

# Estimation of polar motion, polar motion rates, and GNSS orbits in the IGS

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IGS Analysis Center Workshop

Plenary #03 ACC Results and Conventions

Tuesday, February 9, 2016, 11:15–11:30

# Preamble

- In fall 2012 CODE was obliged to replace its overlapping 3-day solution strategy in favor of a non-overlapping 1-day strategy for its IGS submissions.
- This change had quite a few advantages, but also the problem that the estimated rates of the polar motion components  $x$  and  $y$  were no longer compatible with the time derivative calculated from the  $x$  and  $y$  estimates of subsequent days.
- The impact of 1- vs. 3-day orbits on IGS products was studied in detail by :

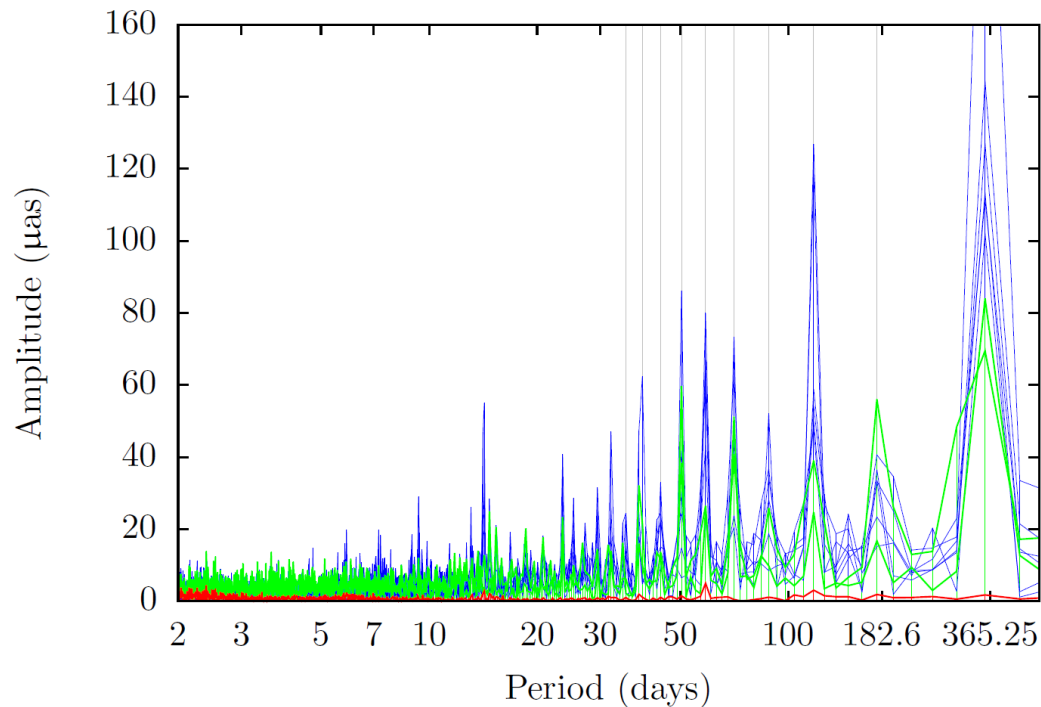
Lutz S, Meindl M, Steigenberger P, Beutler G, Sośnica K, Schaer S, Dach R, Arnold D, Thaller D, Jäggi A (2015): *Impact of the arc length on GNSS analysis results*. Journal of Geodesy, in press. DOI 10.1007/s00190-015-0878-1.

# Contents

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- Findings by Lutz et al. (2015)
- Polar motion components  $x$  and  $y$ , angles  $\alpha$  and  $h$
- The CODE orbits CF2 and CO2 in REPRO2
- The old and new orbit model in 1- and 3-day orbits
- Conclusions/Recommendations

# Findings by Lutz et al. (2015)



**Fig. 1** Amplitude spectra of  $y$ -pole coordinate misclosures from REPRO-2 series in 2009–2013 for six 1-day solutions (blue), two 30-hour solutions (green), and a 3-day solution

- The polar motion misclosures of the IGS ACs' 1-day ERPs at the day boundaries are “of bad quality”. The solution with 3-day orbits (red) does not show problems of this kind.

# Findings by Lutz et al. (2015)

Table 1 Solution series characteristics

Solution	Data span	Description
G1/G3	2008–2011	GPS-only, 1- and 3-day
R1/R3	2008–2011	GLONASS-only, 1- and 3-day
C1/C3	1994–2013	Combined, 1- and 3-day
Cx	1994–2013	Combined, with overlapping 3-day orbit arcs but otherwise 1-day products
Cn	1994–2013	Reconstructed from C3, non-overlapping 3-day solution

- R-, G-solutions from Meindl (2011).
- C, Cx, Cn CODE-solutions from REPRO2; C1 and C3 are the classic 1- and 3-day solutions.
- Focus on C-solutions of REPRO2, time interval 2002–2013

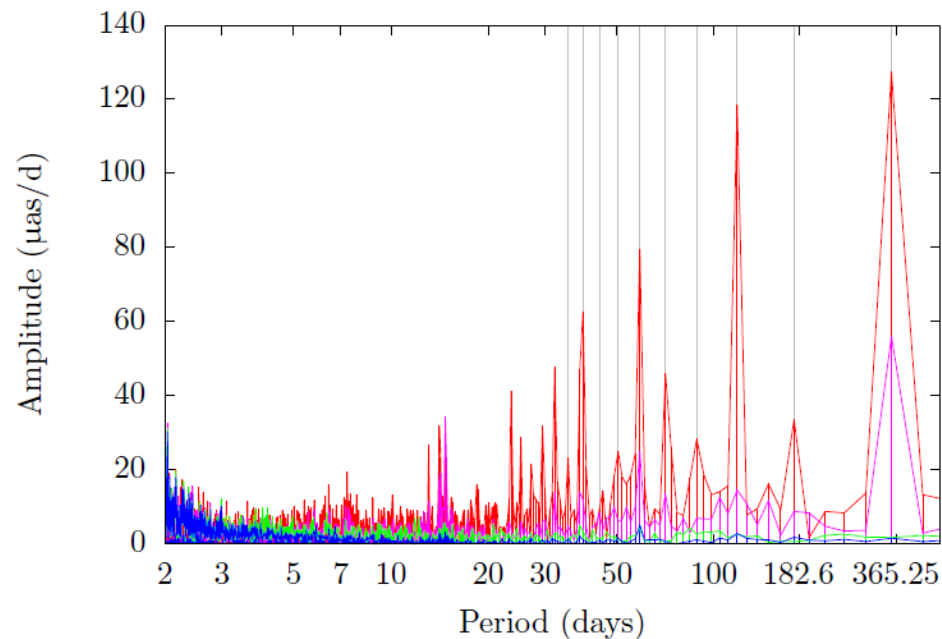
# Findings by Lutz et al. (2015)

**Table 5** Orbit misclosures at day boundaries in the inertial system in mm; period I is based on the years 2002–2008 because of missing GLONASS contributions in the years 2000 and 2001 in the CODE analysis

Sol	GNSS	Period I	Period II	Period III
C1	GPS	72	65	68
C1	GLO	218	115	110
Cx	GPS	40	27	31
Cx	GLO	71	30	30
C3	GPS	41	28	32
C3	GLO	72	31	31

- Period I, II, III: 2002–2008, 2009–2011, 2012–2013 (REPRO2). Growing impact of GLONASS from Period I to III.
- C3 and Cx (both based on 3–day orbits) are about a factor of 2 better for GPS, about 3–4 for GLONASS, w.r.t. 1–day solutions.

# Findings by Lutz et al. (2015)



**Fig. 10** Amplitude spectra of polar motion rate  $\dot{y}$  differences with respect to C04 for the C1- (red), Cx (magenta), Cn- (green), and C3-solutions (blue) (2009–2013)

- The polar motion rates of 1–day solutions are responsible for bad quality of polar motion misclosures.
- Cn (non–overlapping 3–day) is a good candidate for future CODE IGS contribution.

# Polar motion $(x,y)$ and “nutation” $(x,h)$

- Transformation from Earth-fixed (EF) to inertial (IN) performed by matrix

$$\mathbf{M}(t) = \mathbf{P}^T(t) \mathbf{N}^T(t) \mathbf{R}_3(-\Theta) \mathbf{R}_1(y) \mathbf{R}_2(x)$$

where  $\mathbf{P}$ ,  $\mathbf{N}$  are the precession- and nutation- matrices,  $q$  is sidereal time (including UT1-UTC),  $x$  and  $y$  are the polar motion components.  $\mathbf{R}_i(a)$  are rotation matrices about axis  $i$ .

- Assuming that  $x$  and  $y$  are small, one may write:

$$\mathbf{R}_3(-\Theta) \mathbf{R}_1(y) \mathbf{R}_2(x) = \mathbf{R}_1(\eta) \mathbf{R}_2(\xi) \mathbf{R}_3(-\Theta)$$

where  $x$ ,  $h$  are rotation angles about the 2<sup>nd</sup> and 3<sup>rd</sup> axes of the IN system, respectively.

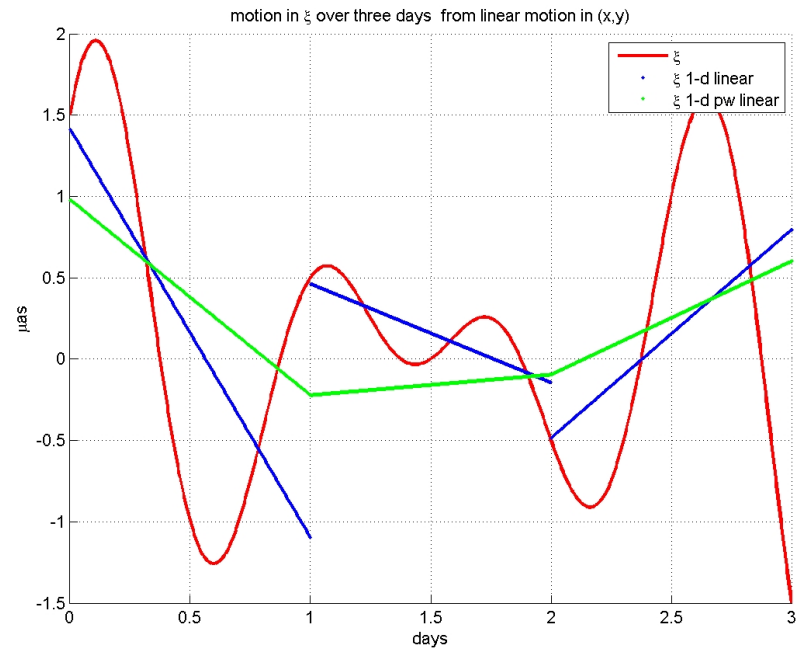
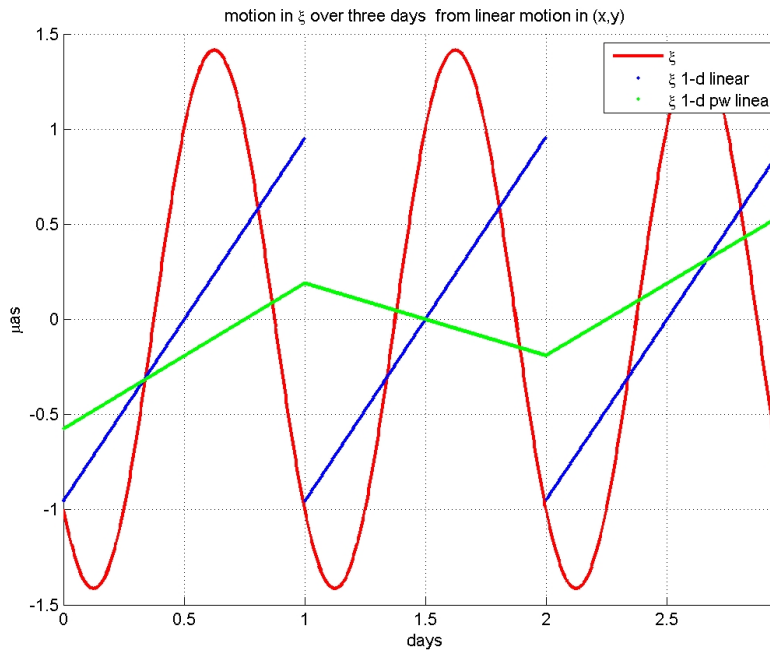


# Polar motion $(x,y)$ and “nutation” $(x,h)$

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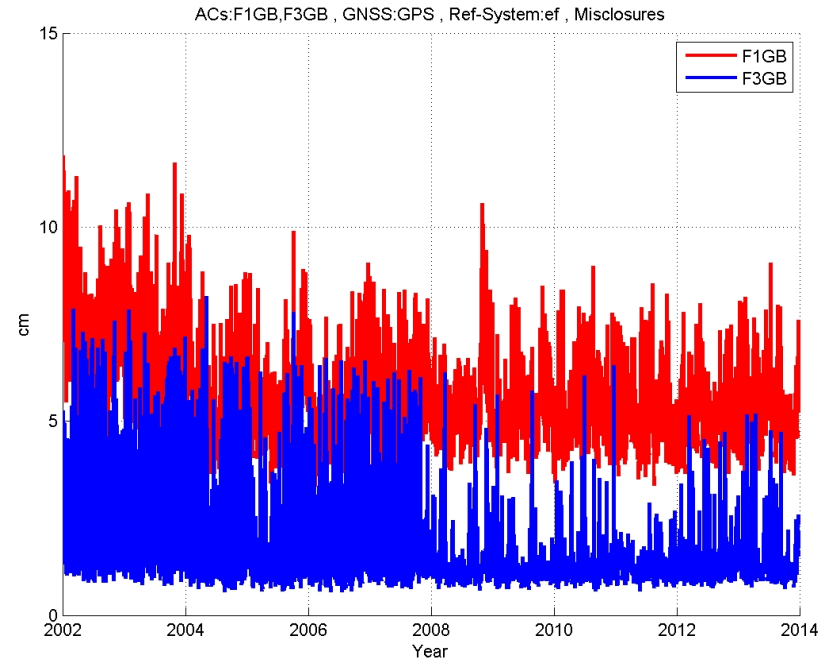
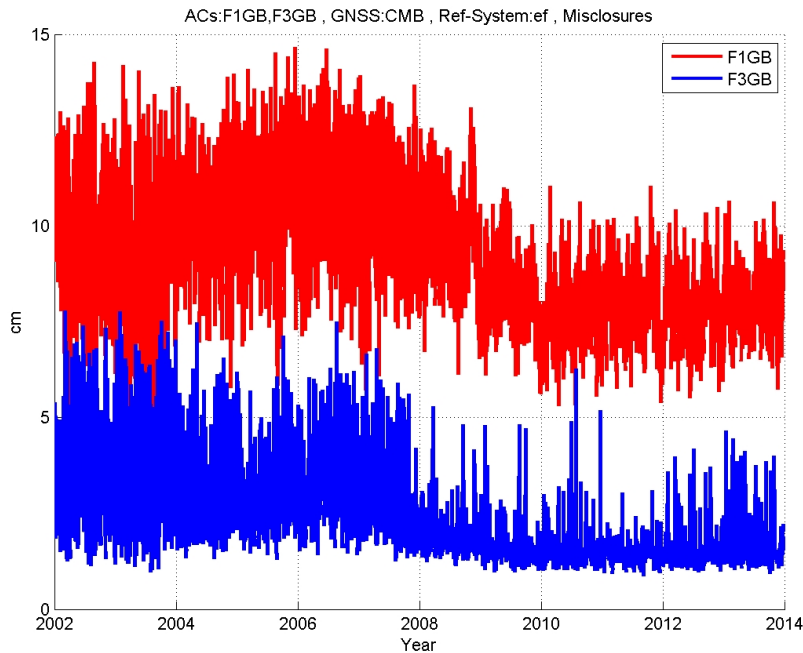
- When generating satellite–geodetic solutions including high–resolution ERPs  $x$  and  $y$  one might as well solve for  $x$  and  $h$ .
- This theme is treated in detail in the **poster** by **Meindl et al.** *Determining sub–daily ERPs using GNSS* in the session *Use of IGS Products*.
- For IGS–like analyses with the two components  $(x, y)$  per day&type, one has to study the **impact of the linear motion in  $(x, y)$  on  $(x,h)$**  and the approximation of the result by linear functions.

# Angles $(x,y)$ and $(x,h)$



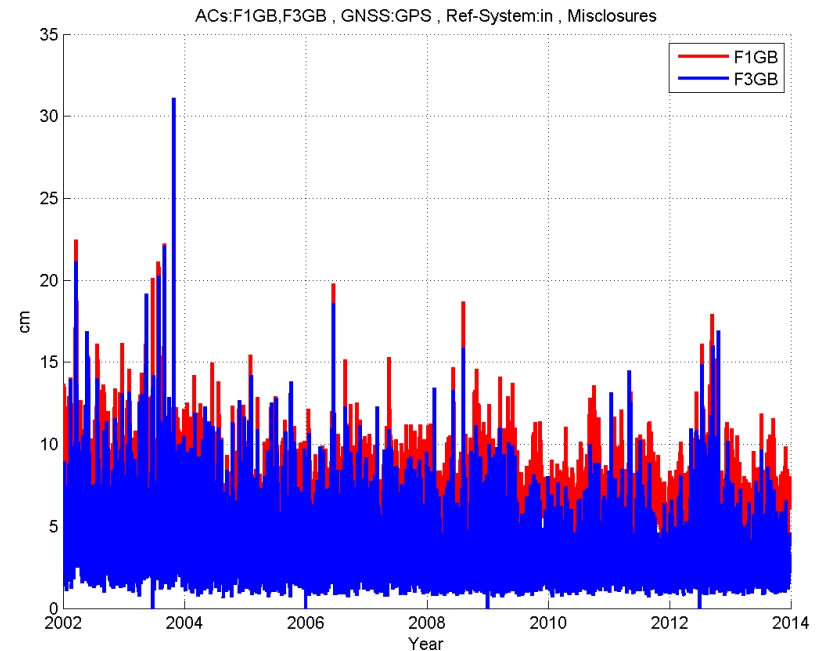
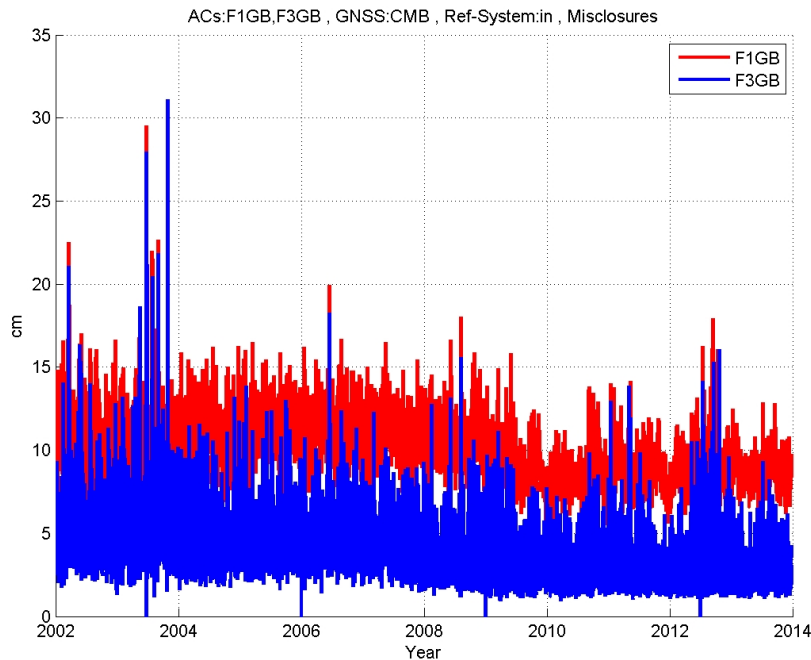
- Left, **red**: effect on angle  $x$  of a constant offset  $(x,y) = (1,1)$
- Right, **red**: effect on angle  $x$  of a constant rate in  $(x,y)=(1,1)$ .
- **Blue**: linear approximation of  $x$  separately over each day,
- **Green**: piecewise linear approximation (corresponds to CODE 3-day solutions C3,Cn).

# CODE orbits CF2 and CO2 in REPRO2



- RMS misclosures in Earth-fixed system, **CF2** and **CO2** orbits.
- Left: GPS and GLONASS, Right: GPS-only
- Time interval 2002–2013 analyzed (CODE started including GLONASS in 2002)

# CODE orbits CF2 and CO2 in REPRO2



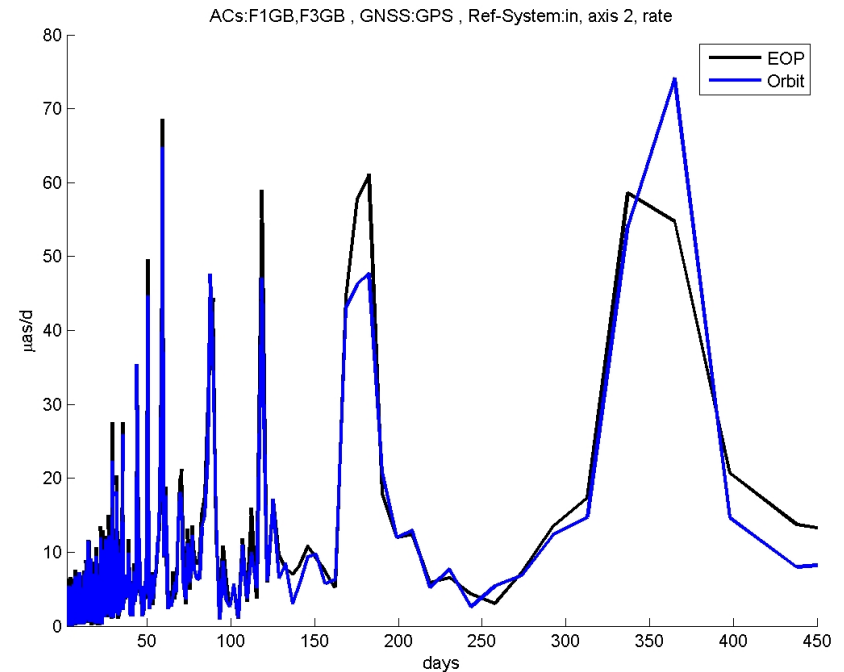
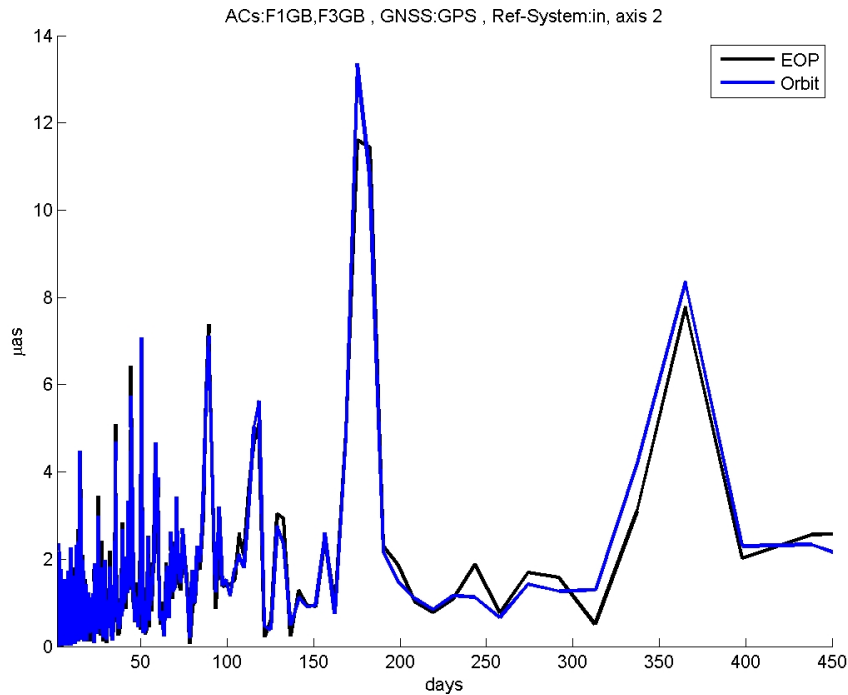
- RMS misclosures in Inertial system, **CF2** and **CO2** orbits.
- Left: GPS and GLONASS, Right: GPS-only
- Time interval 2002–2013 analyzed (CODE started including GLONASS in 2002)

# Comparing GNSS orbits referring to the same day

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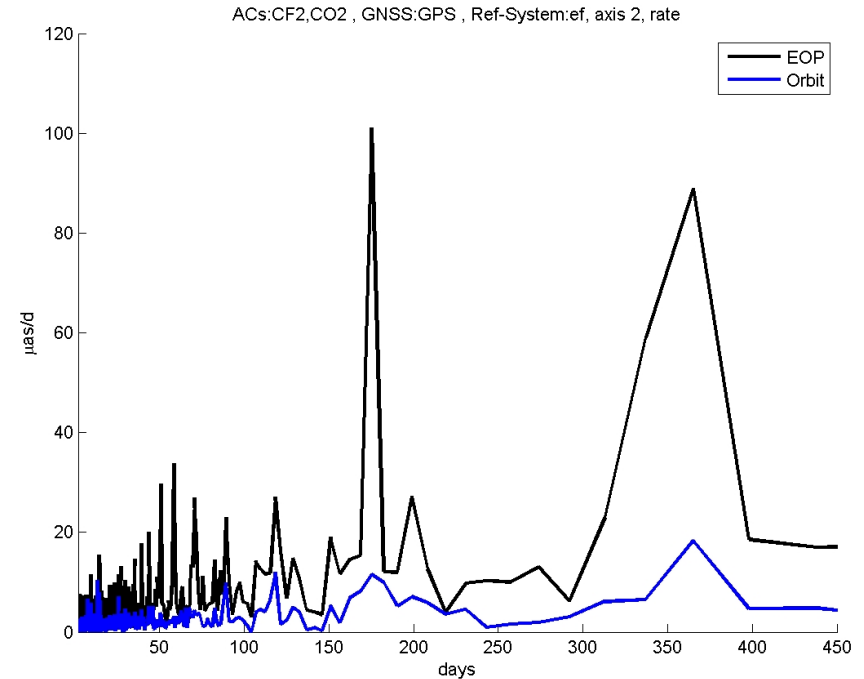
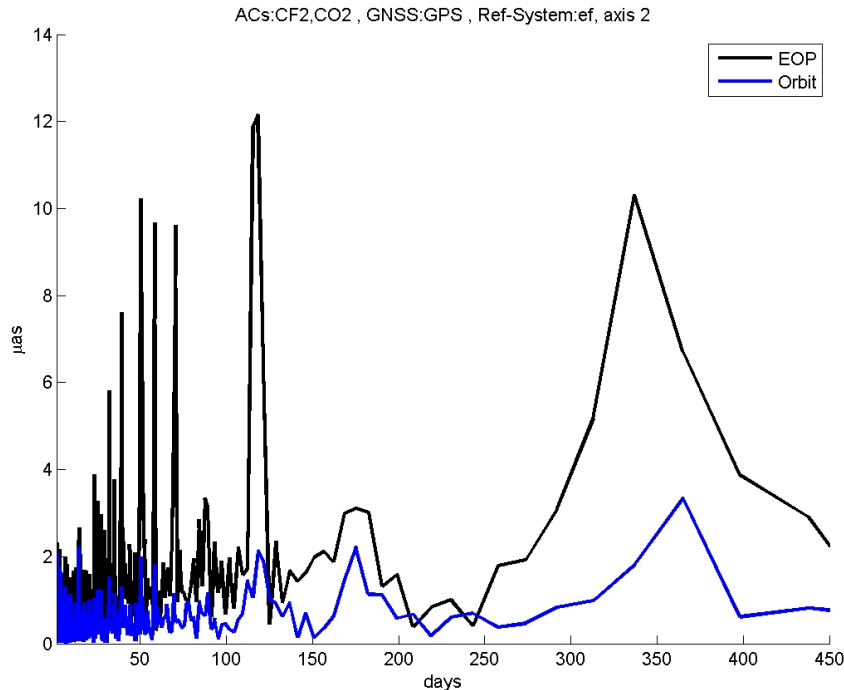
- Conventionally, orbits are compared via 7-parameter Helmert transformations (cf. eg, <http://acc.igs.org/>).
- The seven parameters are:
  - three offsets,
  - three rotation angles about the coordinate axes,
  - scale parameter
- A 14-parameter Helmert transformation (similarity trafo) was developed, where the rates of the 7 classic parameters may be estimated on top of the classic parameters.
- Subsequently, 6-parameter transformations (the three rotation angles and their rates, only) will be applied to further analyze the difference of orbit systems and the corresponding ERPs.

# Comparing GNSS orbits referring to the same day



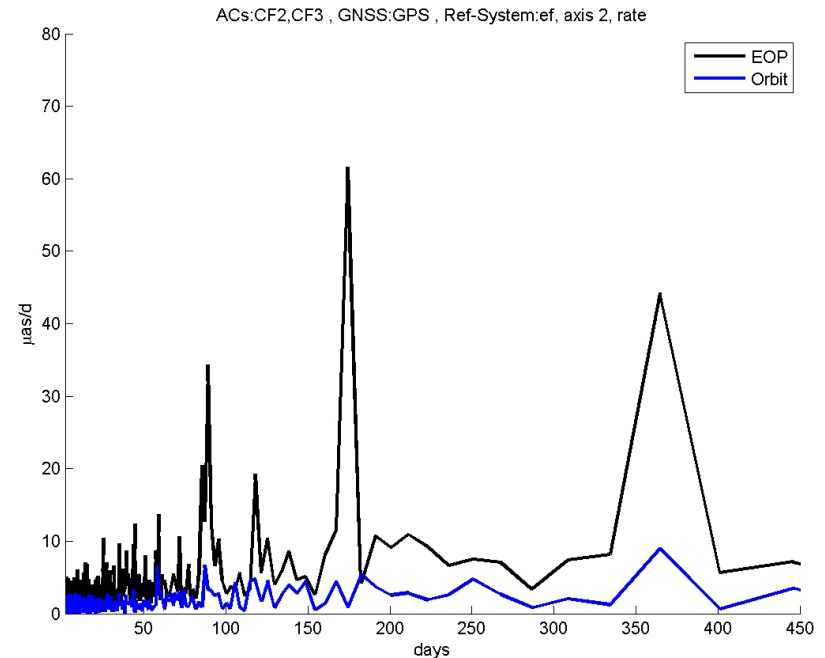
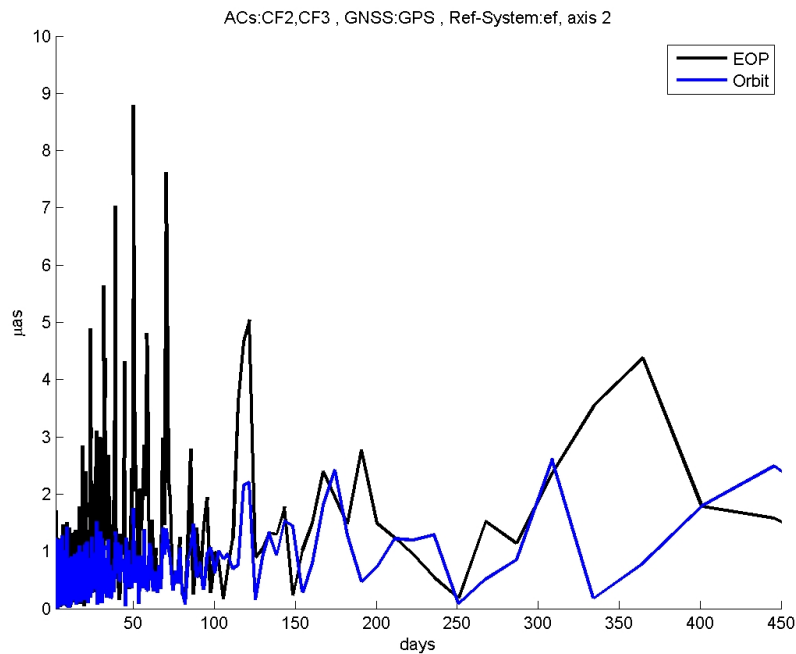
- Spectra of coordinate differences CF2–CO2 and corresponding pole coordinate in **inertial system**.
- Left: Helmert–trafo, 2<sup>nd</sup> axis, right: Helmert–trafo 2<sup>nd</sup> axis, rate.
- Orbit differences reflect ERP differences.

# Comparing GNSS orbits referring to the same day



- Spectra of coordinate differences CF2–CO2 and corresponding pole differences in **Earth-fixed system**.
- Left: Helmert-trafo, 2<sup>nd</sup> axis, right: Helmert-trafo 2<sup>nd</sup> axis, rate.
- 1- and 3-day orbits are “virtually” the same.

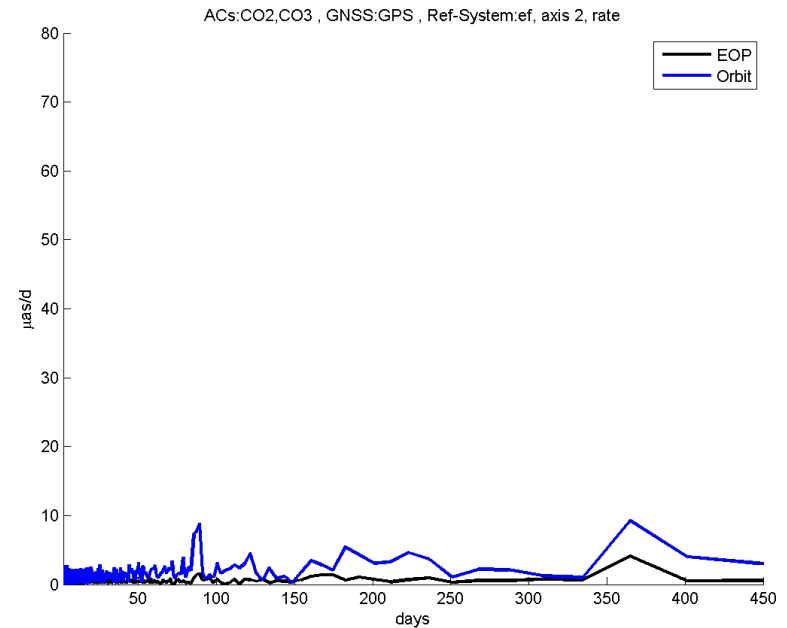
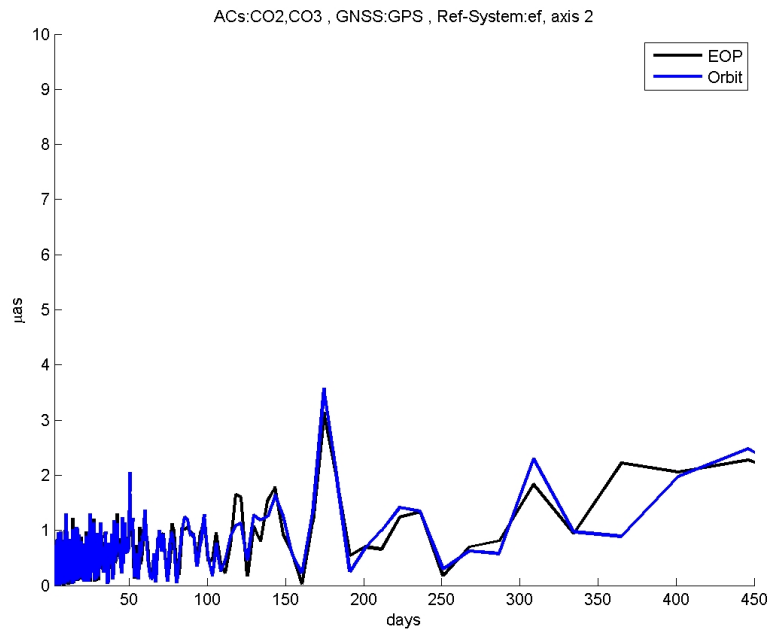
# Comparing GNSS orbits referring to the same day



- Spectra of coordinate differences of **CF2** orbits with old and new ECOM and corresponding pole coordinates in **Earth-fixed system**.
- Left: Helmert-trafo, 2<sup>nd</sup> axis, right: Helmert-trafo 2<sup>nd</sup> axis, rate.



# Comparing GNSS orbits referring to the same day



- Spectra of coordinate differences of **CO2** orbits with old and new ECOM and corresponding pole coordinates in **Earth-fixed system**.
- Left: Helmert-trafo, 2<sup>nd</sup> axis, right: Helmert-trafo 2<sup>nd</sup> axis, rate.
- → 3-day solutions are much less sensitive to differences in orbit model ...

# Conclusions / Recommendations

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- Currently, the **IGS ACs provide incompatible polar motion coordinates and rates** in the sense that the rates are not the first time derivatives of the pole coordinates.
- The current situation is not acceptable (?).
- Solutions to the problem:
  - **Go for longer than 1-day arcs** – in addition to 1-day solutions
  - **Constrain 1-day rates to an IGS/AC-derived a priori pole**, which provides consistent coordinates and rates.

# Backup slides

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# Findings by Lutz et al. (2015)

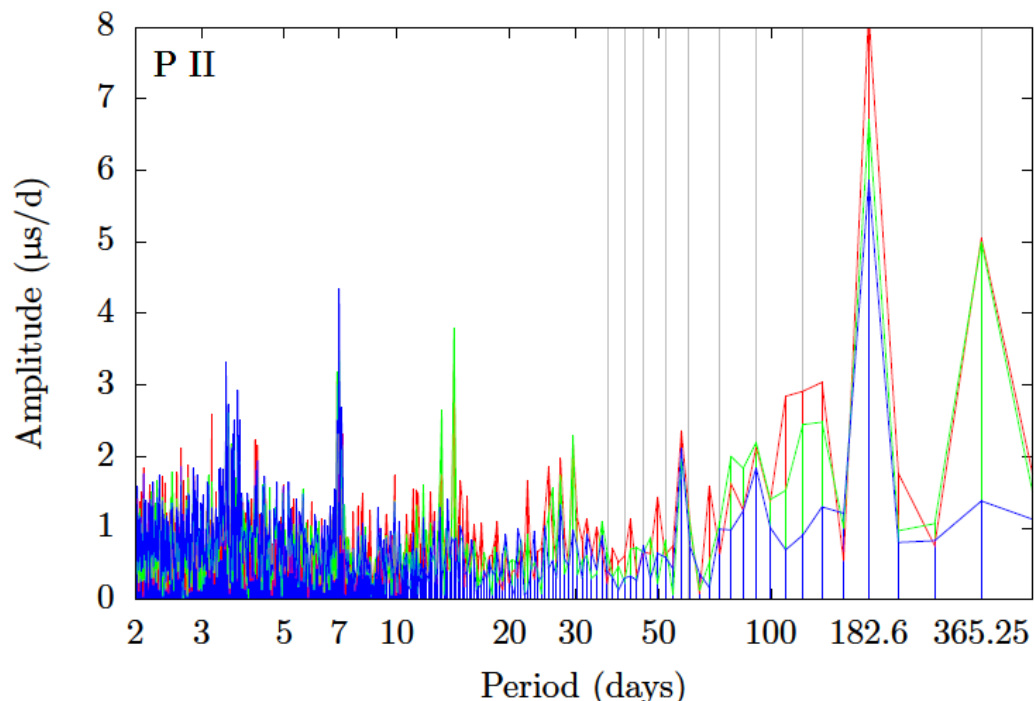
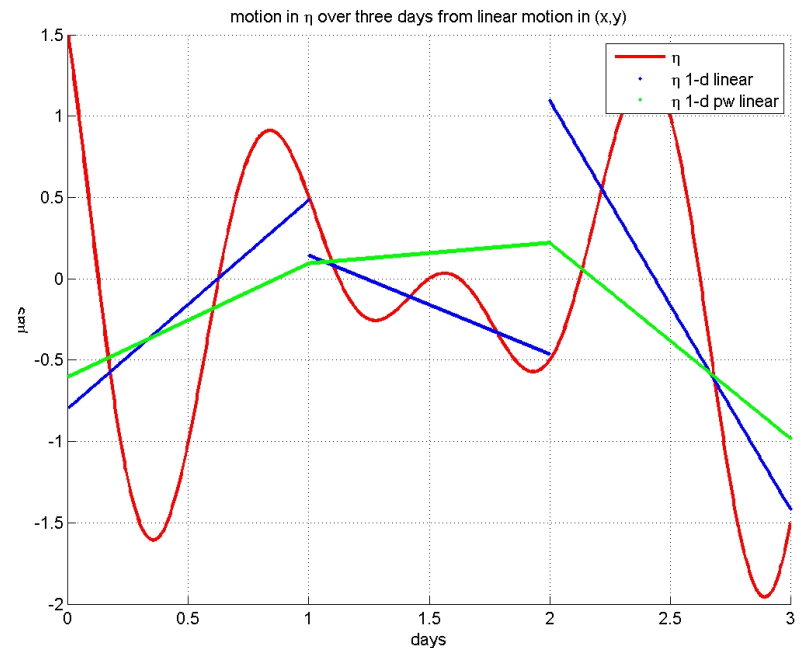
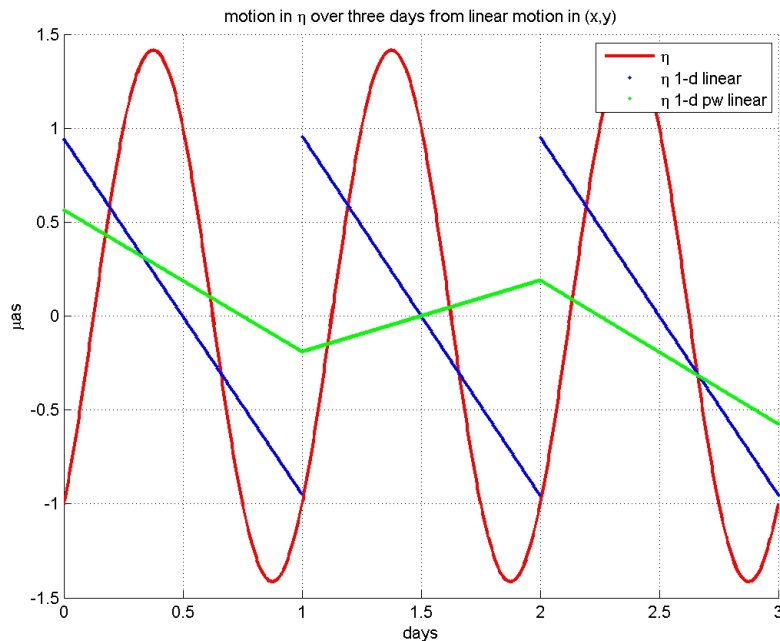


Fig. 9 Amplitude spectra of LOD from combined GPS/GLONASS solutions C1 (red), Cx (green), and C3 (blue).

- Other products, e.g., LOD, also improve when replacing the 1-day by the 3-day strategy.

# Angles $(x,y)$ and $(x,h)$



- Left, **red**: effect on angle  $h$  of a constant offset  $(x,y) = (1,1)$
- Right, **red**: effect on angle  $h$  of a constant rate in  $(x,y) = (1,1)$ .
- **Blue**: linear approximation of  $h$  separately over each day, correspond to IGS 1-day solutions
- **Green**: piecewise linear approximation (corresponds to CODE 3-day solutions).

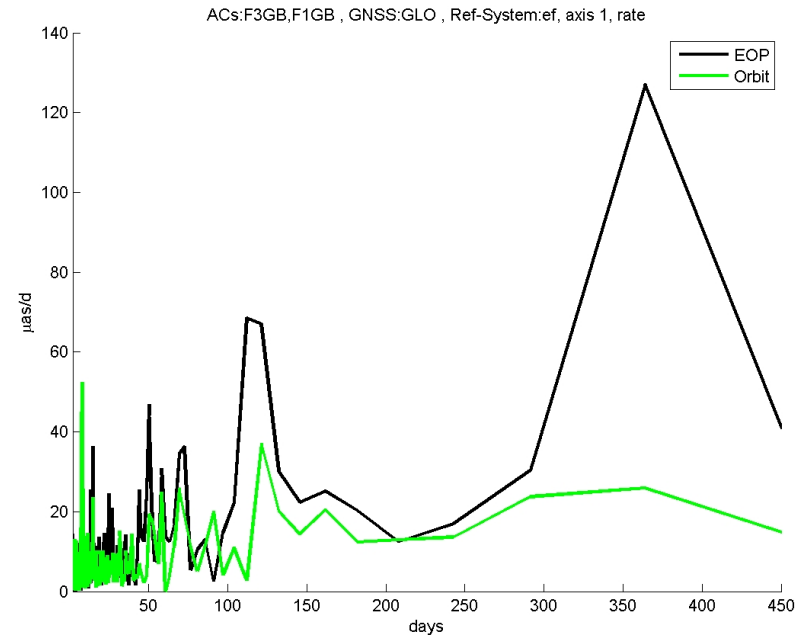
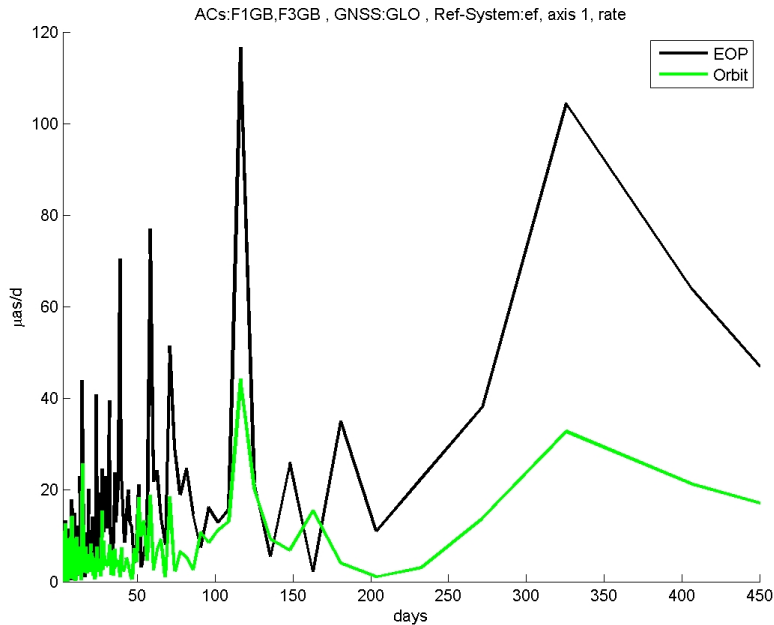
# Experiments with new ECOM = CFA

**Table 7** Quality measures for GLONASS orbits from 1-day solution differences of IGS ACs in the REPRO2 campaign from 2009 to 2013.

Solutions	Ref	RMS <sub>b</sub> (cm)	RMS <sub>n</sub> (cm)	RMS <sub>e</sub> (cm)	RMS <sub>H</sub> (cm)
GR2, CF2	EF	11.9	9.1	11.8	9.7
ES2, CF2	EF	8.6	6.2	8.5	6.5
GR2, ES2	EF	10.9	8.5	11.3	9.1
CF2, CFA	EF	8.4	7.7	8.5	7.7
CO2, CF2	EF	7.5	3.9	7.0	4.0
CO2, CFA	EF	10.2	8.2	10.1	8.3

- CFA=CF2(new ECOM) can be treated as “just another solution”. The GLONASS-only orbits are analyzed above.
- RMS of misclosures 11.6 cm, 11.0 cm, for CF2, CFA, respectively.

# Experiments with new ECOM = CFA



- Helmert angle (rate) about 1<sup>st</sup> axis (y-pole) w.r.t. CO2
- Left: CF2(Repro2), Right: CFA

# Main findings by Lutz et al. (2015)

**Table 3** Effect of the arc length on the RMS values of the EOP solutions 2009–2011; units are  $\mu\text{s}$  for polar motion,  $\mu\text{s}/\text{d}$  for rates,  $\mu\text{s}/\text{d}$  for LOD; offsets removed

Periods included	EOP	R1	G1	R3	G3
all	$x$	238	66	103	54
	$y$	152	71	95	56
	LOD	35	22	19	20
	$\dot{x}$	585	218	136	107
	$\dot{y}$	990	244	154	113
>30d	$x$	151	38	68	42
	$y$	76	46	65	45
	LOD	18	10	4	8
	$\dot{x}$	385	134	18	9
	$\dot{y}$	860	150	26	8

- R1 and R3 are 1- and 3-day GLONASS-only solutions, G1 and G3 GPS-only 1- and 3-day solutions. All ERPs significantly improve from 1 to 3 days. The gain is most significant in the low-pass part (only periods > 30 days included).



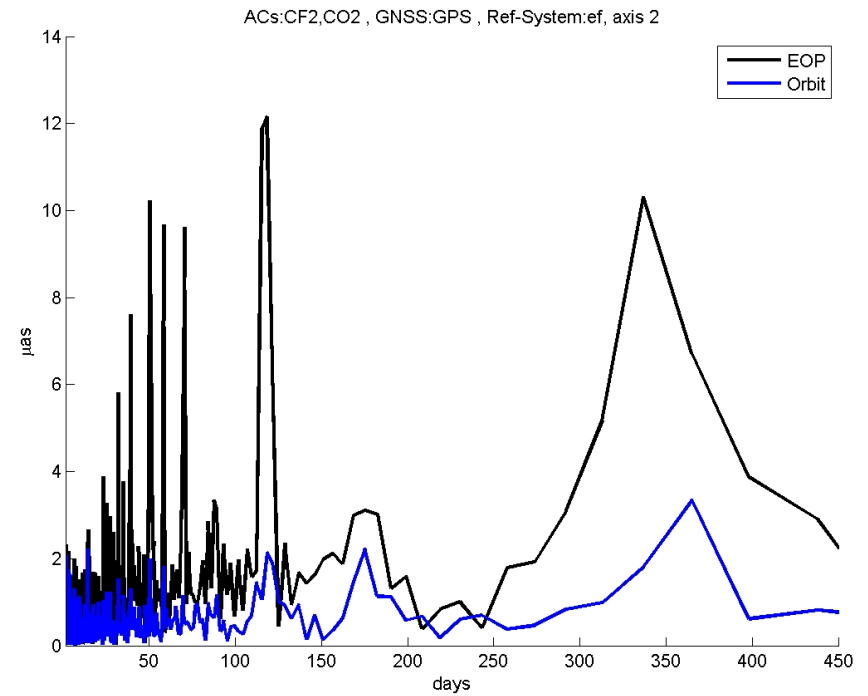
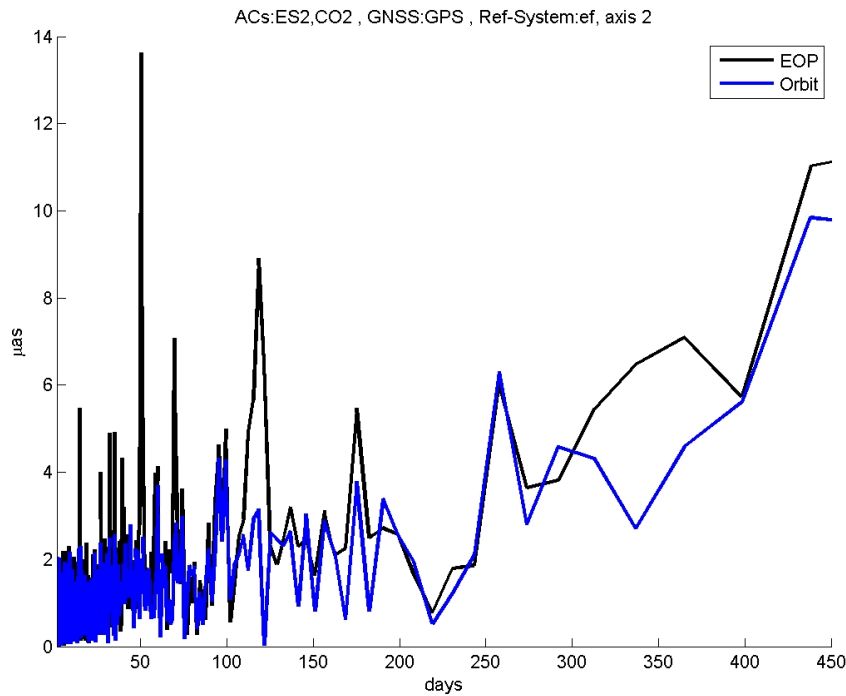
# Main findings by Lutz et al. (2015)

**Table 4** Effect of the arc length on the RMS of the geocenter series for period III (2012–2013); units are mm

Periods included	Coord	C1	Cx	C3
all	$x$	6	6	5
	$y$	5	4	4
	$z$	17	16	16
<30d	$x$	2.6	2.5	1.7
	$y$	2.6	2.6	1.7
	$z$	4.3	3.6	3.1
>30d	$x$	5	5	5
	$y$	4	4	4
	$z$	17	16	15

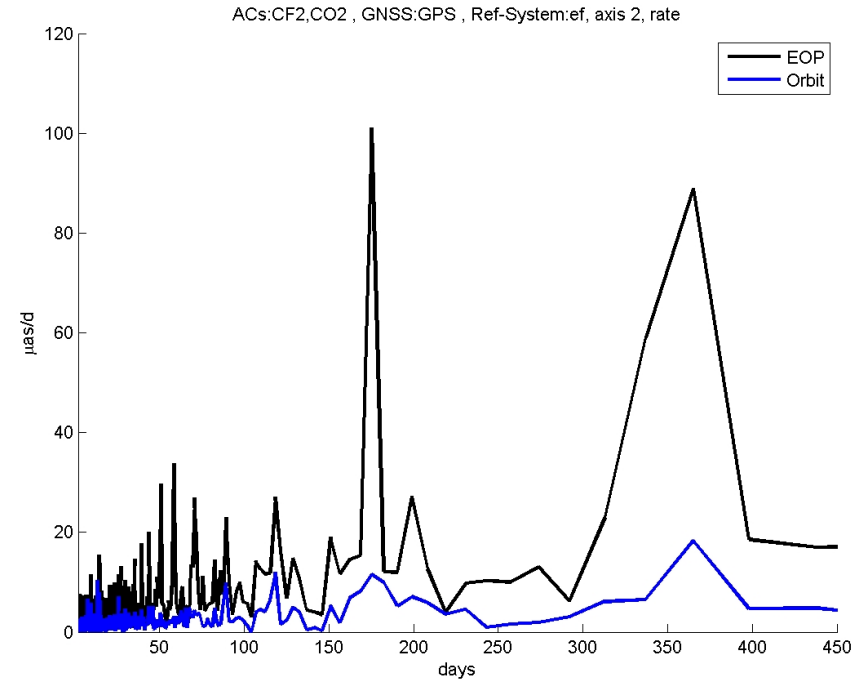
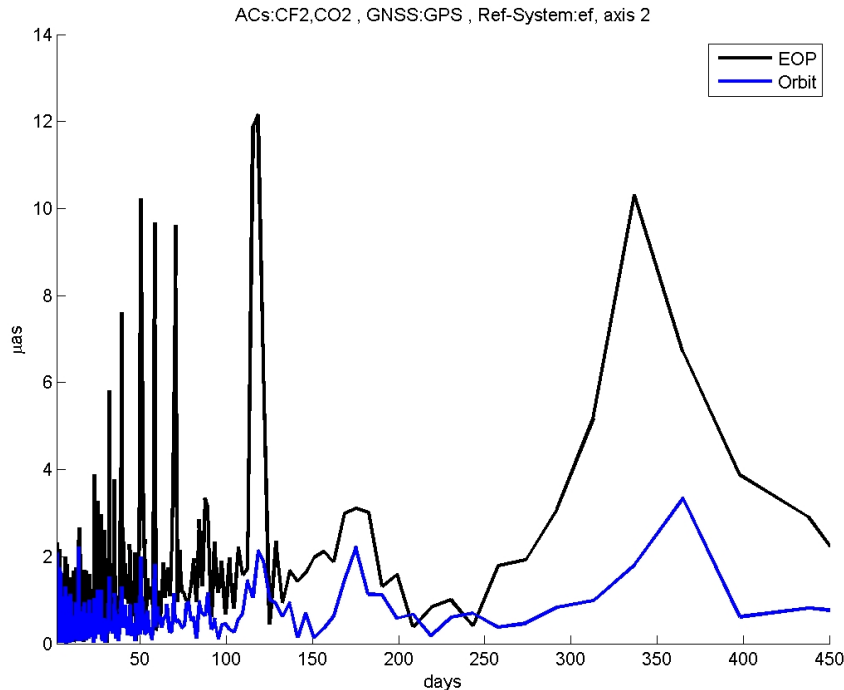
- Geocenter coordinates are not much affected by the arc length – apart from RMS of high-pass part, which is, however, a pure filtering effect (three times more data used in C3 than in C1).

# Comparing GNSS orbits referring to the same day



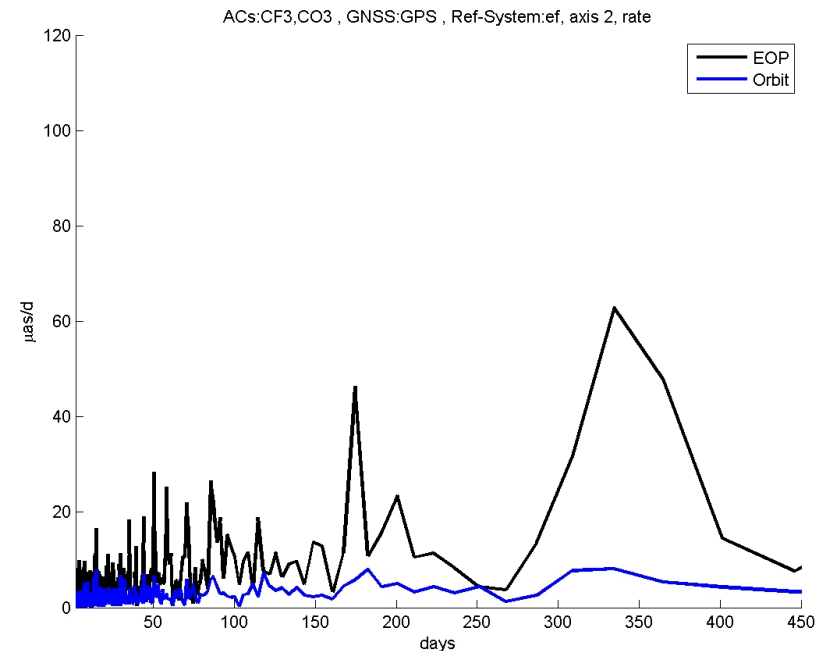
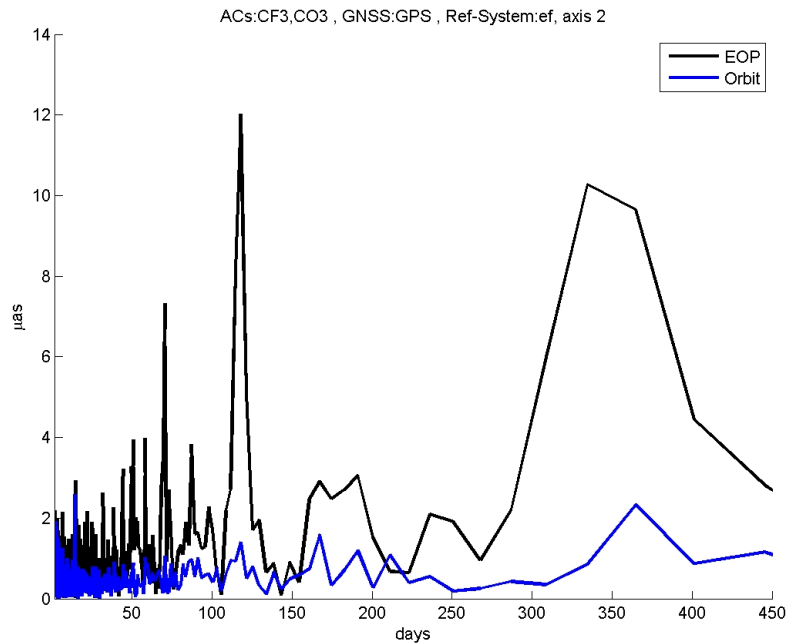
- Spectra of  $y$ -coordinate differences and corresponding ( $-x$ ) coordinate of pole.
- Left: ES2-CO2, right: CF2-CO2, orbit spectrum empty.
- Effects are small:  $1 \text{ mas} \approx 0.128 \text{ mm}$  at maximum at GPS height!

# Comparing GNSS orbits referring to the same day



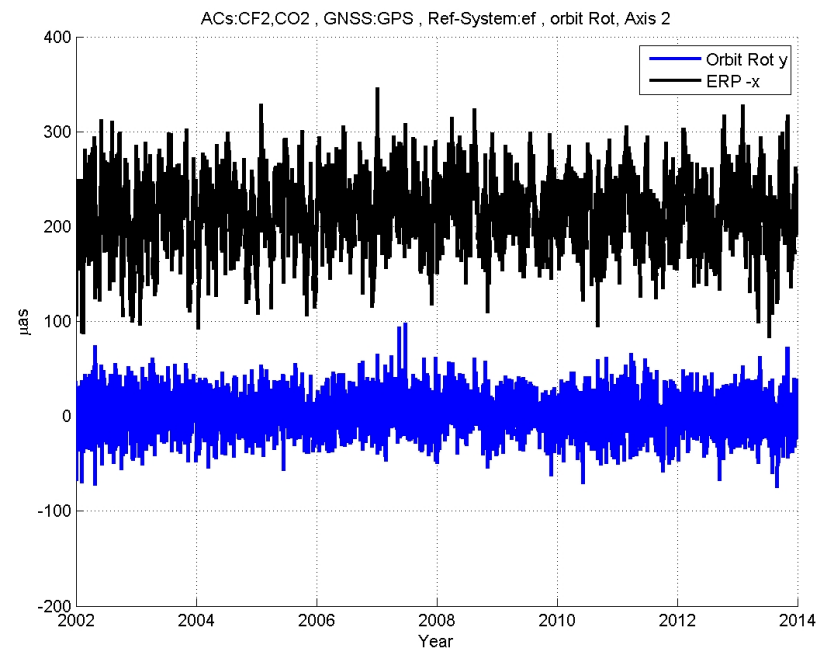
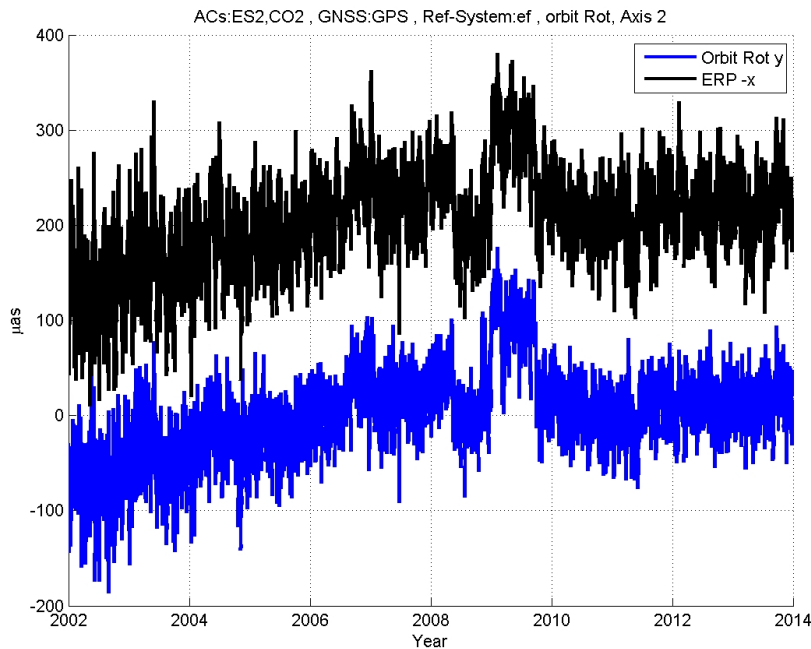
- Spectra of coordinate differences CF2–CO2 and corresponding pole differences in **Earth-fixed system**.
- Left: Helmert-trafo, 2<sup>nd</sup> axis, right: Helmert-trafo 2<sup>nd</sup> axis, rate.
- 1- and 3-day orbits are “virtually” the same.

# Comparing GNSS orbits referring to the same day



- Spectra of coordinate differences of **CF2** orbits with new ECOM and corresponding pole coordinates in **Earth-fixed system**.
- Left: Helmert-trafo, 2<sup>nd</sup> axis, right: Helmert-trafo 2<sup>nd</sup> axis, rate.

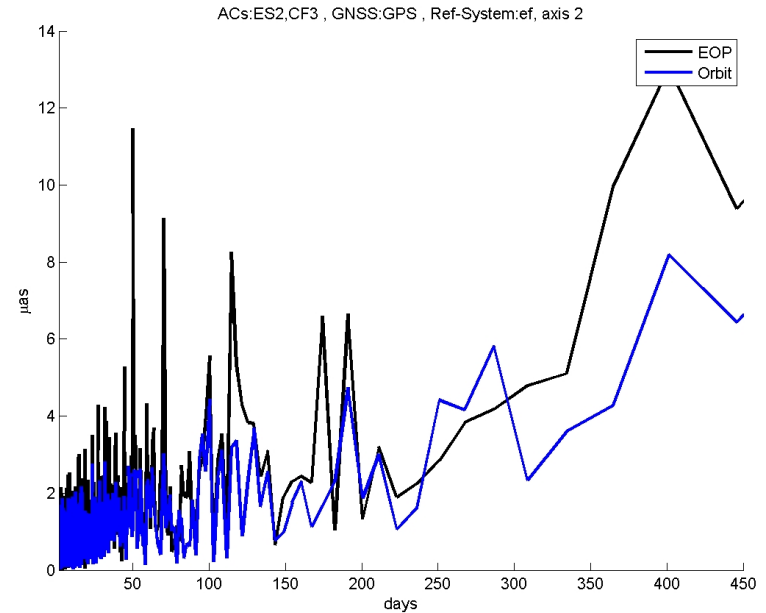
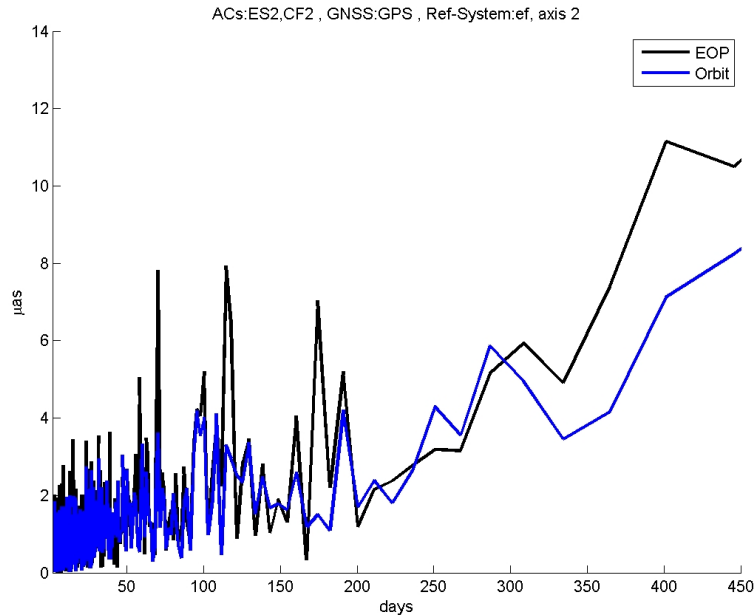
# Comparing GNSS orbits referring to the same day



- Rotations of orbits about 2<sup>nd</sup> Earth-fixed axis and (-x)-coordinate of the pole (offset 200µs).
- Left: ES2-CO2, IGS “normal case”<sup>\*)</sup>, right: CF2-CO2

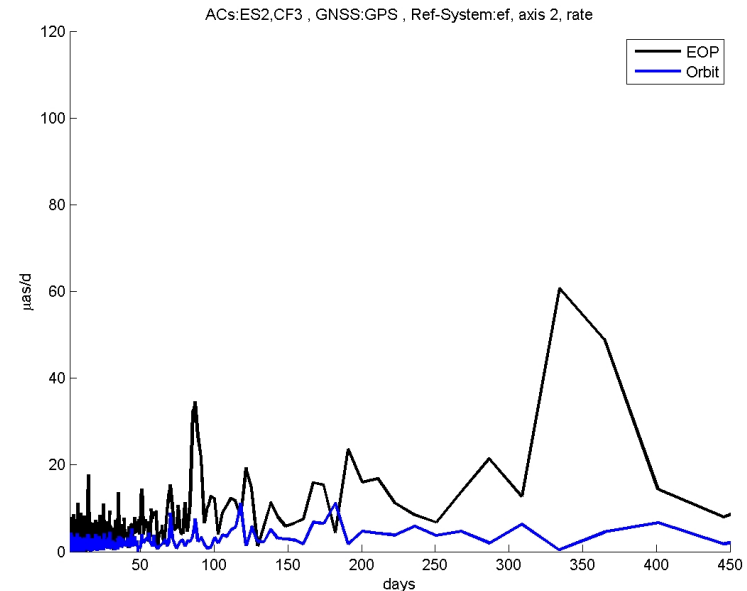
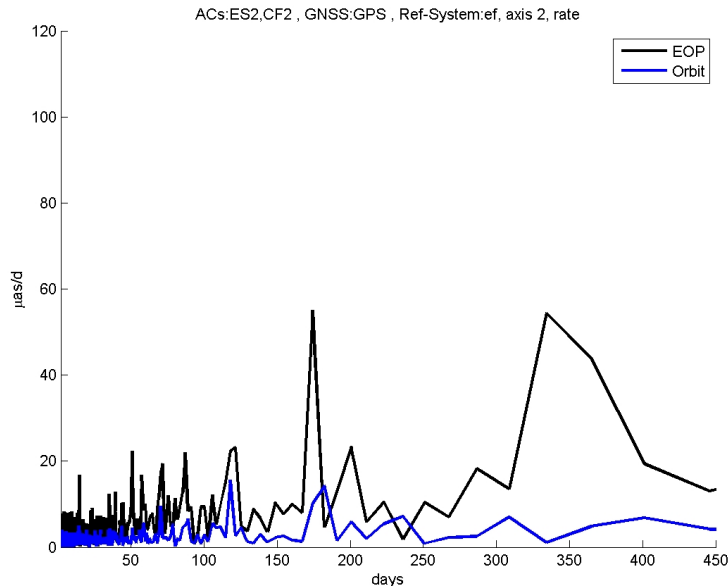
<sup>\*)</sup> Beutler G, Kouba J and Springer TA, (1995) Combining the orbits of the IGS Analysis Centers, Bulletin Geodesique 69: 200–222.

# ES2 and CF2 with old&new ECOM



- Spectra of coordinate differences of **CF2** orbits with old&new ECOM and ES2 plus corresponding pole coordinates in **Earth-fixed system**.
- Left: Helmert-trafo, 2<sup>nd</sup> axis, right: Helmert-trafo 2<sup>nd</sup> axis.
- Old ECOM: left, new ECOM: right.

# ES2 and CF2 with old&new ECOM



- Spectra of coordinate differences of **CF2** orbits with old&new ECOM and ES2 plus corresponding pole coordinates in **Earth-fixed system**.
- Left: Helmert-trafo, 2<sup>nd</sup> axis, right: Helmert-trafo 2<sup>nd</sup> axis, rate.
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