velocity accuracy

Solution	Radial [mm]	Along-track [mm]	Cross-track [mm]	Position (3D rms, [mm])
RT_BCE	+7 ± 195	+157 ± 329	+25 ± 228	473
Solution	**Radial [mm/s]**	**Along-track [mm/s]**	**Cross-track [mm/s]**	**Velocity (3D rms, [mm/s])**
RT_BCE	-0.15 ± 0.34	+0.06 ± 0.16	+0.01 ± 0.24	0.48

Bending Angles Comparison



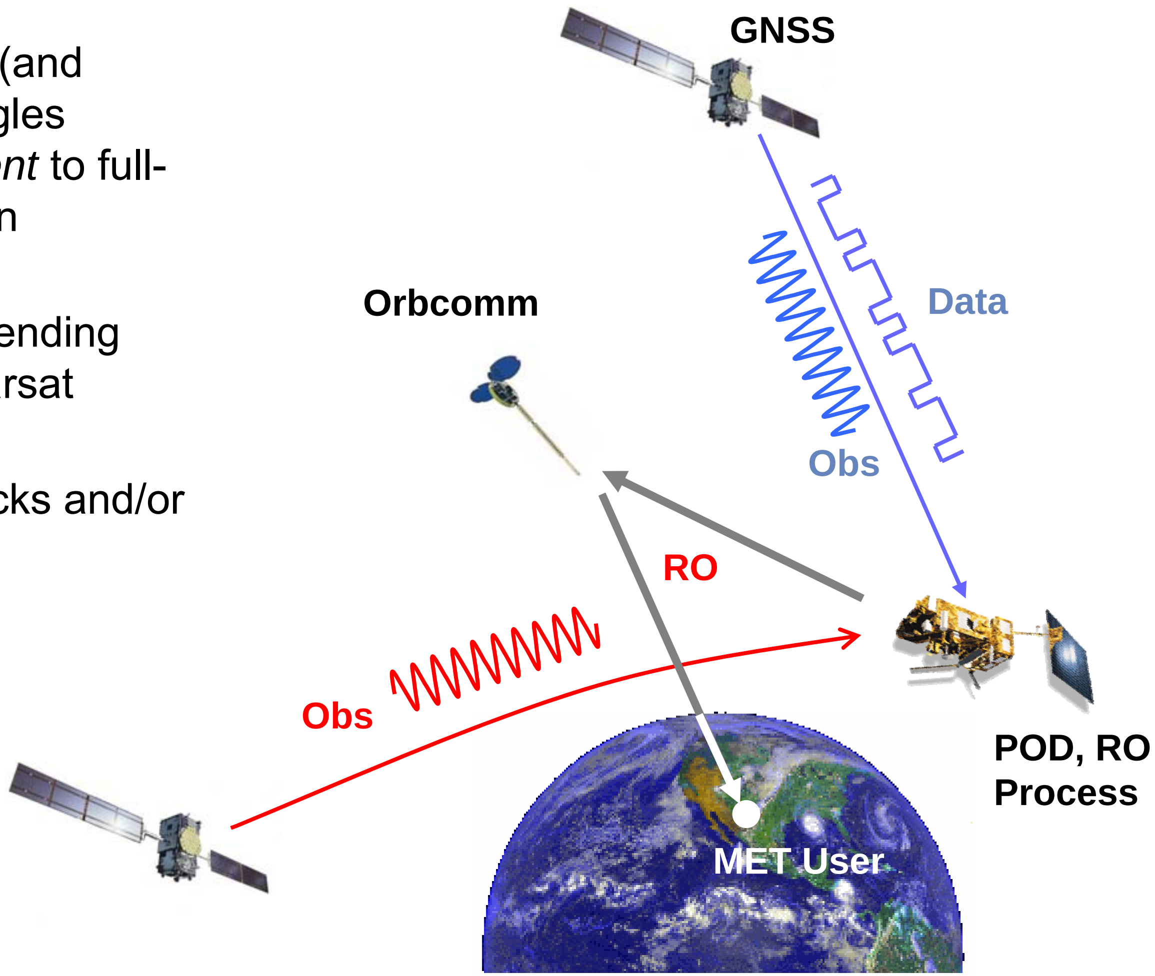
(Montenbruck et al. 2013)

Bending Angles Comparison (cntd.)

- Offline vs. near-real-time POD
  - Virtually identical standard deviation of bending angles w.r.t. to forward modeling from ECMWF data up to altitudes of >50 km
- (Simulated) real-time onboard orbit determination vs. „precise“ results
  - Discernible differences above 40 km
  - Accuracy compatible with data weighting in assimilation for NRT weather forecast

Vision RO 2020

- Onboard orbit determination (and geometric optics bending angles computation) as a *complement* to full-featured ground processing in future RO missions
- Fast real-time download of bending angles via Orbcomm or Inmarsat
- Improved accuracy through high-performance GNSS clocks and/or real-time correction data



Summary and Conclusions

- (Near-)real-time GPS/GLO orbit and clock products for RO work
  - Free public services (IGS RTS) and dedicated providers with guarantee-of-service
  - High-accuracy enables LEO POD with (more than) adequate accuracy
- Multi-GNSS agenda
  - Global real-time multi-GNSS network(s) established (e.g. MGEX)
  - R/T Galileo (+QZSS+BeiDou) products within reach
  - Still waiting for FOC, space receivers and flight data
- Real-time onboard POD and RO processing
  - Acceptable accuracy; compatible with onboard computing power
  - Low data volume (bending angles) enables instantaneous downlink