Federal Agency for Cartography and Geodesy

BKG Wir geben Orientierung.

COSPAR 2022 | 16-24 July 2022 | Athens, Greece

Earth rotation parameters estimated from combined GNSS and VLBI data and its impact on satellite orbits

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(3) Astronomical Institute of the University of Bern (AIUB, Bern, Switzerland)

Motivation for a combined ERP product

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ERP	GNSS	VLBI INT	VLBI R1/R4	SLR
dUT1	-	✓	✓	-
LOD	✓	-	✓	✓
Polar motion	✓	-	✓	✓

Techniques’ contributions to Earth Rotation Parameters (ERP)

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ERP	GNSS	VLBI INT	VLBI R1/R4	SLR	COMBI
dUT1	-	✓	✓	-	✓
LOD	✓	-	✓	✓	✓
Polar motion	✓	-	✓	✓	✓

Techniques' contributions to Earth Rotation Parameters (ERP)

Benefits of multi-technique combination

- **GNSS** + **VLBI INT** → daily resolution and shorter latency of a consistent set of all ERPs
- multi-day combination → stabilization of ERP

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- 24h **VLBI R1/R4** twice/week → stabilization of ERP

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- multi-day combination → stabilization of ERP
- 24h **VLBI R1/R4** twice/week → stabilization of ERP
- stable contribution of LOD from **SLR** → improvement of ERP

Motivation for a combined ERP product

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dUT1	-	✓	✓	-	✓
LOD	✓	-	✓	✓	✓
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Techniques' contributions to Earth Rotation Parameters (ERP)

Current ERP daily combination

- combination at **parameter level**

@ IERS RS/PC → IERS-14-C04

@ IERS EOP PC → IERS-Bulletin-A

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Techniques' contributions to Earth Rotation Parameters (ERP)

Current ERP daily combination

- combination at **parameter level**

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@ IERS EOP PC → IERS-Bulletin-A

Benefits of combination at NEQ level (SINEX)

- considers correlations
- consistent set of parameters
- assures same underlying reference frame
- (positive) impact on other technique-specific parameters

New BKG ERP product under development

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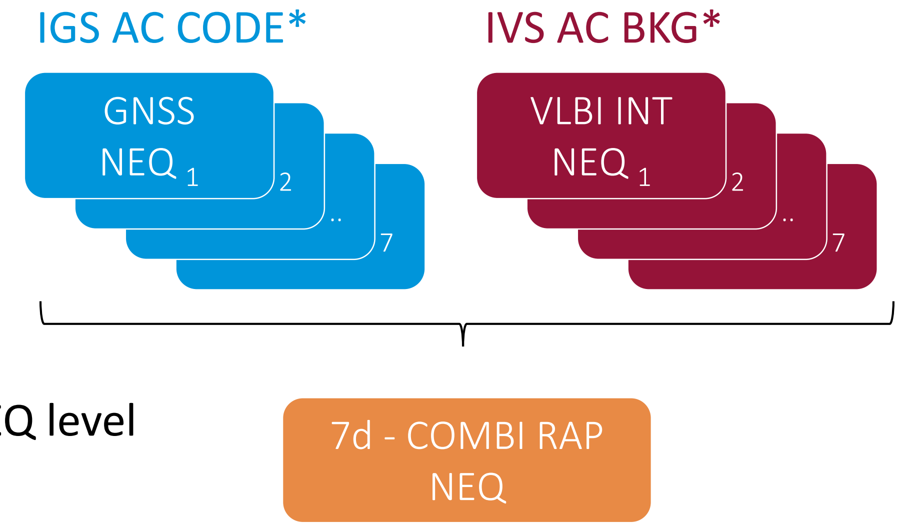

- Derived from combination at NEQ level
- Using NEQ from SINEX files

* official GNSS rapid solution from IGS Analysis Center “CODE”

* official VLBI Intensives solution from IVS Analysis Center “BKG”

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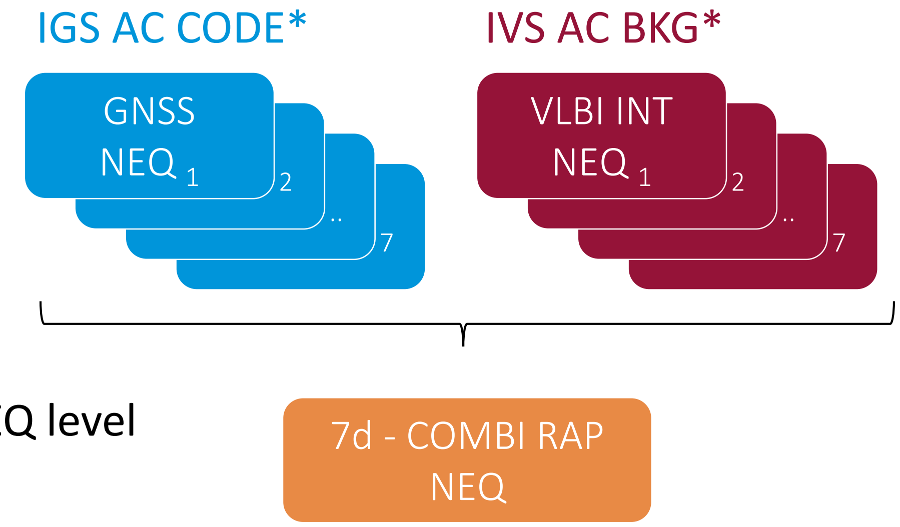

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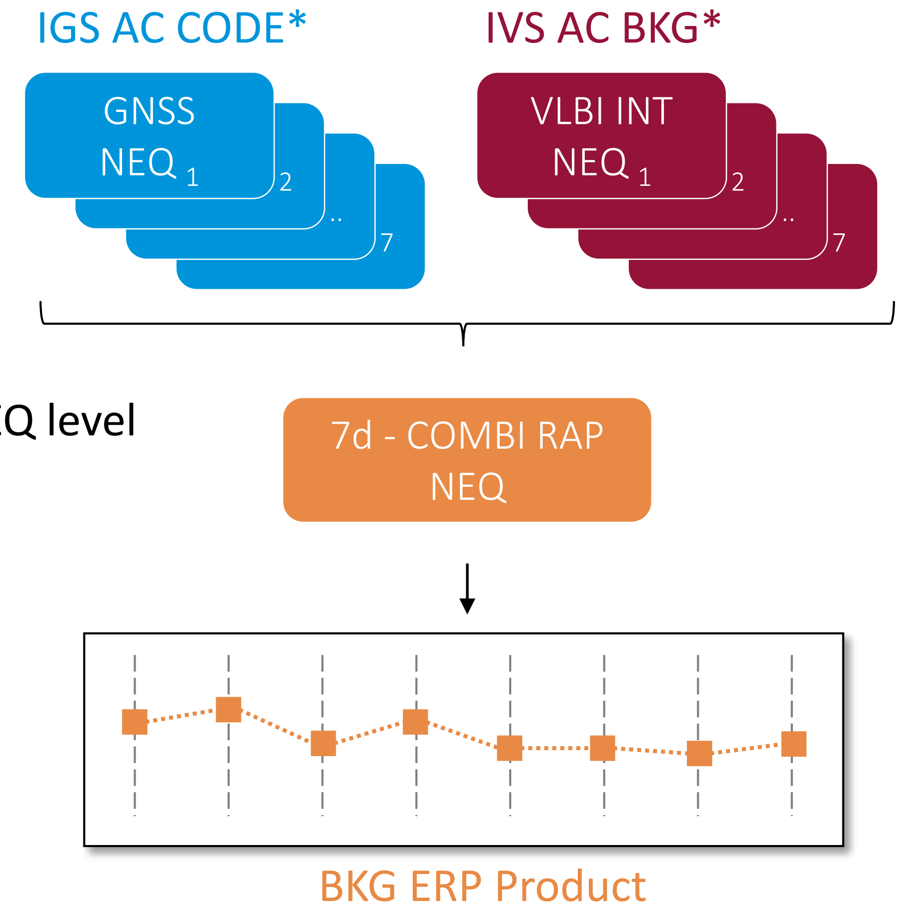
CODE = Center for Orbit Determination in Europe, a consortium of

– Astronomical Institute of the University of Bern (AIUB, Bern, Switzerland)
– Swiss Federal Office of Topography (swisstopo, Wabern, Switzerland)
– Federal Agency for Cartography and Geodesy (BKG, Frankfurt a. M., Germany)
– Institut für Astronomische und Physikalische Geodäsie, Technische Universität München (IAPG/TUM, Munich, Germany)

IGS AC CODE is operated by AIUB, using the Bernese GNSS Software

New BKG ERP product under development



- Derived from combination at NEQ level
- Using NEQ from SINEX files
- Best ERP result:
  7-day piecewise linear polygon

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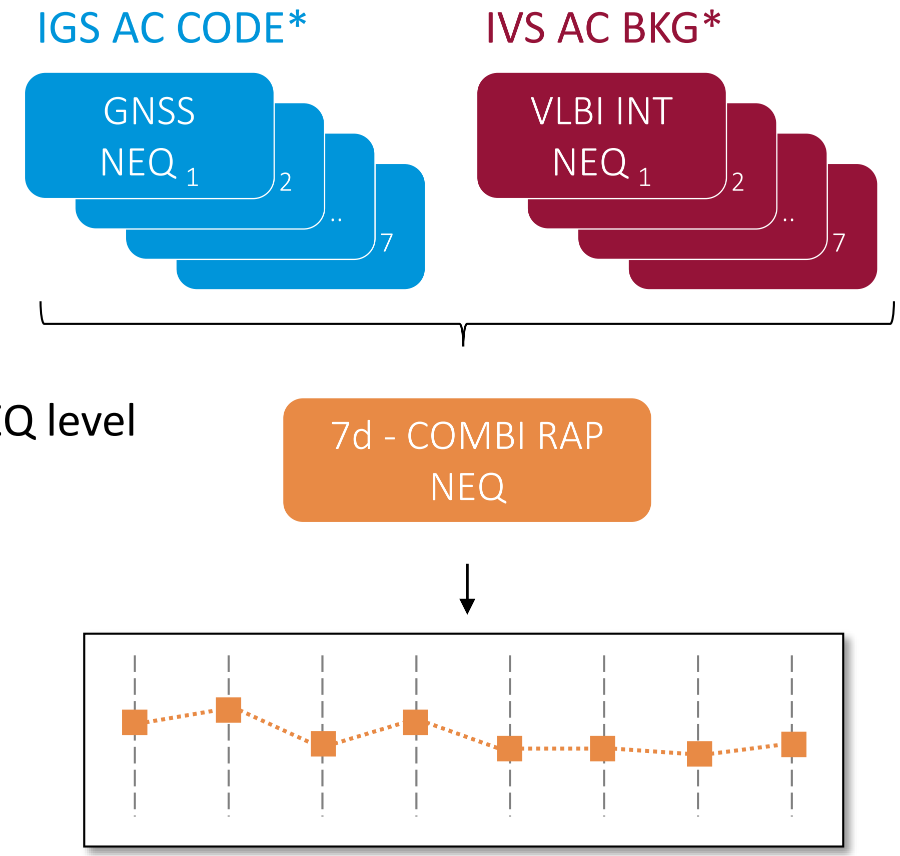

BKG ERP Product

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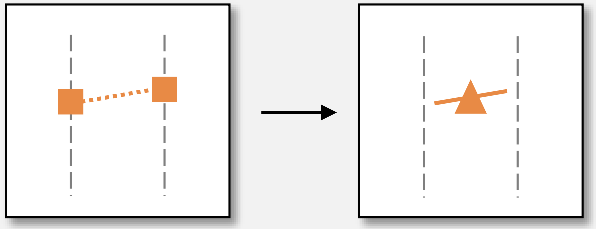
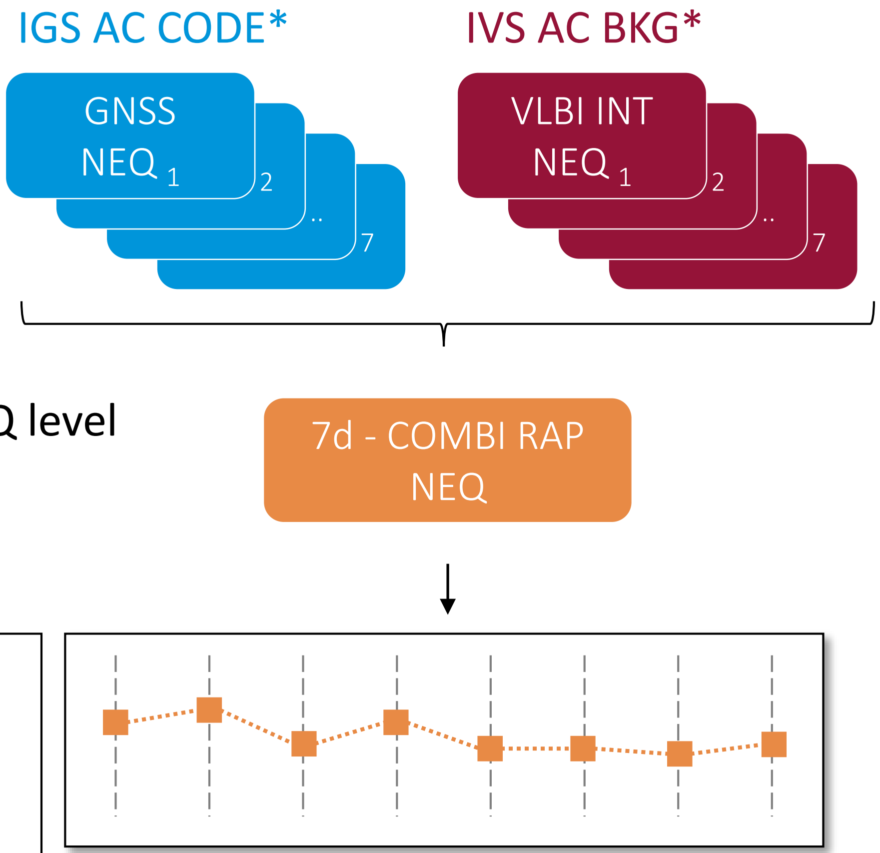
dUT1 parameter representation contains LOD implicitly



2 piecewise linear offsets

offset + drift

New BKG ERP product under development



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Lengert L, Thaller D, Flohrer C, Hellmers H, Girdiuk A (2021):
Combination of GNSS and VLBI data for consistent estimation of Earth Rotation Parameters.
Proceedings of the 25th European VLBI Group for Geodesy and Astrometry Working Meeting (EVGA 2021). (eds. R. Haas). ISBN: 978-91-88041-41-8.
https://www.oso.chalmers.se/evga/25_EVGA_2021_Cyberspace.pdf

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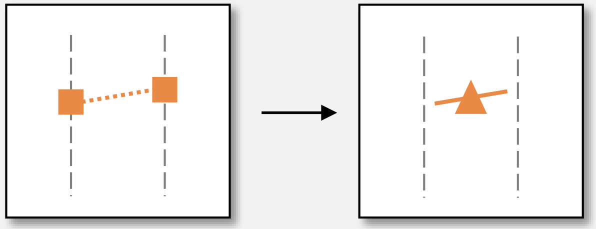

2 piecewise linear offsets → offset + drift

ERP product validation – OPTION 1

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Compare ERP product w.r.t. external reference

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Reference series:	IERS-Bulletin-A, IERS-14-C04, ..
Validation epoch:	12:00 UTC, middle of VLBI observation epoch, ..
ERP product:	different solutions A, B, C (technique, arc-length, ..)

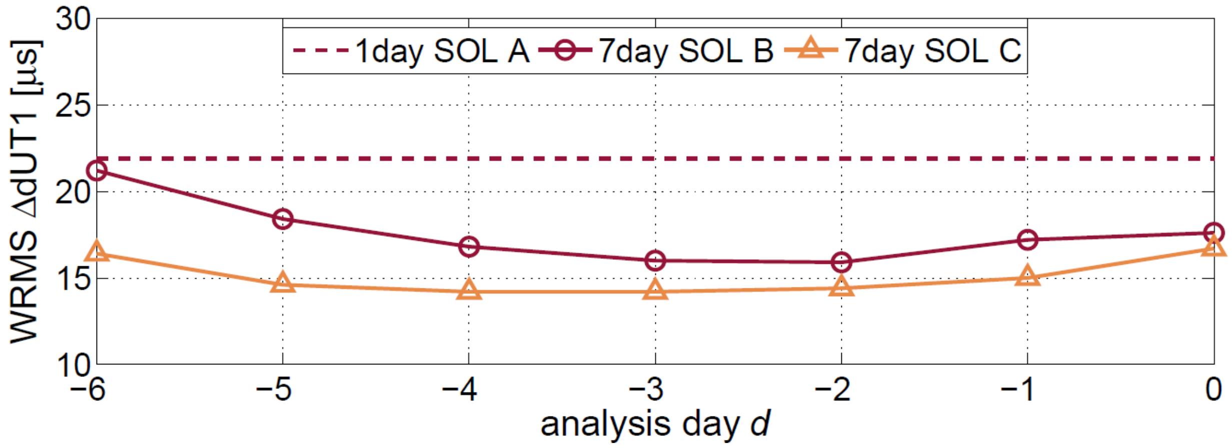
ERP product validation – OPTION 1

Compare ERP product w.r.t. external reference

Reference series:	IERS-Bulletin-A, IERS-14-C04, ..
Validation epoch:	12:00 UTC, middle of VLBI observation epoch, ..
ERP product:	different solutions A, B, C (technique, arc-length, ..)

Analyse WRMS of ERP differences

- absolute value → depends on the reference
- relative value → shows improvement, but also w.r.t. reference
- reference ≠ "truth"



ERP product validation – OPTION 2

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Check impact on other parameter from same solution

ERP product validation – OPTION 2

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Which impact has the combined solution (ERP from combining GNSS+VLBI) on GNSS orbit parameters?

ERP product validation – OPTION 2

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Which impact has the combined solution (ERP from combining GNSS+VLBI) on GNSS orbit parameters?

Why to look at orbits?

GNSS orbits still have some deficiencies

.. Solar radiation pressure modelling
.. CODE estimates 3-day arcs
.. LOD bias exists, but not understood

ERP product validation – OPTION 2

Check impact on other parameter from same solution

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Why to look at orbits?

GNSS orbits still have some deficiencies

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Potential answers:

- Improved orbits
- No impact
- Worse orbits

ERP product validation – impact on orbits

Overview of estimated parameters in combined solution

ERP product validation – impact on orbits

Overview of estimated parameters in combined solution

Combined NEQ (7 days)	
GNSS Rapid - CODE	VLBI INT - BKG
IGS station coordinates	IVS station coordinates
ERP – Pole coordinates – dUT1 (piecewise linear offsets)	
Orbits – Keplerian elements – Dynamical parameter – Stochastic pulses	
Troposphere – Zenith wet delays – N/E Gradients	Troposphere – Zenith wet delays

ERP product validation – impact on orbits

Overview of estimated parameters in combined solution

Combined NEQ (7 days)

GNSS Rapid - CODE	VLBI INT - BKG	
IGS station coordinates	IVS station coordinates	Explicit in SINEX NEQ
ERP – Pole coordinates – dUT1 (piecewise linear offsets)		Explicit in SINEX NEQ
Orbits – Keplerian elements – Dynamical parameter – Stochastic pulses		Implicit in SINEX NEQ
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Orbits – Keplerian elements – Dynamical parameter – Stochastic pulses		Implicit in SINEX NEQ
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ERP product validation – impact on orbits

Overview of estimated parameters in combined solution

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GNSS Rapid - CODE	VLBI INT - BKG	
IGS station coordinates	IVS station coordinates	Explicit in SINEX NEQ
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Orbits – Keplerian elements – Dynamical parameter – Stochastic pulses		Implicit in SINEX NEQ
Troposphere – Zenith wet delays – N/E Gradients	Troposphere – Zenith wet delays	Implicit in SINEX NEQ

No access to orbit parameters on SINEX NEQ level!

ERP product validation – impact on orbits

Estimated parameters

GNSS NEQ

GNSS Rapid - CODE

Explicit:

IGS station coordinates

ERP
- Pole coordinates
- dUT1 (pwl offsets)

Orbits
- Keplerian elements
- Dynamical parameter
- Stochastic pulses

Implicit:

Troposphere
- Zenith wet delays
- N/E Gradients

Get access to orbit parameters from combined analysis by

- Re-running GNSS Rapid solution from CODE
- Using NEQs provided by CODE (containing orbits as explicit parameters)

ERP product validation – impact on orbits

Estimated parameters

GNSS NEQ

GNSS Rapid - CODE

IGS station coordinates

ERP
- Pole coordinates
- dUT1 (fix all)

Orbits
- Keplerian elements
- Dynamical parameter
- Stochastic pulses

Troposphere
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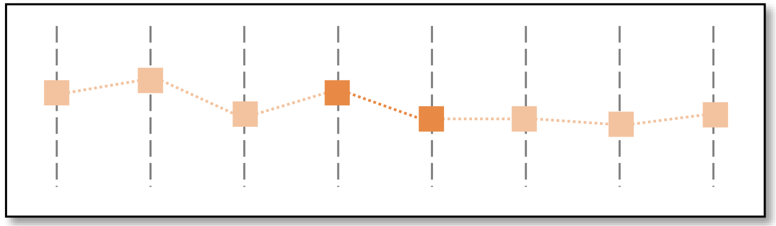

Get access to orbit parameters from combined analysis by

- Re-running GNSS Rapid solution from CODE
- Using NEQs provided by CODE (containing orbits as explicit parameters)
- Introducing combined ERP product and fixing all dUT1 values

ERP product validation – impact on orbits

Estimated parameters

GNSS NEQ

GNSS Rapid - CODE

IGS station coordinates

ERP
– Pole coordinates
– dUT1 (fix all)

Orbits
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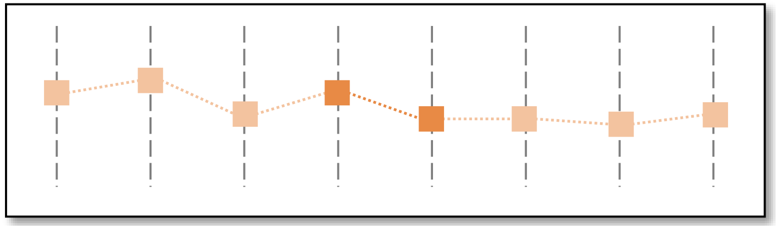

BKG solution

BKG

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ERP product validation – impact on orbits

Estimated parameters

GNSS NEQ

GNSS Rapid - CODE

IGS station coordinates

ERP
- Pole coordinates
- dUT1 (fix first)

Orbits
- Keplerian elements
- Dynamical parameter
- Stochastic pulses

Troposphere
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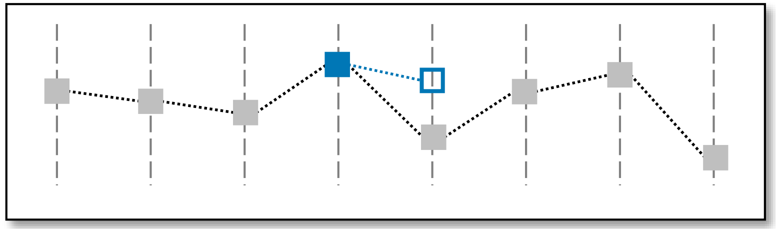


Reference solution

REF

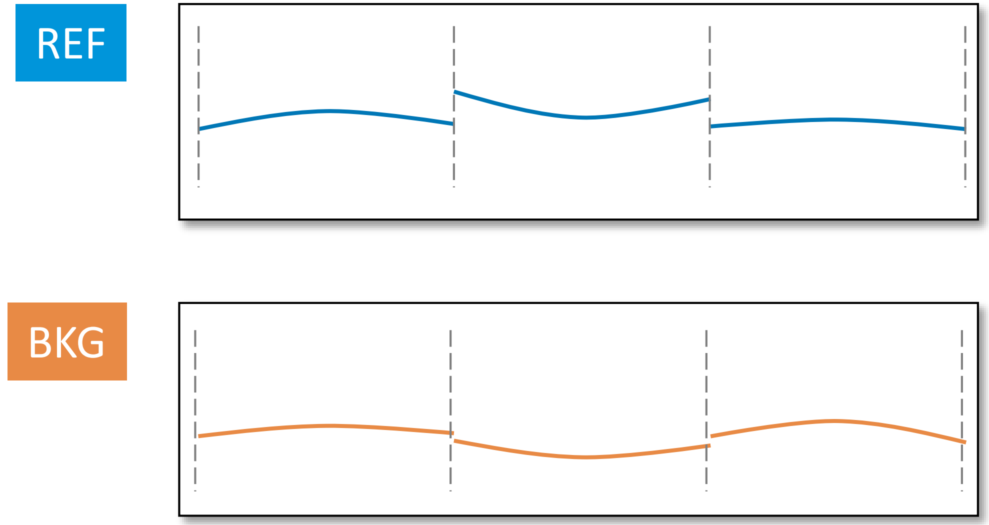
Use GNSS Rapid solution from CODE as reference

- Using IERS-Bulletin-A as a priori ERP
- Fix first dUT1 value

Orbit validation

Orbit validation

- 3 GNSS: GPS | GLONASS | Galileo
- 1-day arcs
- 113 days
- DoY 045-157 2022



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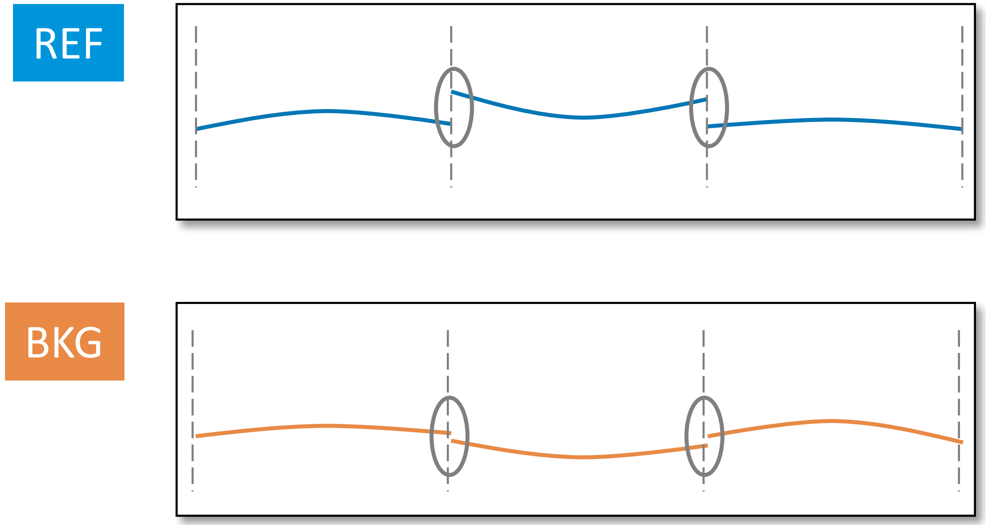
- 1-day arcs
- 113 days
- DoY 045-157 2022

Analyse orbit differences at day boundaries



Satellite-specific orbit differences at day boundaries (1-day arcs)

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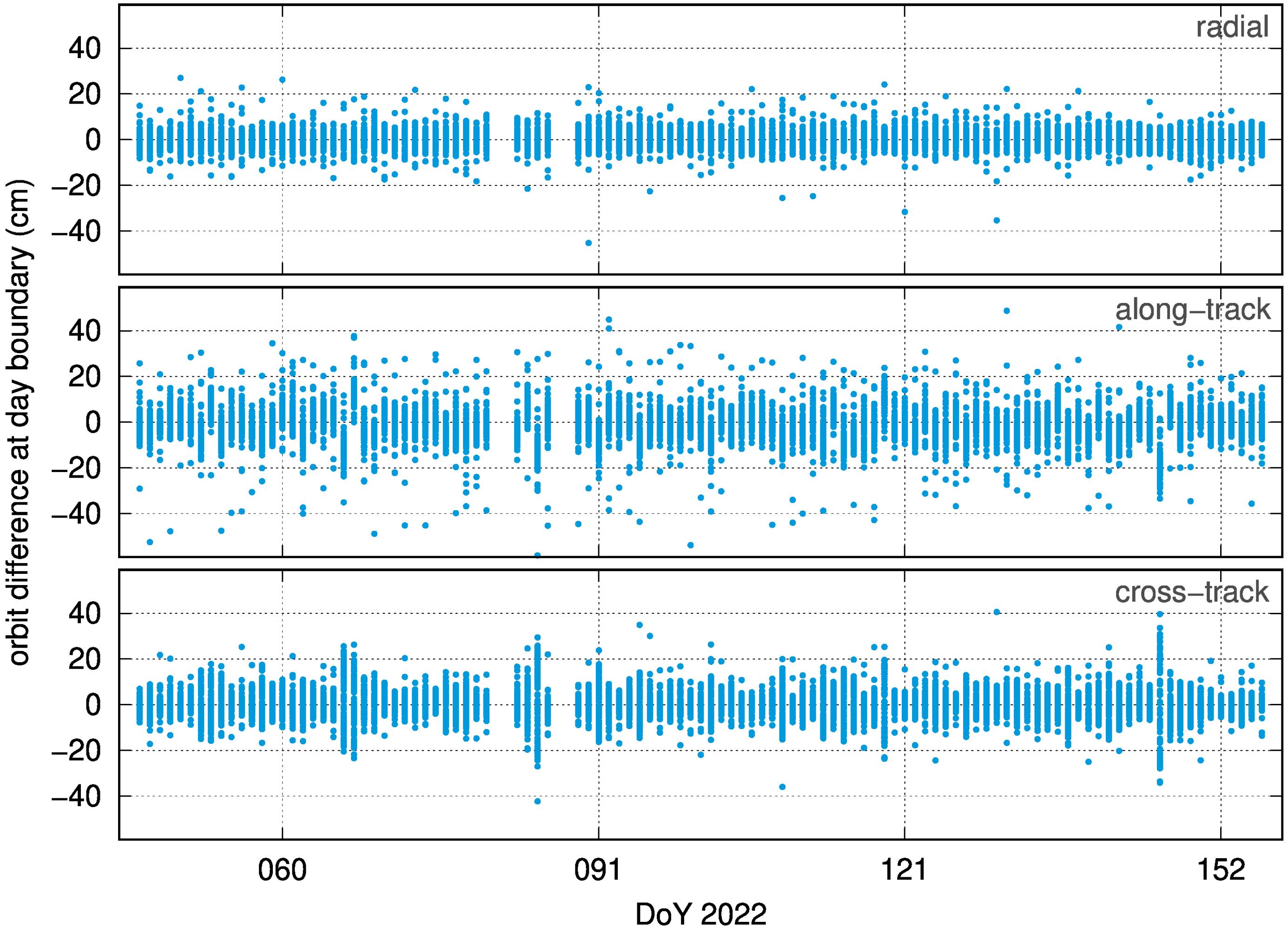

Satellite-specific orbit differences at day boundaries (1-day arcs)

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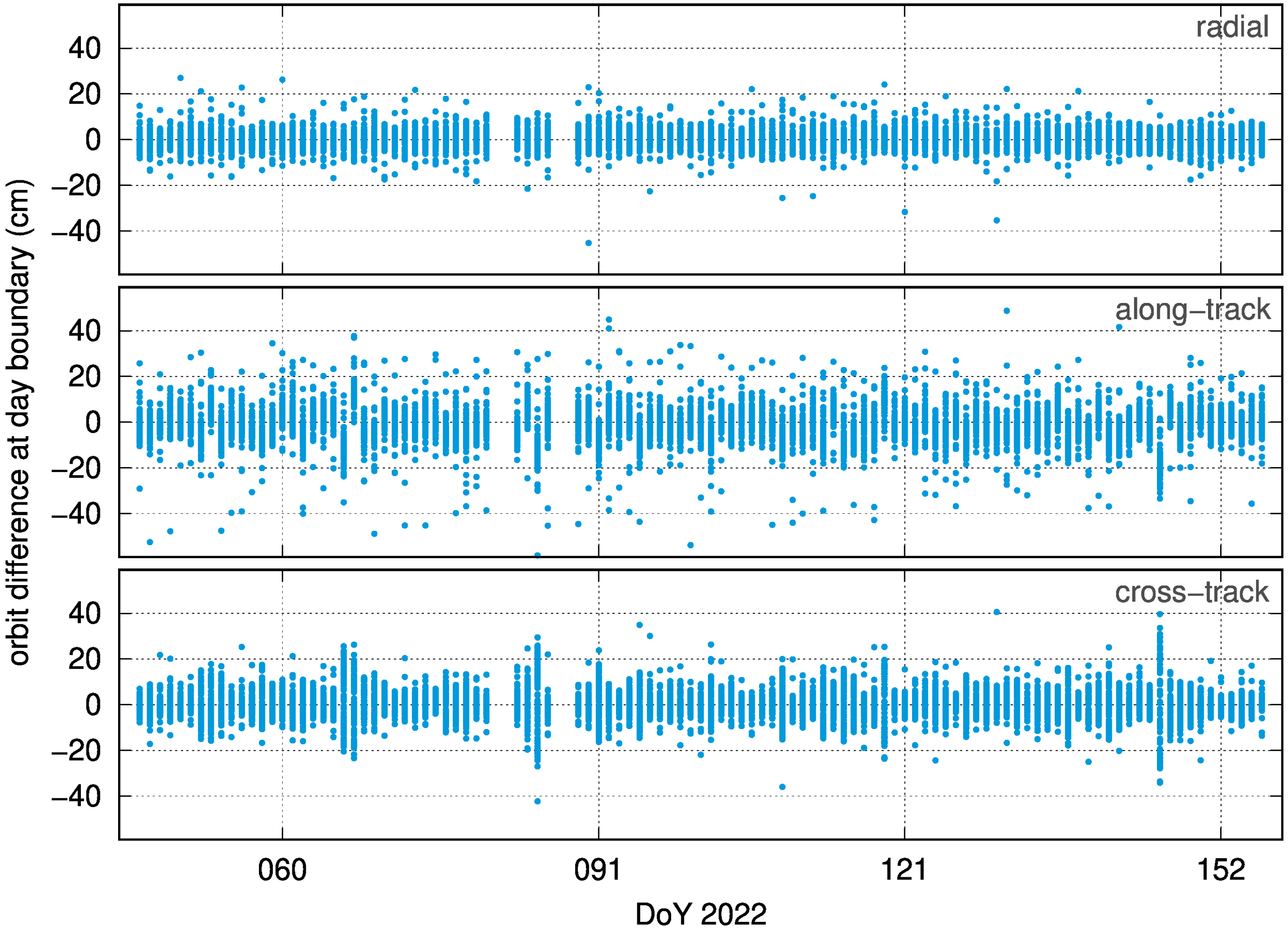
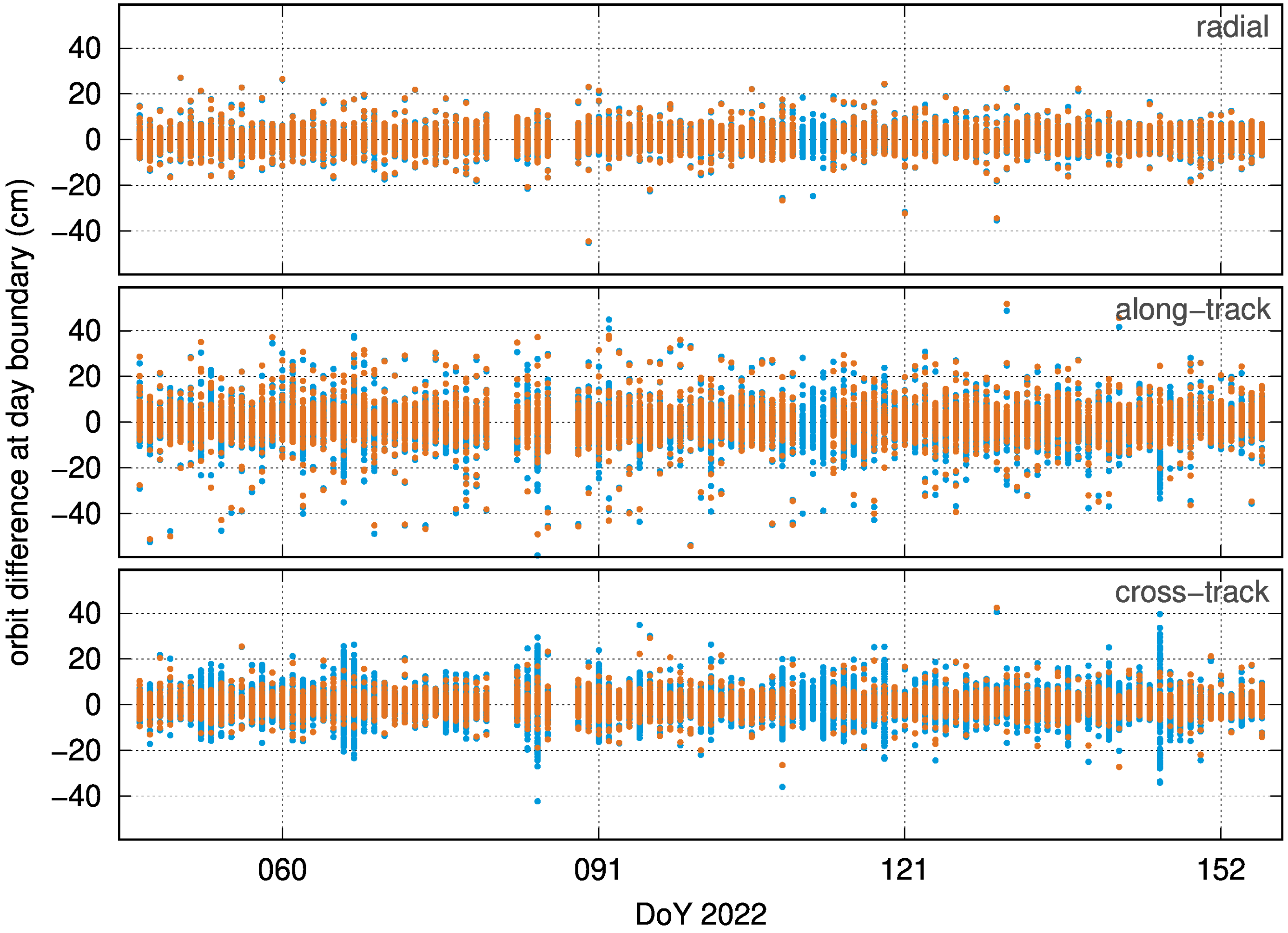


RMS (cm)
ALL
3.8
8.0
6.2

Satellite-specific orbit differences at day boundaries (1-day arcs)

RMS (cm)

REF BKG

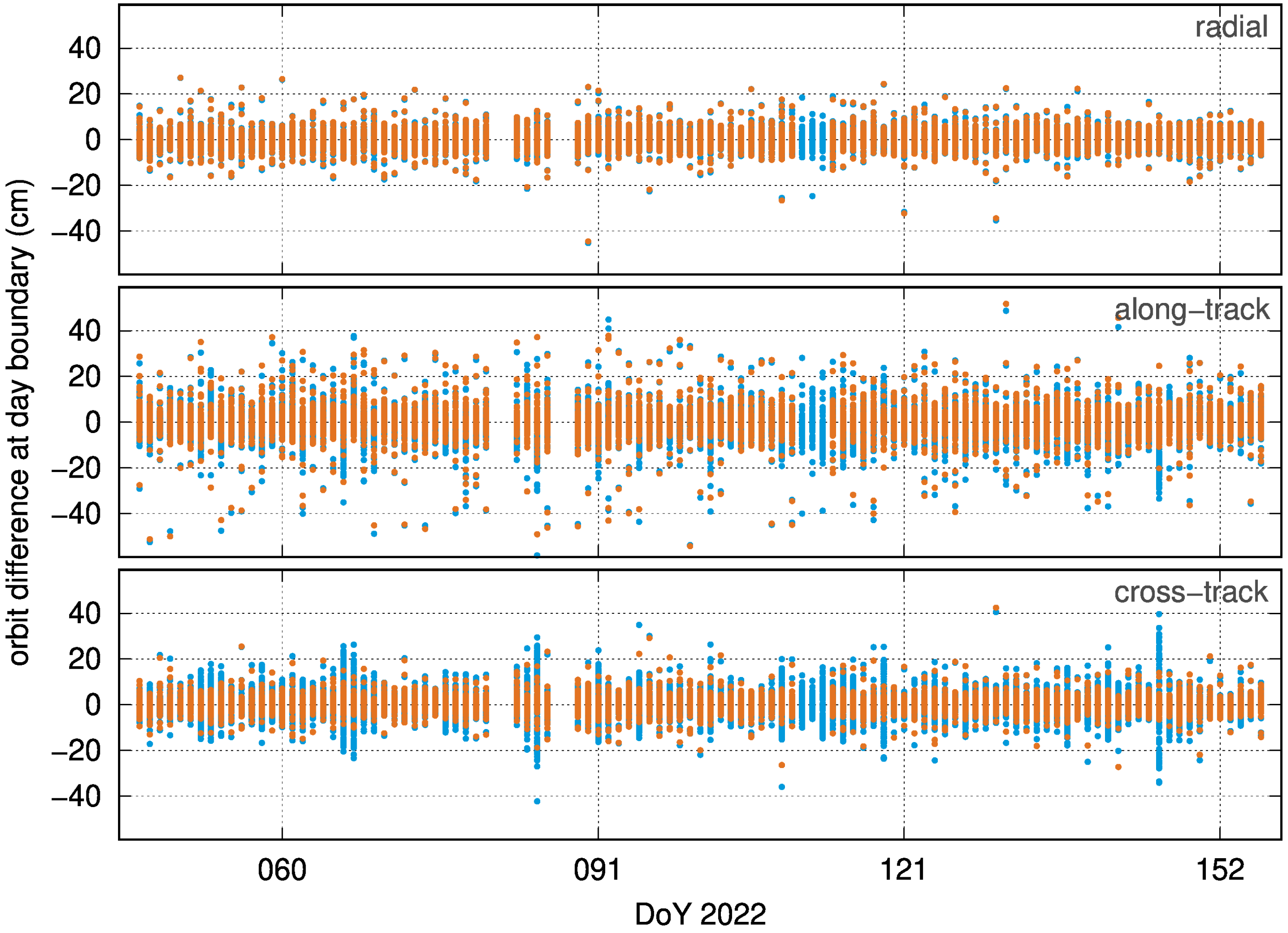


ALL	
3.8 (REF)	3.8 (BKG)
8.0 (REF)	6.6 (BKG)
6.2 (REF)	3.6 (BKG)

Satellite-specific orbit differences at day boundaries (1-day arcs)

RMS (cm)

REF BKG

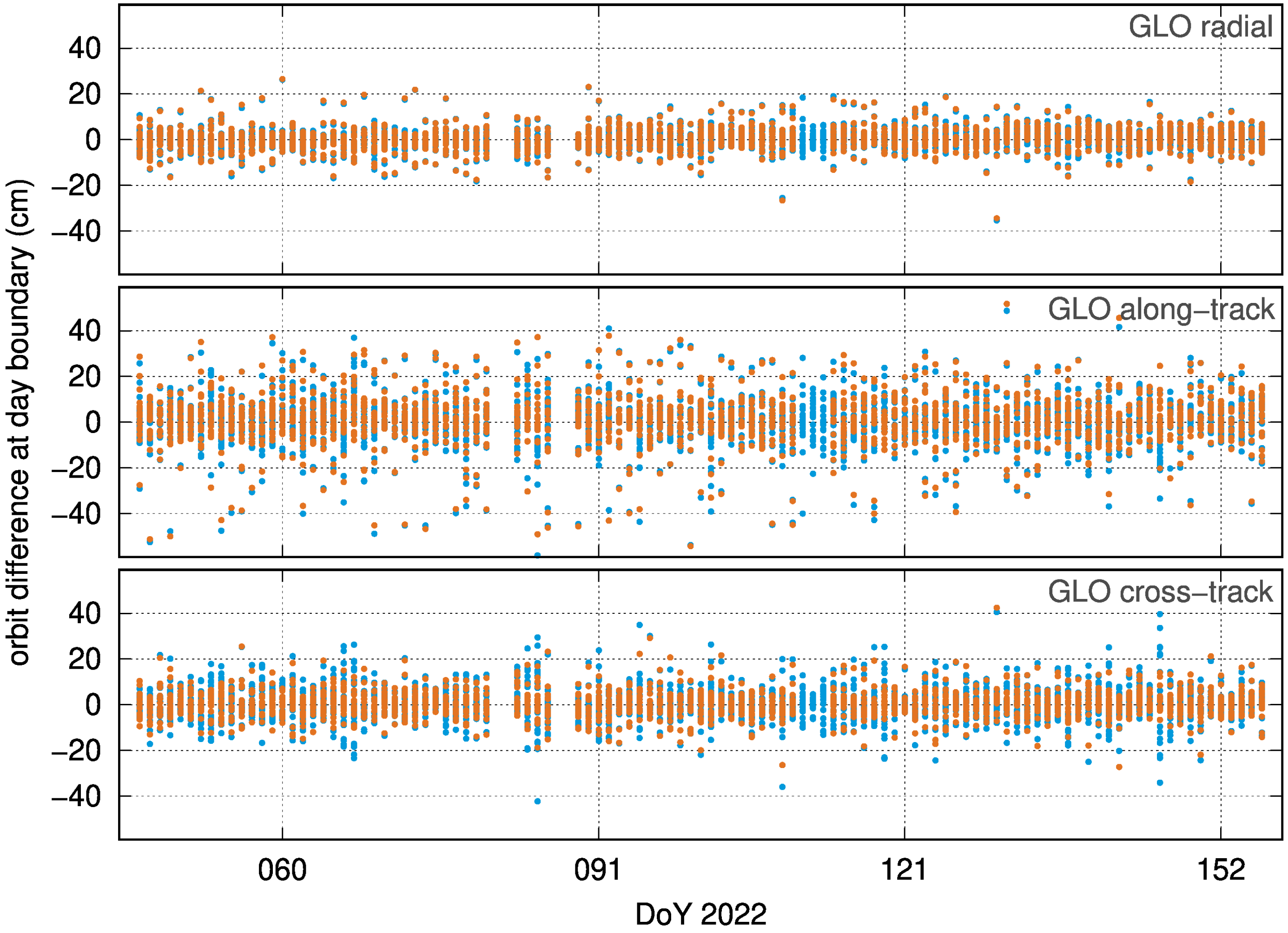


ALL
3.8 / 3.8
8.0 / 6.6
6.2 / 3.6

Improvement in along-track and cross-track

Satellite-specific orbit differences at day boundaries (1-day arcs)

REF BKG

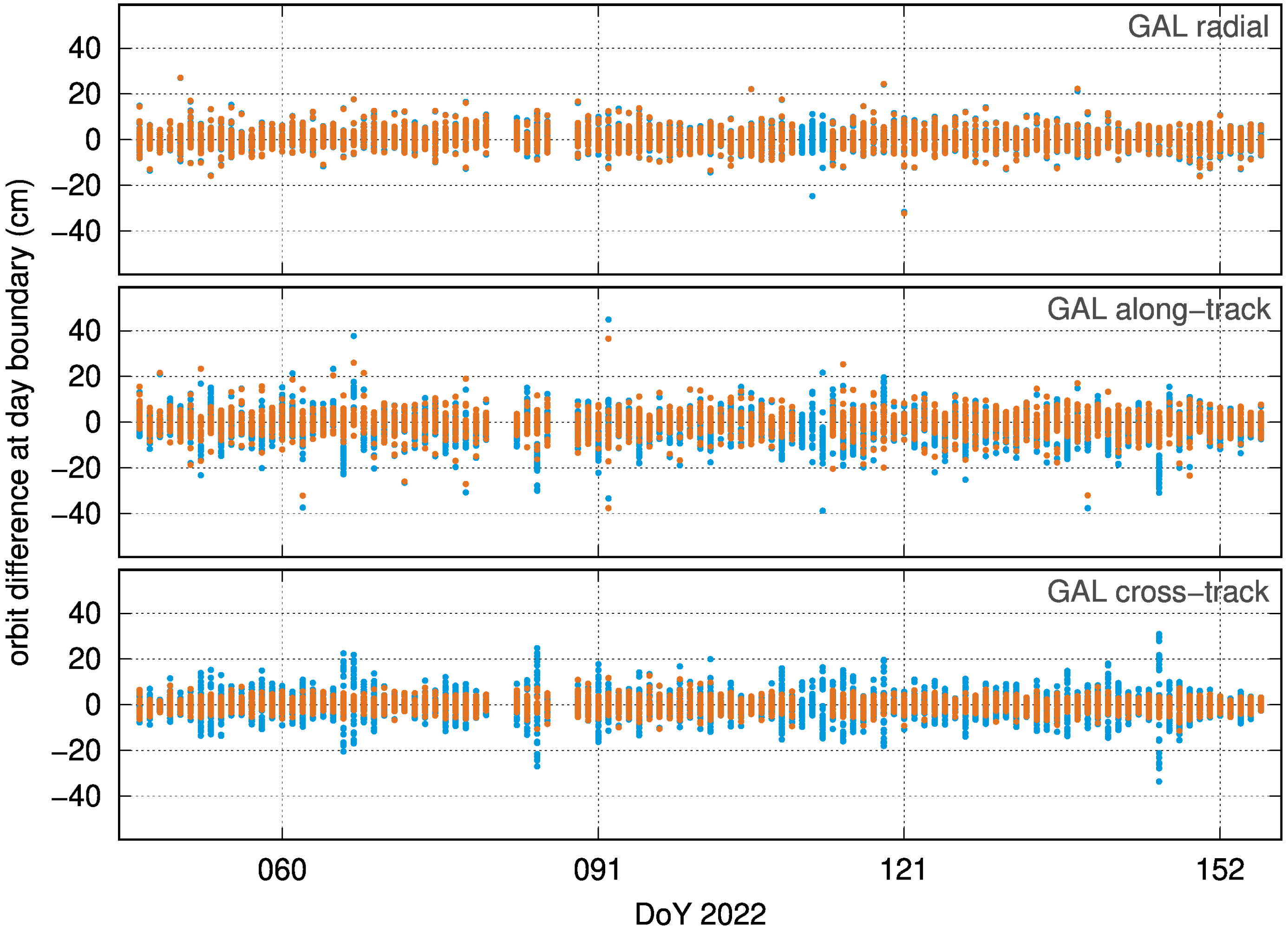


RMS (cm)

	ALL	GLO
radial	3.8 / 3.8	4.7 / 4.7
along-track	8.0 / 6.6	11.4 / 10.9
cross-track	6.2 / 3.6	7.6 / 5.6

Satellite-specific orbit differences at day boundaries (1-day arcs)

REF BKG

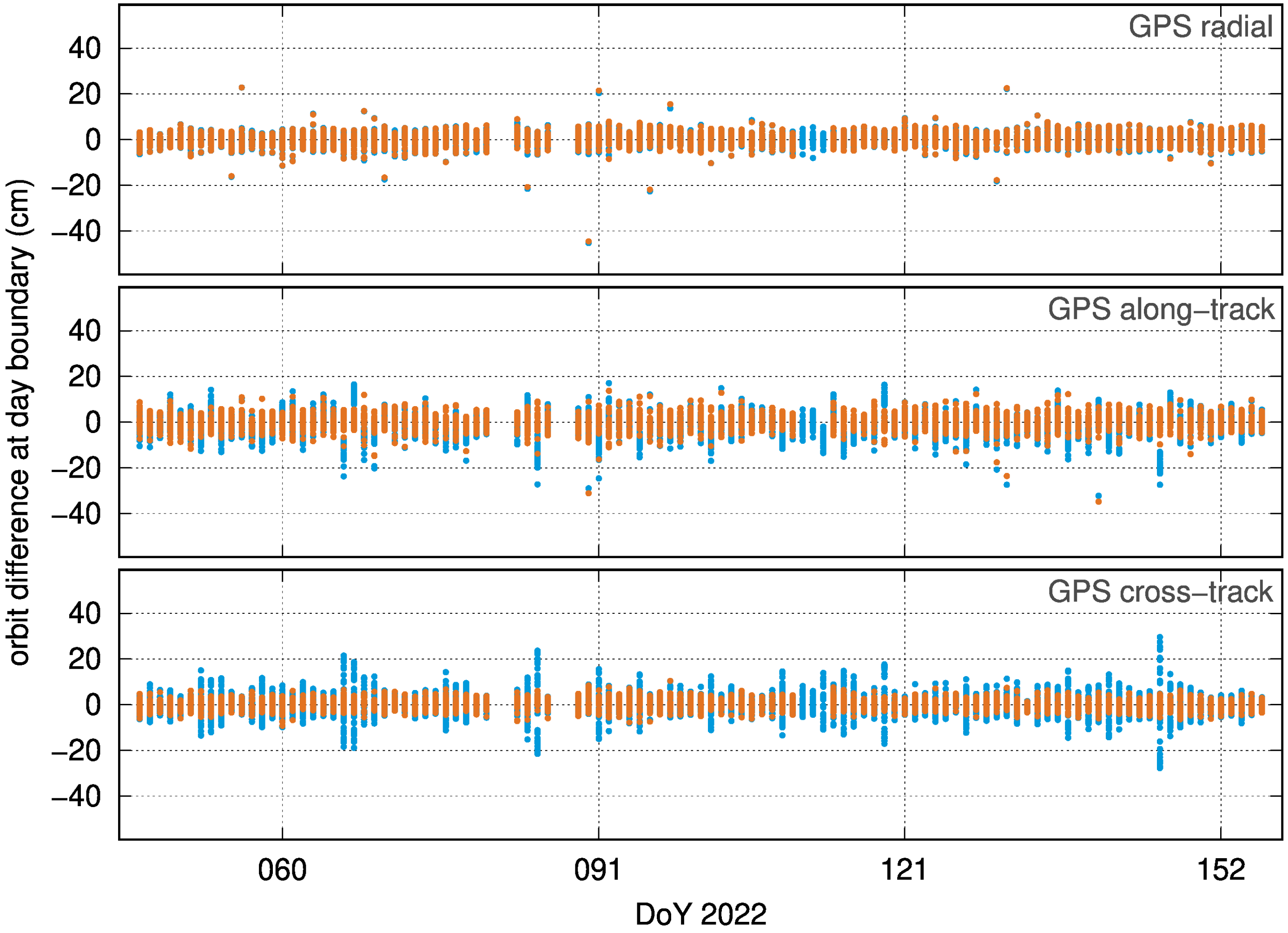


RMS (cm)

	ALL	GLO	GAL
radial (REF)	3.8	4.7	4.1
radial (BKG)	3.8	4.7	4.1
along-track (REF)	8.0	11.4	7.4
along-track (BKG)	6.6	10.9	4.9
cross-track (REF)	6.2	7.6	6.0
cross-track (BKG)	3.6	5.6	2.7

Satellite-specific orbit differences at day boundaries (1-day arcs)

REF BKG



RMS (cm)

ALL	GLO	GAL	GPS
3.8	4.7	4.1	2.8
3.8	4.7	4.1	2.9
8.0	11.4	7.4	5.8
6.6	10.9	4.9	3.5
6.2	7.6	6.0	5.4
3.6	5.6	2.7	2.3

Conclusions

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Which impact has the combined solution (ERP from combining GNSS+VLBI) on GNSS orbit parameters?

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Using combined BKG ERP product, derived from combination of NEQs of

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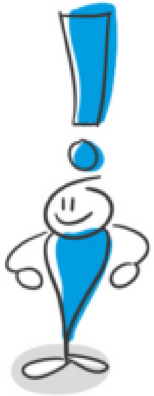

Answer: Improved orbits

- in along-track and cross-track orbit differences at day boundaries
- for GPS, GLONASS, Galileo
- for 1-day (and 3-day) arcs

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Additional VLBI-based LOD information is clearly beneficial for all considered GNSS!

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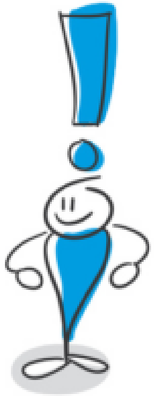

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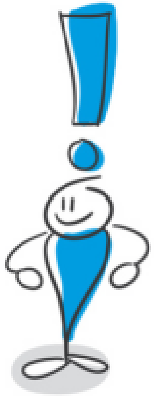

Answer: Improved orbits
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Solar radiation pressure modelling?
Plane-specific dependencies?
Eclipse behavior?
LOD bias?
..

Federal Agency for
Cartography and Geodesy

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Thank you for your kind attention!

Federal Agency for Cartography and Geodesy (BKG)
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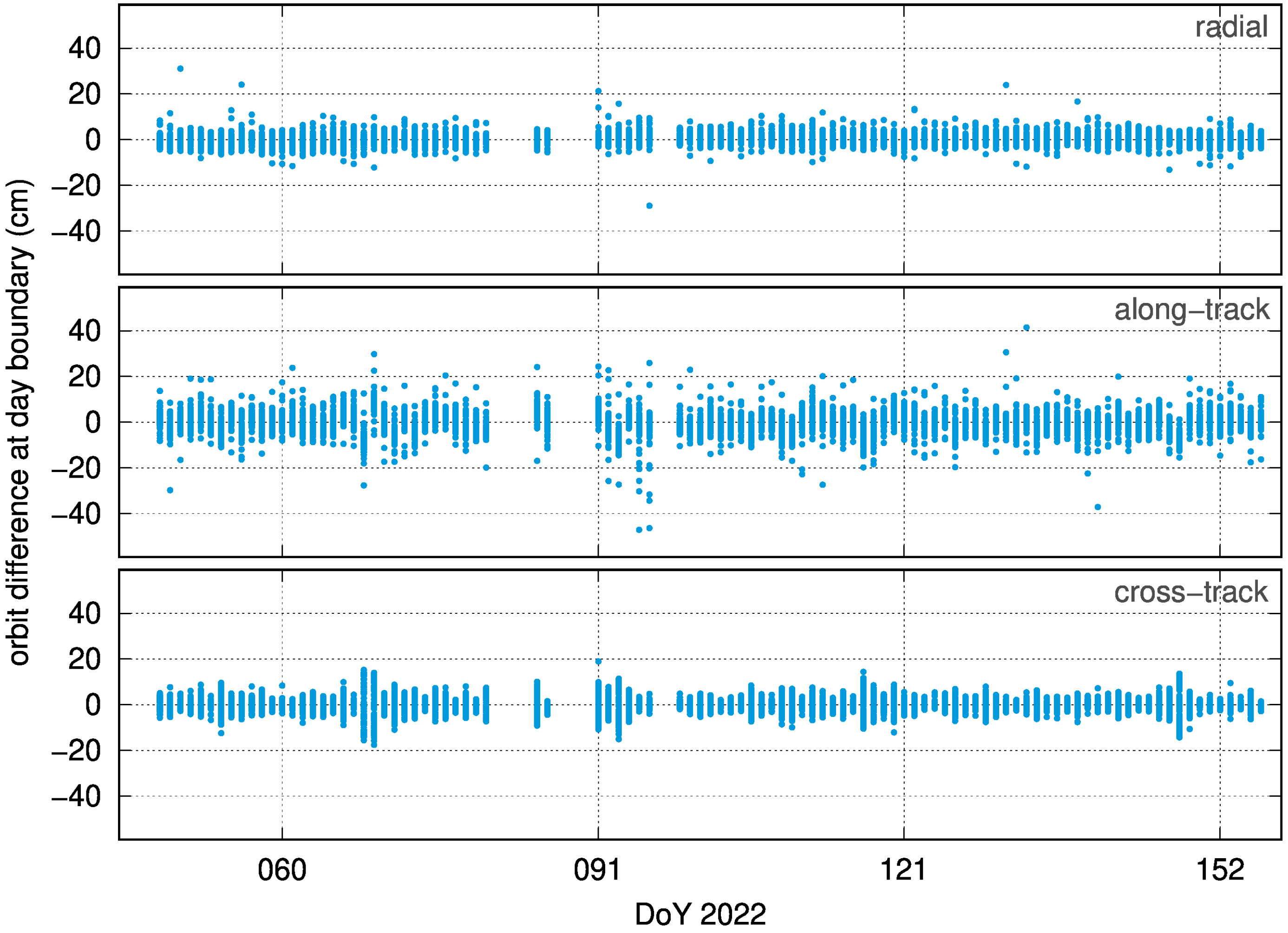
Satellite-specific orbit differences at day boundaries (3-day arcs)

RMS (cm)

REF

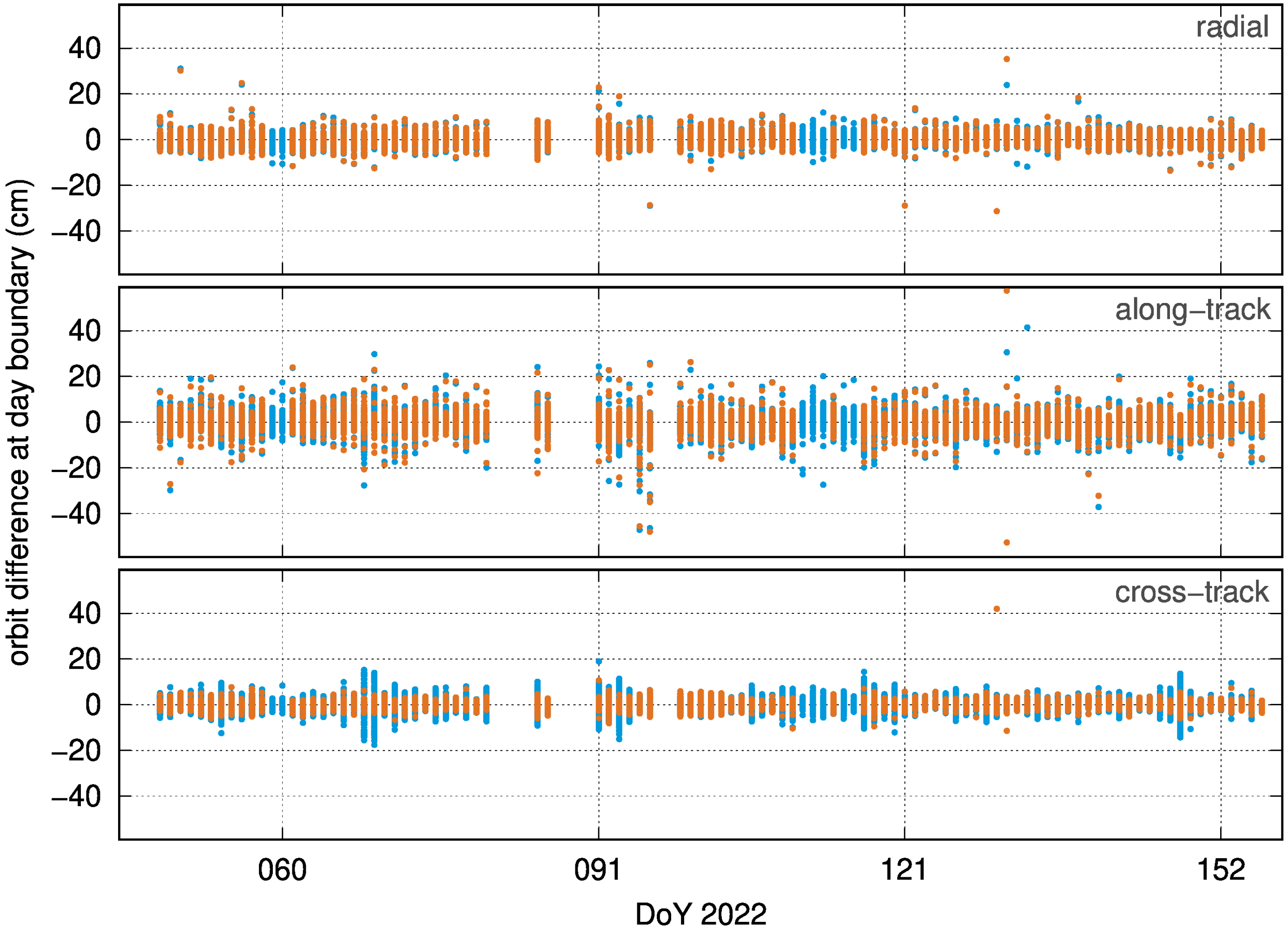


ALL
3.8
8.0
6.2

Satellite-specific orbit differences at day boundaries (3-day arcs)

RMS (cm)

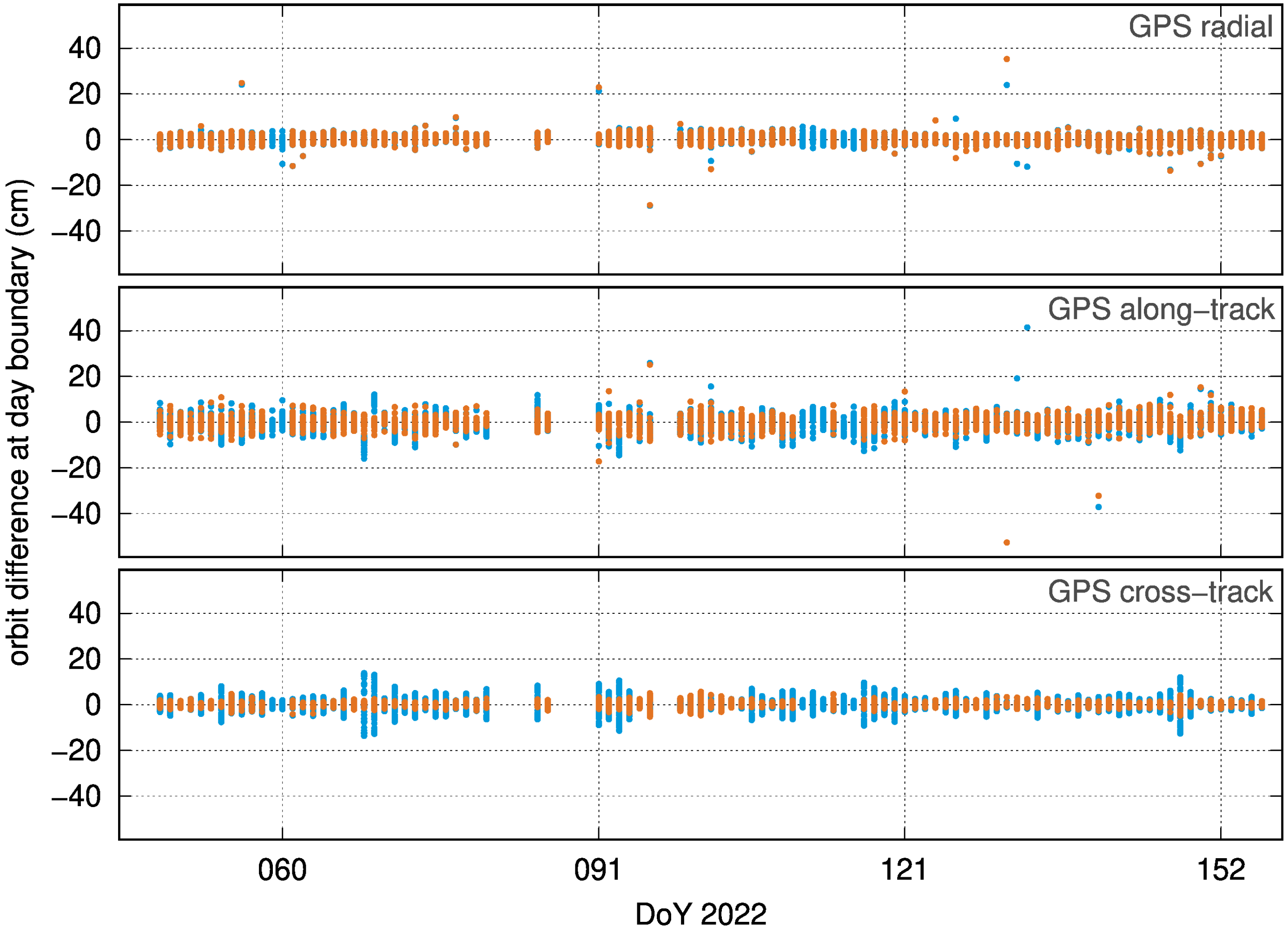
REF BKG



	ALL
radial	2.2 / 2.5
along-track	4.8 / 4.1
cross-track	3.3 / 1.6

Satellite-specific orbit differences at day boundaries (3-day arcs)

REF

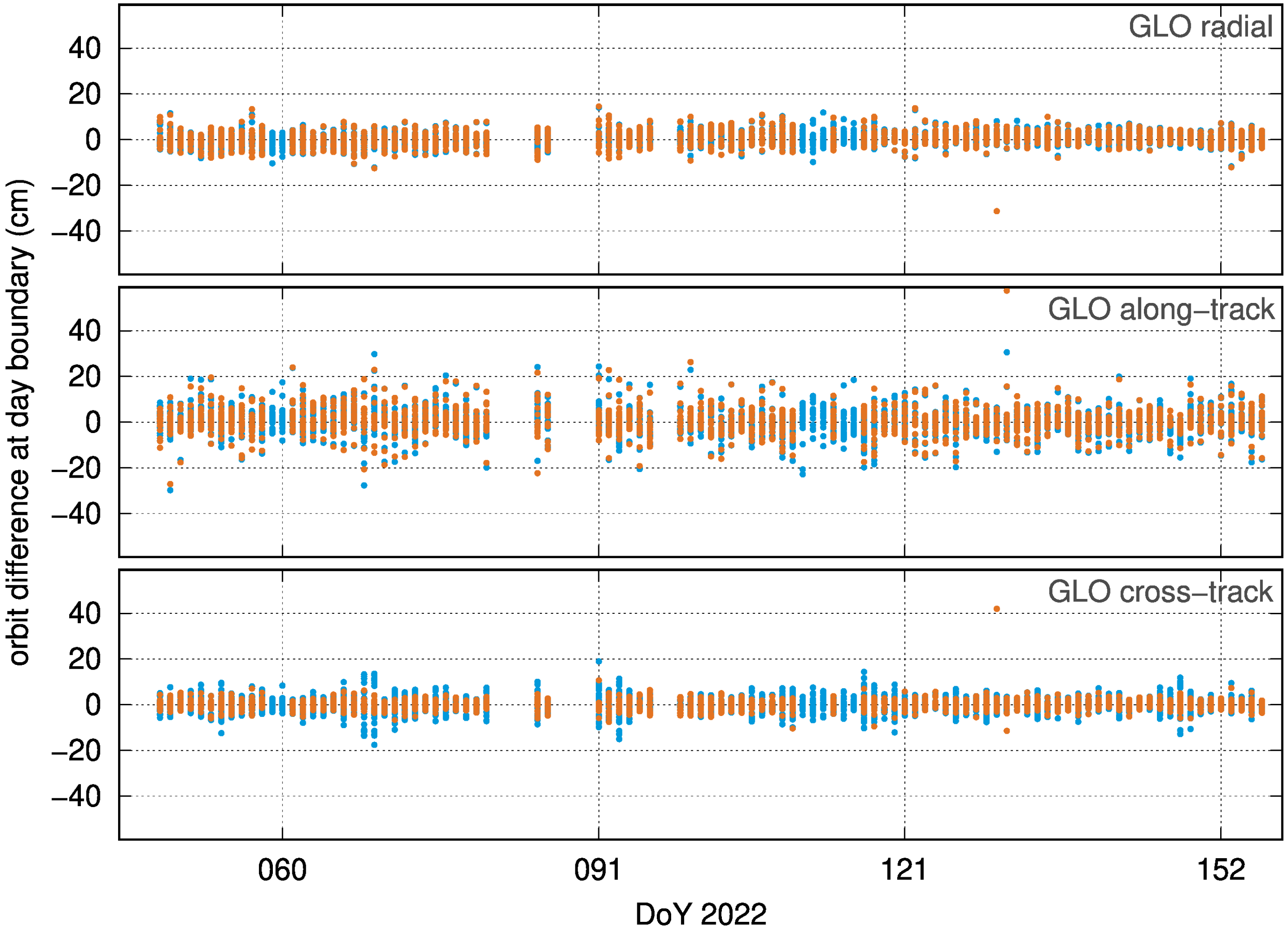


RMS (cm)

	ALL	GPS
radial	2.2 / 2.5	1.7 / 1.8
along-track	4.8 / 4.1	4.1 / 2.7
cross-track	3.3 / 1.6	3.1 / 1.1

Satellite-specific orbit differences at day boundaries (3-day arcs)

REF



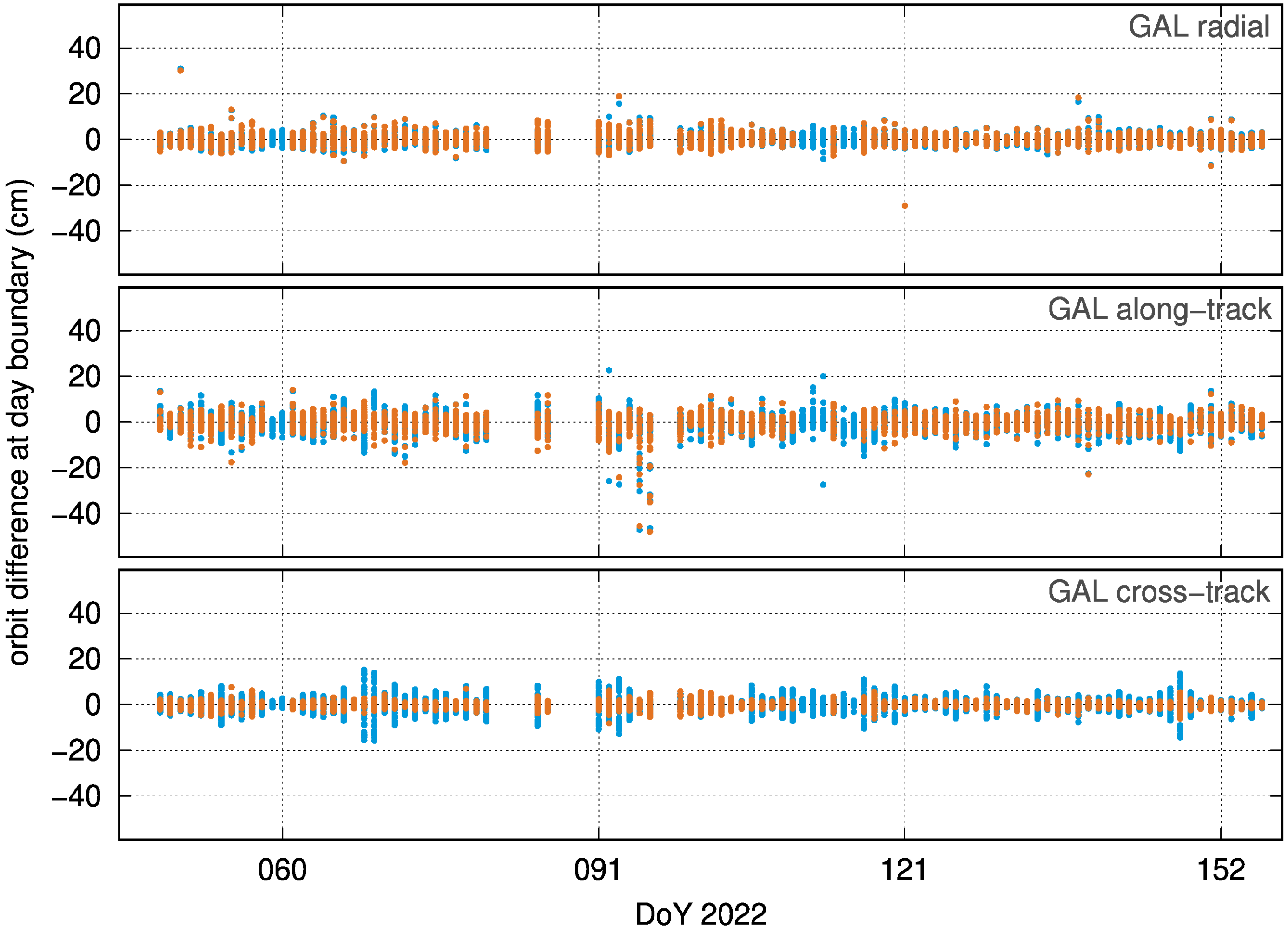
RMS (cm)

ALL	GPS	GLO
2.2 2.5	1.7 1.8	2.9 3.2
4.8 4.1	4.1 2.7	6.0 5.9
3.3 1.6	3.1 1.1	3.6 2.2

Satellite-specific orbit differences at day boundaries (3-day arcs)

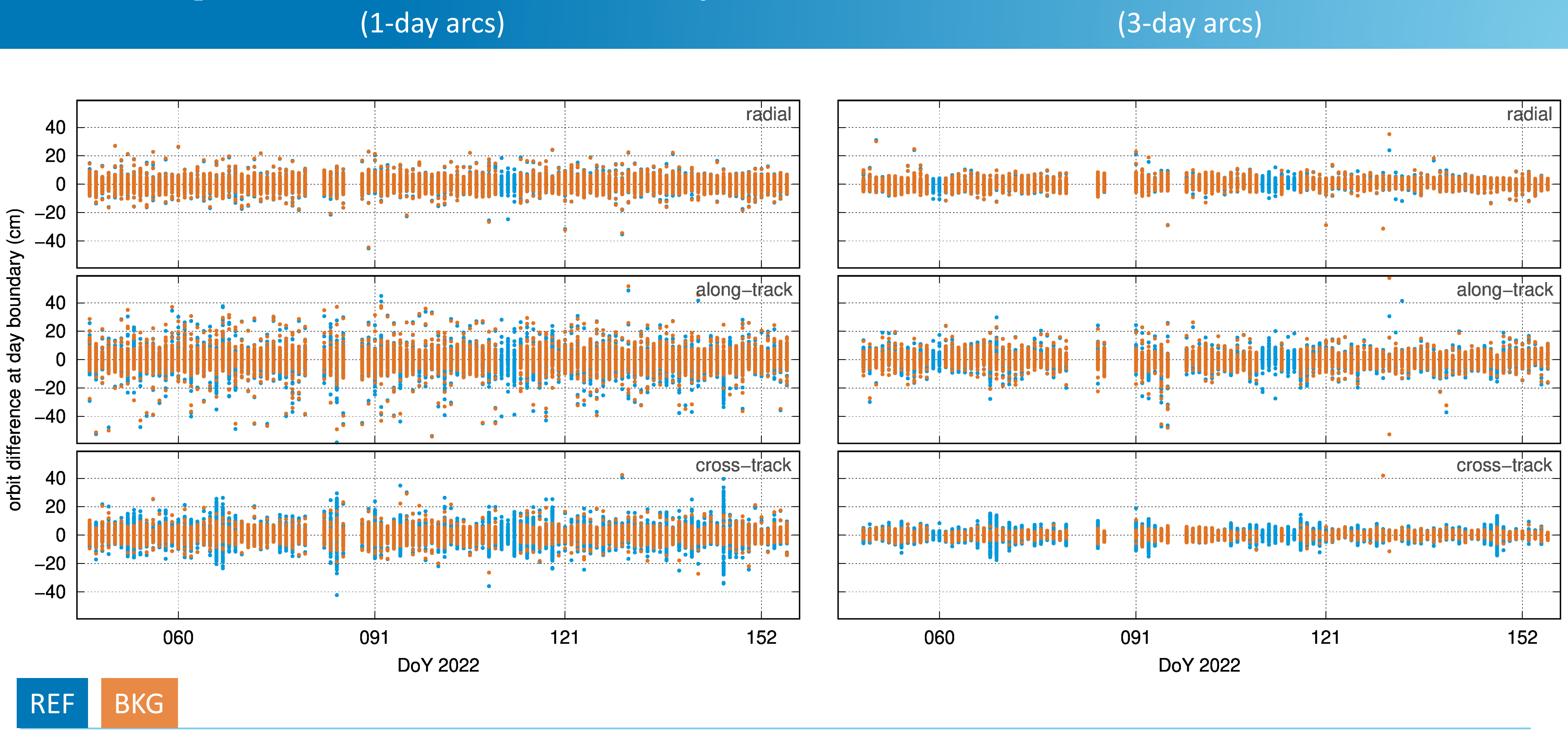
RMS (cm)

REF



	ALL	GPS	GLO	GAL
radial	2.2 2.5	1.7 1.8	2.9 3.2	2.2 2.5
along-track	4.8 4.1	4.1 2.7	6.0 5.9	4.8 3.8
cross-track	3.3 1.6	3.1 1.1	3.6 2.2	3.4 1.5

Satellite-specific orbit differences at day boundaries



2019-2022 (GALILEO ab 2071_4)
GNSS LOD Bias – 7-day GNSS single-technique

7-day GNSS **without** LOD bias correction

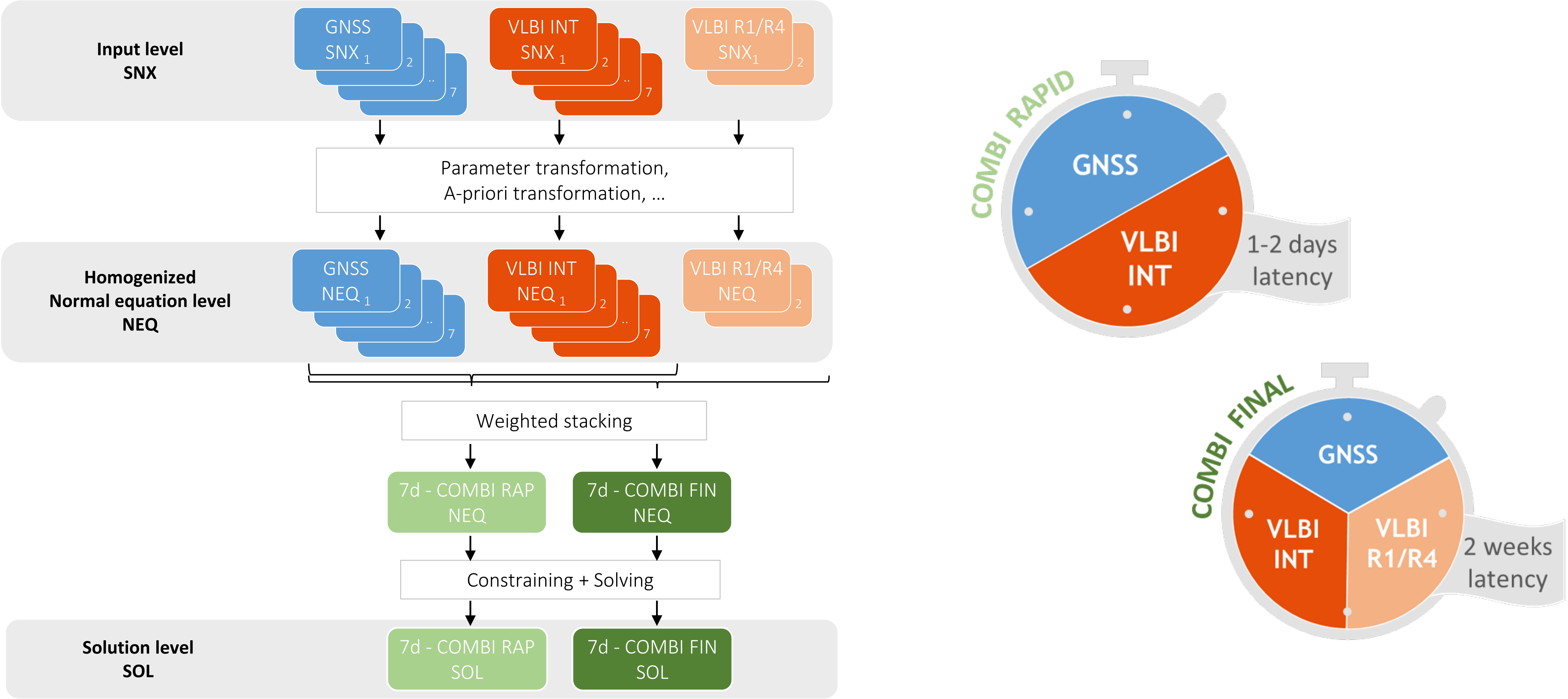
Day n	μ_{dUT1} [ms]	LoD [ms/d] (μ_{dUT1_n} - μ_{dUT1_n-1})
-6	0.0032	
-5	0.0093	0.0061
-4	0.0154	0.0061
-3	0.0213	0.0059
-2	0.0275	0.0061
-1	0.0336	0.0061
0	0.0396	0.0060

7-day GNSS **with** LOD bias correction of **6.1µs**

Day n	μ_{dUT1} [ms]	LoD [ms/d] (μ_{dUT1_n} - μ_{dUT1_n-1})
-6	0.0002	
-5	0.0003	0.0001
-4	0.0008	0.0005
-3	0.0010	0.0002
-2	0.0014	0.0004
-1	0.0018	0.0004
0	0.0025	0.0007

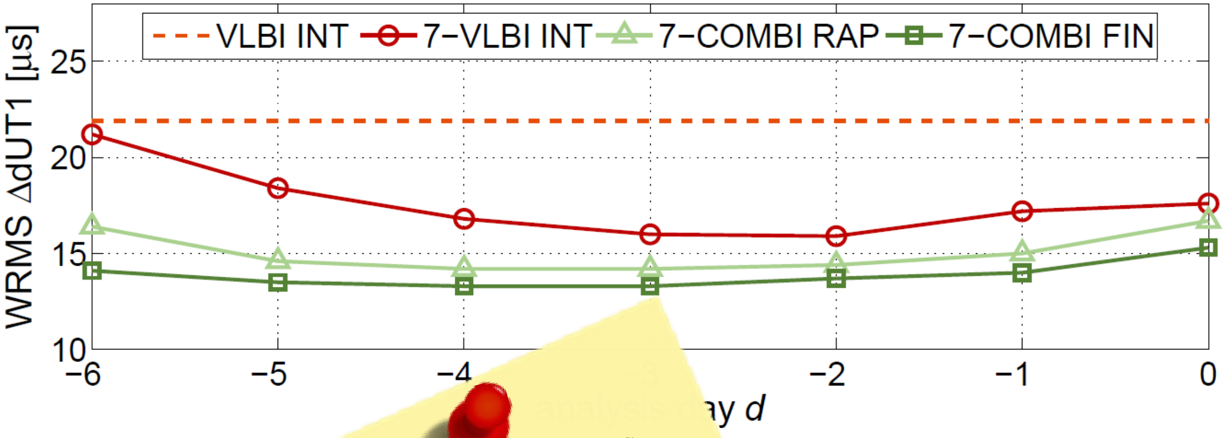
GNSS RAP CODE (72h session)			
explicit	Station coordinates		constant offset
	ERP	Pole coordinates	PWL offsets every 24h (4/72h)
		dUT1	PWL offsets every 24h (4/72h)
	Geocenter		constant offset
	Satellite PCO	Z-direction	constant offset
implicit	Satellite orbit	Keplerian elements	
		Dynamical parameter	constant offsets in D-, Y-, and B-direction
			periodic 1pr in B-direction
			periodic 2pr in D-direction
		Stochastic pulses	small velocity changes every 12h in radial along-track and out-of-plane direction
	Troposphere	ZWD	PWL offsets every 2h for each station
		Gradients	constant offsets for 24h
VLBI INT BKG (1h session)			
explicit	Station coordinates		constant offset
	ERP	Pole coordinates	constant offset
		Pole rates	drift
		dUT1	constant offset
		LOD	drift
implicit	Source coordinates		constant offset
	Troposphere	ZWD	constant offset for each station
	Station clocks		quadratic polynomial for each station

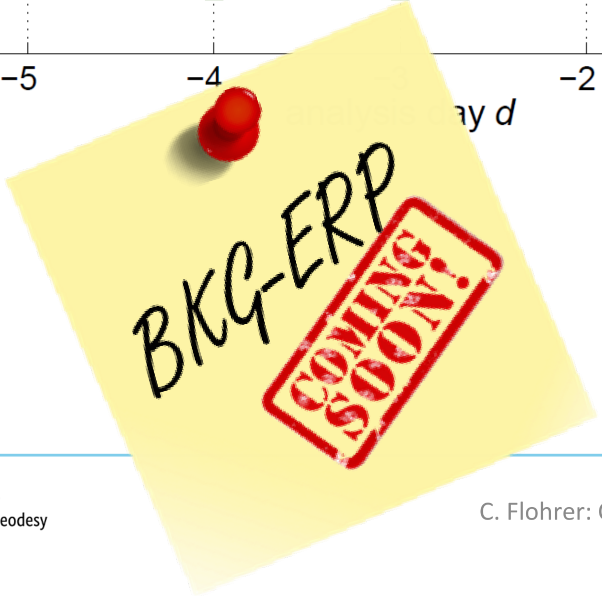
Combination Scheme – 7-day Combination of VLBI and GNSS

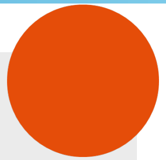


Results – 7-day Combination of VLBI and GNSS

Validation epoch: **12:00 UTC**
Reference series: **IERS-Bulletin-A**

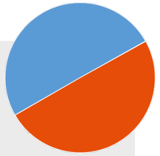






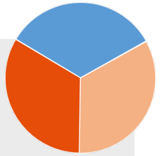
7-day VLBI INT

- significant reduction of the WRMS values
- no constraining of the LOD is required
- improves accuracies outside the INT observation period



7-day COMBI RAPID

- significant reduction of the WRMS values
- polar motion and LOD from GNSS complements dUT1 from VLBI INT
  - → **daily, consistent and regularly spaced high-precision ERP**
  - → **short latency of 1-2 days**



7-day COMBI FINAL

- significant reduction of the WRMS values, especially at the boundary days of the 7-day polygon (d = 0, -6)
- stabilization of all ERP through 24h VLBI R1/R4 twice a week
  - → **daily, consistent and regularly spaced high-precision ERP including the celestial pole offsets**
  - → **latency of 14 days**