3.7.2 Working Group on Combination at the Observation Level

The IERS WG COL has contributed to the ITRF2014 realization by combination of the geodetic techniques (DORIS, GNSS, SLR, VLBI) at the Normal Equation level. Twelve years of daily Normal Equations (NEQs) from 2002 to 2013 has been processed for each technique (Tab. 1). The combined Normal Equations at weekly bases in SINEX format has been produced and transferred to the IGN in order to have comparison of the Earth orientation parameters solutions (EOP) and station positions with the new referential frame ITRF2014.

A concluding report about the COL activities has been presented during the last meeting at the BKG in Frankfurt, February 19th, 2016.

The memory stacking for Normal Equations from different Analysis Centres have been defined. For DORIS the arc length is 3.5d for each satellite available during 2002–2013, their Normal Equations contain orbit and geodetic parameters not used for this combination products but interesting for further studies. The list of stations to be estimated and compared with ITRF2014 has been produced. The year 2009 is chosen to test the intra and inter technics combination. Discontinuities of stations positions have been also considered in order to be compatible with Dynamo software.

Normal Equation pre-processing per technique

- NEQ reduction: keeping parameters are EOP, station coordinates, quasar coordinates, tropospheric zenithal delay for all techniques (Tab. 2). For DORIS orbital elements and non-gravitational parameters are kept for further studies. Laser measurements from DORIS satellites such as Topex, Jason 1 & 2, Envisat, Cryosat, Hy2a are also considered and weekly Doris-Laser NEQ are generated to contribute in this combination.
- Stacking the weighted daily NEQs at weekly bases, synchronous to the GPS week: for DORIS satellites is applied the Helmert weighting algorithm using EOP as common parameters, for SLR satellites using stations as common parameters, for GNSS satellites the daily NEQ stacking is unitary weighted, for VLBI R1 & R4 sessions are weekly stacked with unitary weighting.
- Tropospheric parameters bias & gradients are synchronized every 2h interval (01h, 03h, …, 23h) for selected collocated GNSS, VLBI and DORIS stations. Their estimated positions are tested over one year (2009) when the common tropospheric parameters are mutualized (see IERS Annual Report 2014).

- For satellite techniques, the UT parameter at the beginning of each week is forced to the C04 a priori to estimate the LOD parameter, not applied for combination.
- Introduction of stations constraints to cancel the systematic technique effects: application of transformation parameters (origin & scale for satellite techniques, scale for VLBI technique) by the transformation equation:

$$X_{Tech} = X_{Tech\_ITRF} + A.\Theta_{Tech}$$

- where X_{Tech_ITRF} are the station parameters of each technique expressed in the ITRF2008 referential frame, X_{Tech} the station parameters which are reduced from the normal equation at the next step, and Θ_{Tech} the systematic effects, which are kept for estimation.
- Introduction of polar motion constraint to cancel the diurnal retrograde oscillation for sub-daily EOP (for DORIS, SLR and VLBI techniques which have EOP at 6h interval, not apply to GNSS technique for which EOP are 1 point per day).

Normal Equation combination processing strategy

- At the weekly bases, DORIS, DORIS-Laser, SLR and VLBI NEQs are weighted (Helmert algorithm).
- Orbital parameters and non-gravitational parameters are reduced.
- Elimination of EOP outside the GPS week by forcing them with their a priori values.
- Whitening technique's identifiers from tropospheric parameters to stack their equations for collocated stations.
- Daily linear constraints on 6h interval EOP corrections are applied. Option is considering to reduce or not EOP at 0h, 6h, 18h, 24h for keeping only daily EOP at 12h. The weekly global DORIS, DORIS-Laser, SLR and VLBI NEQ is generated.
- Stacking at the weekly bases the DORIS, DORIS-Laser, SLR, VLBI global NEQ with GNSS weekly NEQ using the Helmert weighting algorithm.
- Mutualizing the diurnal retrograde oscillation parameters for all techniques.
- Application of Non Rotation on the set of quasars (NNR).
- The global weekly NEQ DORIS, DORIS-Laser, GNSS, SLR and VLBI is generated.

Inversion

The weekly global NEQ DORIS, DORIS-Laser, GNSS, SLR and VLBI is inverted with added constraints:

- Minimal constraints with the seven Helmert parameters are applied on the DORIS, GPS, SLR and VLBI core stations and forced to zero with ±0.01mm.

- Diurnal retrograde oscillation correction parameters variation are forced to ±1frd interval.
- Variations on Non rotation correction parameters for quasar ensemble are constrained to ±100nrd interval.
- Stabilization constraint on zenithal tropospheric parameters of ±1m and quasar correction of ±100nrd.
- Weekly solutions: EOP, station coordinates and for some of them with the zenith tropospheric bias or clock bias, quasar coordinates and centre of mass for DORIS satellites.

Normal Equation delivered for the ITRF2014 comparison campaign: period 2002–2013

The parameters and delivered Normal Equations from each GRGS analysis centre are shown in Tables 1–2.

Table 1: Parameters to estimate for comparison with ITRF2014 and added parameters for further studies

Parameters	***Estimated Parameters***	***Initial Values***
Pole, UT1-TAI	**XPO**, **YPO**, **UT** : PWL @ 12Hr (PX, PY into GINS)	IERS EOP 08-C04
Pole Rate	**XPOR**, **YPOR** 1pt/day @ 12Hr (PXR, PYR into GINS)	0.0
LOD	**LOD** 1pt/day @ 12Hr (PTR into GINS)	IERS EOP 08-C04
Precession/Nutation Corrections	**NUT_X**, **NUT_Y** : PWL @ 12Hr IAU2000A/2006 model corrections (dX,dY) (NX, NY dans GINS)	0.0
Station Coordinates	**SX**, **SY**, **SZ** 1 pt/week	ITRF2008
Radio sources Coordinates	**RS_RA**, **RS_DE** 1pt/week (QRA, QDE into GINS)	ICRF2
Supplementary Parameters non used for ITRF2014 comparison		
Zénithal Tropospheric Delay wet component & Horizontal Gradients	**TROWET** @ {01, 03, 05, … 23} Hr: Estimation of wet component versus tropospheric model & **TGETOT**, **TGNTOT** 1 pt/d @ 00Hr	GPT2/GMF1 Model for radioelectric waves & Mendes-Pavlis for SLR/LLR + tropospheric gradient per station North & East directions

Results

We present herewith some results obtained by this combination strategy. Figure 1 shows the adjustment of the quasar coordinates w.r.t. ICRF2 celestial reference frame along the 2002–2013 period. Table 3 resumes the mean and RMS values of these corrections and Table 4 the rotation parameters estimated between the ensemble of quasars coordinates and the ICRF2 referential.

Concerning the pole and UT parameters Figure 2 shows the adjustment values w.r.t. C04 series over the 12 years of processing that presents an annual effect. This effect is observed on GNSS pole and affects the combination solution at the same amplitude. Table 5 resumes the statistics on pole and UT solutions.

Table 2: Techniques used for combination, delivered GRGS Normal Equations (NEQs)

GNSS: CNES-CLS Toulouse	DORIS: CNES-CLS Toulouse	SLR: IMCCE GRGS Paris	VLBI: OB LAB Bordeaux
4372 daily NEQ, Period January 1st 2002 to December 30th 2013 GPS week **1147** to **1773,** GPS – Glonass Constellations, between 23 and 55 GNSS satellites	Weekly NEQ per 3,5d arc length & per satellite: **Doris Doppler**: **288 Topex** 2002-2004, **1077 Envisat** 2002-2012, **1071 Spot-2** 2002-2009, **1228 Spot-4** 2002-2013, **1236 Spot-5** 2002-2013, **386 Jason-1** 2004-2008, **573 Jason-2** 2008-2013, **372 Cryosat2** 2011-2013, **234 Hy2a** 2011-2013 **Doris Laser:** **284 Topex**2002-2004, **1072 Envisat** 2002-2012, **382 Jason-1** 2004-2008, **573 Jason-2** 2008-2013, **371 Cryosat2** 2011-2013, **234 Hy2a** 2011-2013	Weekly NEQ per 9d arc length & satellites **628 LAGEOS-1**, **628 LAGEOS-2**, **628 ETALON-1**, **628 ETALON-2**	Session R1 & R4, **621** NEQ R1 session **621** NEQ R4 session
Pole: PX, PY 1pt/d @12:00 **Pole Rates:** PXR, PYR 1pt/d @12:00 **LOD** 1pt/d @12:00 **Stations** coordinates SX, SY, SZ 1pt/d	**Pole**: PX, PY, **UT1-TAI** 4pt/d @ 00,06,12,18:00 **Nutation** NX, NY 2pt/d @ 00, 12:00 **Stations** SX, SY, SZ 1p/week @ 12:00 **Tropospheric MZB** (Zenith Tropospheric Delay) 12pt/d @ 02h **MGE, MGN** East & North Gradients 1pt/d -- *__CDX,CDY,CDZ__ Center of mass correction on satellites 1/sat/week *__Global station bias__ SXC, SXS, SXD, SXT, SXB 1pt/arc *__Doppler frequency offset__ MFO @ 02h. *__Orbital elements__ EX, EY, EZ, EXP, EYP, EZP 1pt /arc *__Atmospheric__ drag and lift FD *__Radiation Solar pressure__ FS 1pt/arc. *__Orbit Biases__ BT, BN *__Radiation forces__, 1 to 8: -specular reflectivity of panel RRS -diffuse reflectivity of panel RRD *__Emissivity of panel__ 1 à 8 per arc RE, RF *__Gravity field coefficients__ normalized: GCN cosinus, GSN sinus 0 up to 40 degree	**Pole** : PX, PY 4pt/d @ 00,06,12,18h:00 **UT1-TAI** : PT 4pt/d @ 00,06,12,18:00 **Nutation** NX, NY 2pt/d @ 00:00, 12:00 **Stations**: SX, SY, SZ 1pt/week @12:00 **Station range Bias** MRB 1/w/station ------------------------------------ *__Orbital elements__ EX, EY, EZ, EXP, EYP, EZP 1pt /arc *__Radiation Solar pressure__ 1pt/week/sat *__Orbit Biases__ 1pt/week/sat *__Gravity field coefficients__ normalized: GCN cosinus, GSN sinus degree 0 to 40 *__Oceanic tides coefficients__ normalized OCN, OSN	**Pole** : PX, PY 4pt/d @ 00,06,12,18:00 **UT1-TAI** : PT 4pt/d @ 00,06,12,18:00 **Nutation** : NX, NY 4pt/d @ 00,06,12,18:00 **Stations** : SX,SY,SZ 1pt/week @12:00 **Quasars** : QRA, QDE 1pt/week **Tropospheric zenithal delays MZB** 12pt/d @ 02h (01,03,05,07,09,11,13,15,17,19, 21,23) -- *__Clock error MTB__ for VLBI stations @01:00h

* Added parameters for further studies which are reduced or eliminated for this step of development

Nutation parameters plotted in Figure 3 show large discrepancies compared to the C04 corrections series w.r.t. IAU200A/2006 model mainly due to GRGS VLBI NEQ where these parameters are not suitably processed. Investigation is in progress to perfect this nutation parameter estimation by GRGS-VLBI processing. Table 6 resumes the means and RMS values for the set of dX and dY estimated by GRGS combination over the 2002–2013 period.

Station positions were estimated. The Wettzell site with GPS, SLR and VLBI collocated stations have represented in X, Y, Z corrections w.r.t. ITRF2008 a priori in Figure 4. It shows an annual oscillation due to the atmospheric loading effect, this model is not included during the process. Tables 7–8 give some statistical values showing the consistency between GPS, SLR and VLBI solutions.

The systematic effects are estimated on this 2002–2013 period. Figure 5 shows the X, Y, Z translations for satellite techniques and scale factor for satellite and VLBI techniques. Table 9 resumes the means and RMS values of these systematic effects. We note high discrepancies on VLBI scale factor from 2008 year and great annual oscillation on GNSS Z-translation ±25mm in opposite sign comparing from DORIS, DORIS-Laser and SLR variations. In this

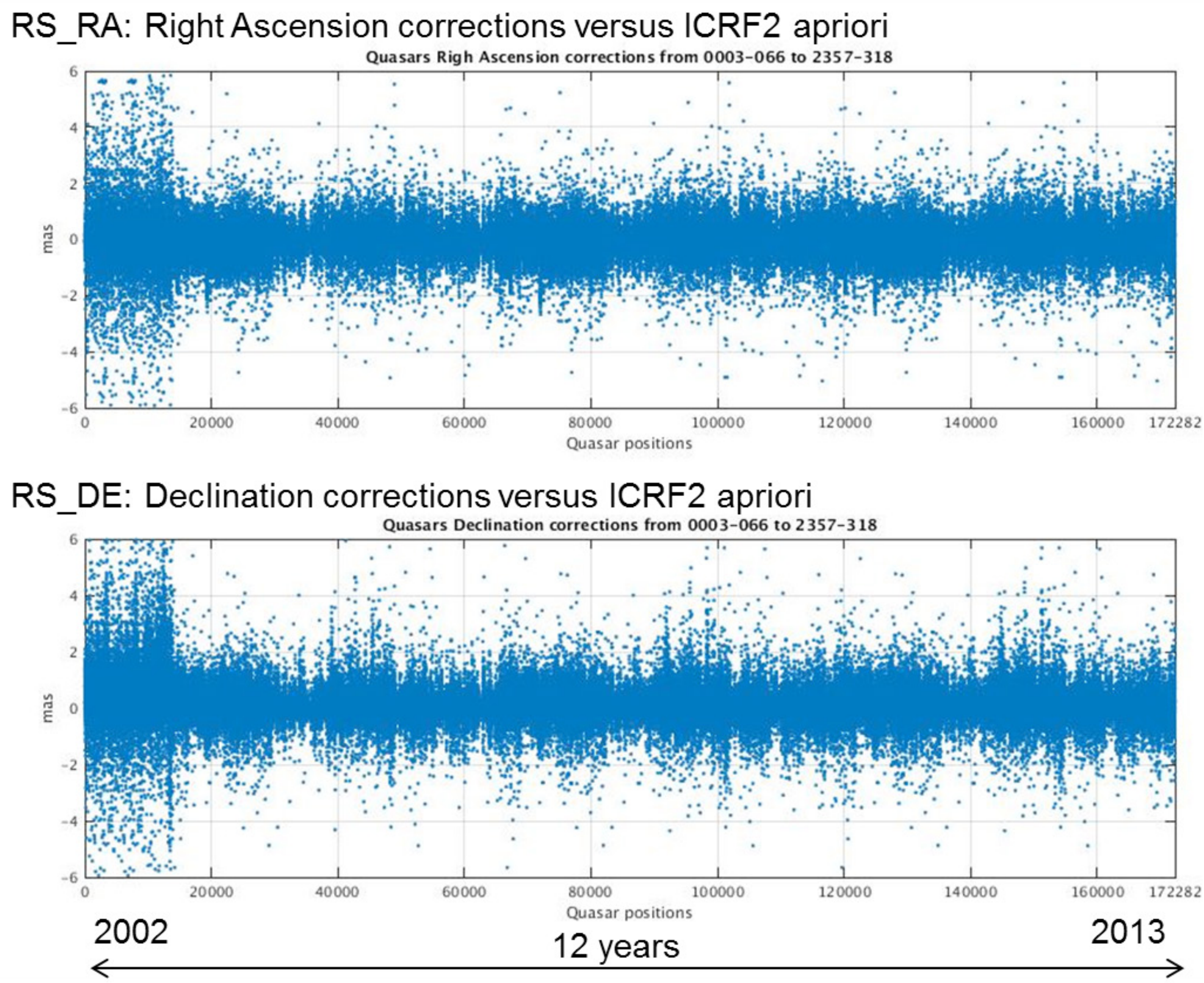

Fig. 1: Radio source corrections w.r.t. ICRF2

Table 3: Means & RMS of quasar corrections w.r.t. ICRF2

	Mean (mas)	RMS (mas)
Right ascension RS_RA	–0.0343	0.7221
Declination RS_DE	0.1334	0.7907

Table 4: Rotation parameters w.r.t. ICRF2

	R1 (mas)	R2 (mas)	R3 (mas)
Mean	0.0982	0.0198	0.1537
Uncertainty	212.720	186.267	154.292

Table 5: Pole & UT1, mean & RMS w.r.t. C04

	xp (mas)	yp (mas)	UT1–UTC (μs)
Mean	–0.0294	–0.0042	–2.0
RMS	0.0512	0.0373	26.4

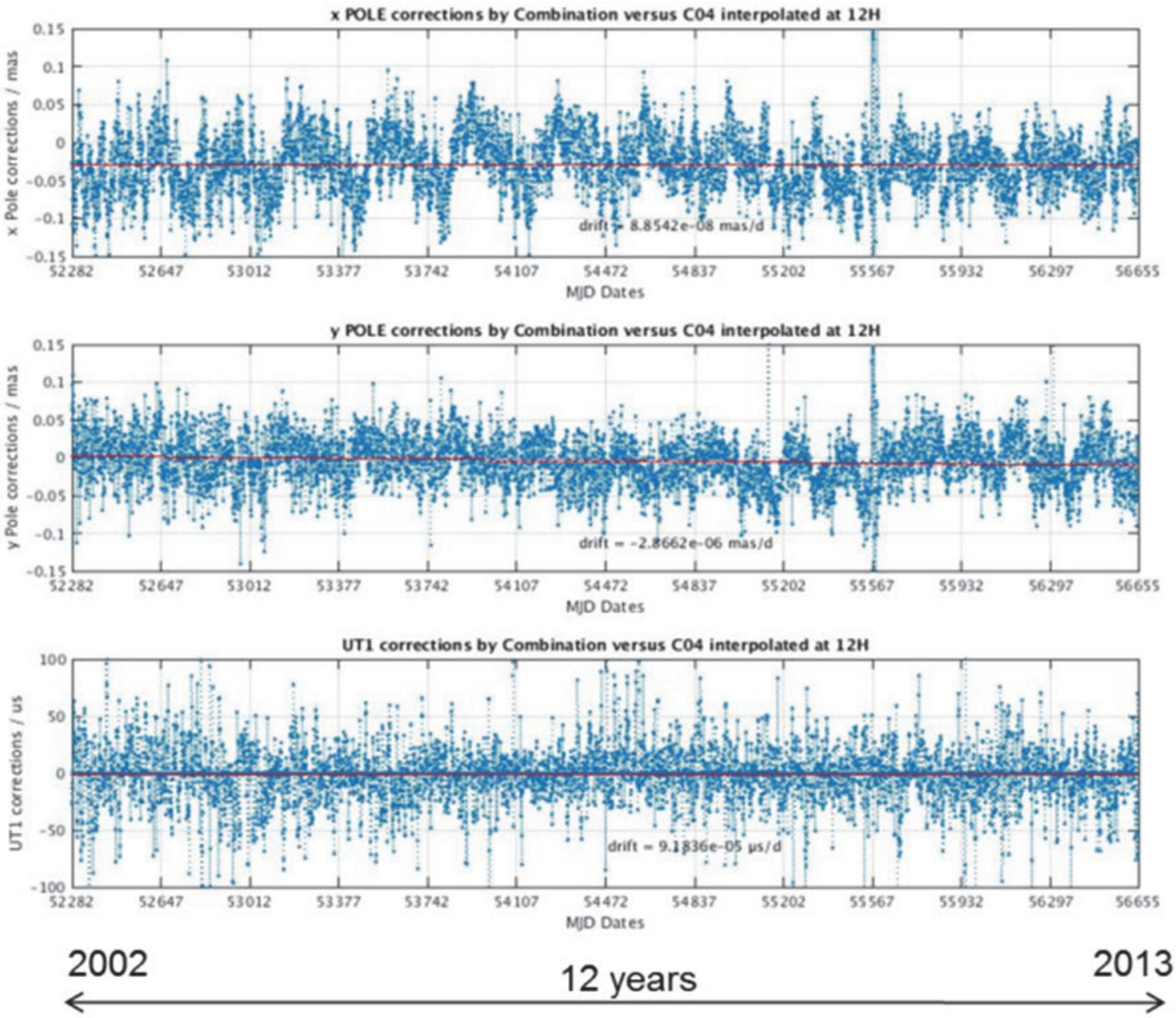

Fig. 2: Pole and UT corrections w.r.t. C04 series over 2002–2013 period

Table 6: Nutation corrections w.r.t. IAU2000A/2006

	dX (mas)	dY (mas)
Mean	0.0039	0.0195
RMS	0.3670	0.3482

Table 7: RMS3D of Wettzell station

	RMS 3D (m)
GPS	0.0149
SLR	0.0464
VLBI	0.0205

Table 8: Rates of Wettzell station

rate	(m/y)	(m/y)	(m/y)
GPS	–0.0171	0.0173	0,009
SLR	–0.0148	0.0169	0.105
VLBI	–0.0167	0.0176	0.0101

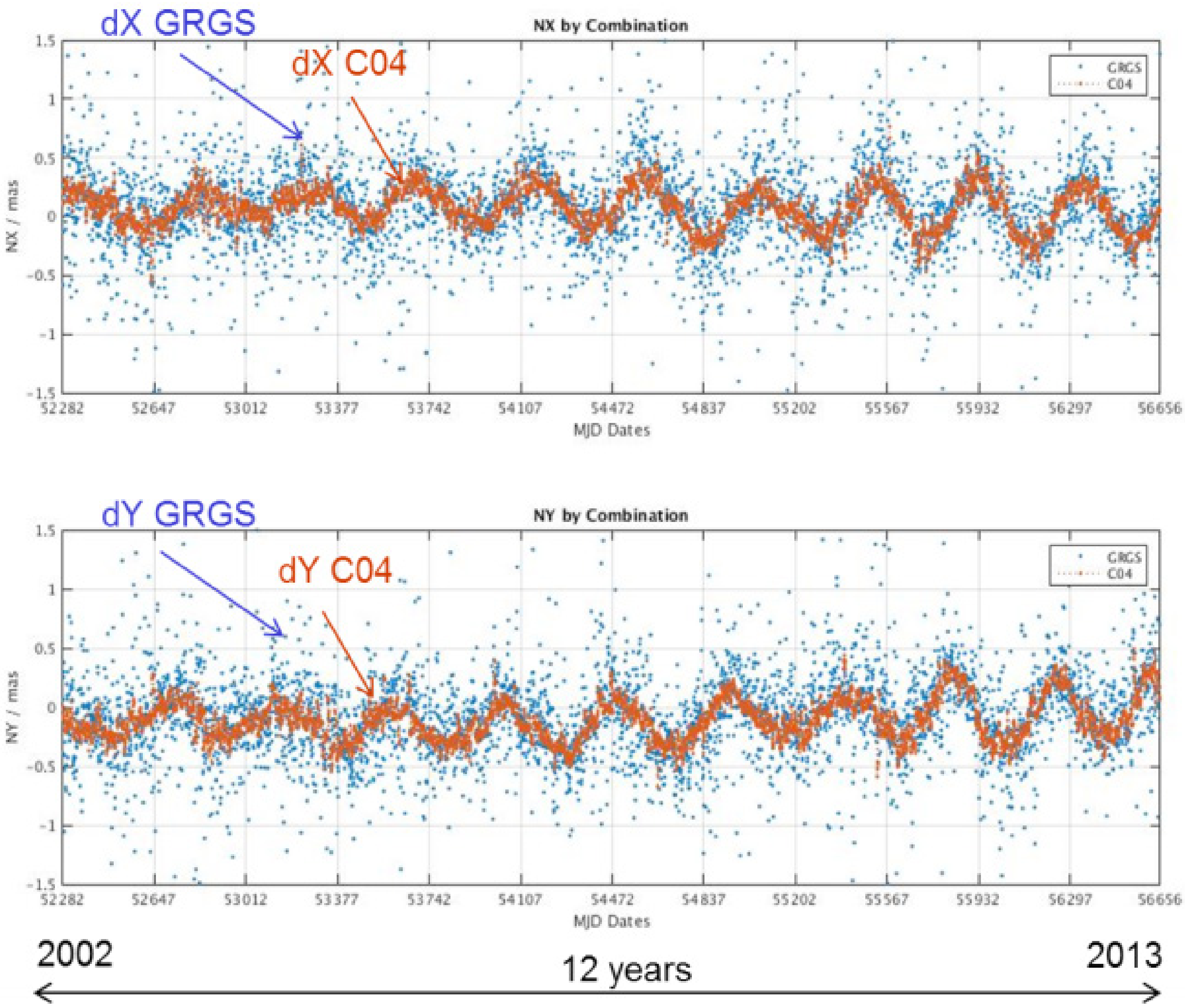

Fig. 3: Nutation corrections w.r.t. model IAU2000/2006A

Table 9: Systematic effects by techniques, means and RMS values for translation and scale factor

	DORIS		SLR on DORIS satellites		GNSS		SLR on SLR satellites		VLBI	
	Mean	RMS	Mean	RMs	Mean	RMS	Mean	RMS	Mean	RMS
TX (mm)	–2.8	16.0	0.0	3.9	–6.1	7.3	0.0	7.6		
TY (mm)	0.0	16.5	0.0	3.9	–1.2	4.8	0.0	3.6		
TZ (mm)	–1.9	12.4	0.0	6.1	–5.7	14.3	0.0	5.9		
Scale (mm)	2.5	17.0	–2.4	5.4	–1.6	2.5	–2.5	13.0	–5.3	25.8

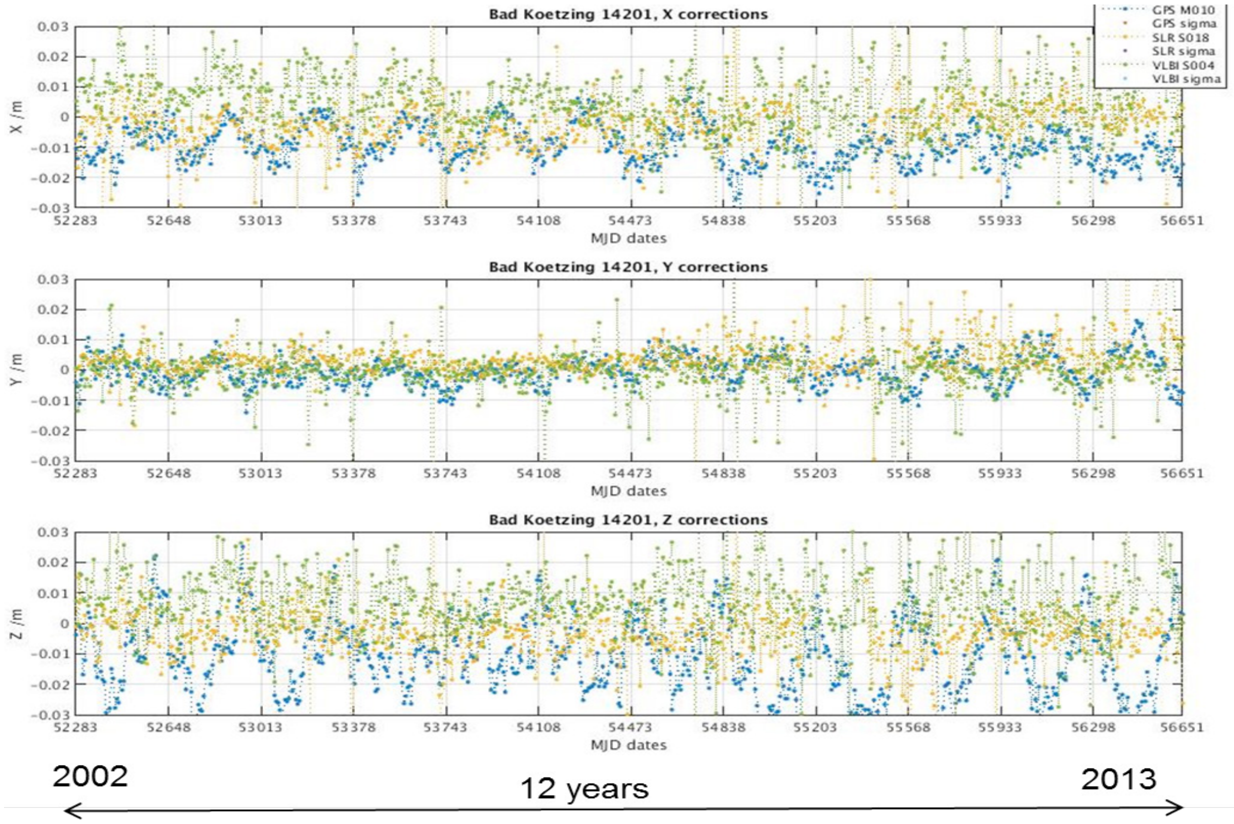

Fig. 4: Wettzell (Bad Koetzting) station with GPS: 14201M010 SLR: 14201S018 VLBI: 14201S004, corrections in X, Y, Z w.r.t. their ITRF2008 a priori

process, systematic effects are applied to the whole set of stations with seismic phenomena not excluded. A better estimation of these effects consists to exclude seismic stations from these systematic effects cancellation constraints.

Transformation parameters in three translations, scale and three rotations are weekly estimated. Figure 6 shows these parameters on the 2002–2013 period and Table 10 resumes the means and uncertainties values per techniques. We note the perturbation on translations (5cm) and rotations (5µas) for VLBI during the years 2008–2009 probably due to a badly datum constrained and the annual oscillation on GPS translations (+/-25mm for TZ) due to the atmospheric loading effect model not included.

Conclusions

In this combination at Normal Equation level performed by the GRGS Combination Centre the COL-WG have shown the possibility to determine simultaneously quasar coordinates, Earth orientation parameters and station coordinates. Algorithms developed to process DORIS GNSS SLR and VLBI techniques are available to perform combination with some modification on systematic effects cancellation and datum selection for minimal constraints applica-

Table 10: Means and uncertainties for transformation parameters in translation, scale factor and rotations for DORIS, GNSS, SLR and VLBI techniques

	TW (mm)	TY (mm)	TZ (mm)	Sc (mm)	RX (μas)	RY (μas)	Rz (μas)
DORIS	–2.0±4.6	0.0±3.7	–2.8±7.2	**–3.2±7.1**	0.2±2.4	–1.0±3.0	0.0±3.1
GNSS	**–6.3±7.4**	–1.1±4.6	**–5.5±14.5**	–1.7±2.1	–0.07±0.3	–0.4±0.6	–0.2±0.9
SLR	–1.1±3.3	–0.2±2.7	–0.2±5.5	**4.0±5.6**	0.7±2.8	–0.9±2.8	–0.3±4.2
VLBI	**–4.0±11.7**	**3.8±12.2**	1.6±5.9	**3.1±7.8**	**–2.8±10.5**	**–1.7±8.6**	0.8±5.4

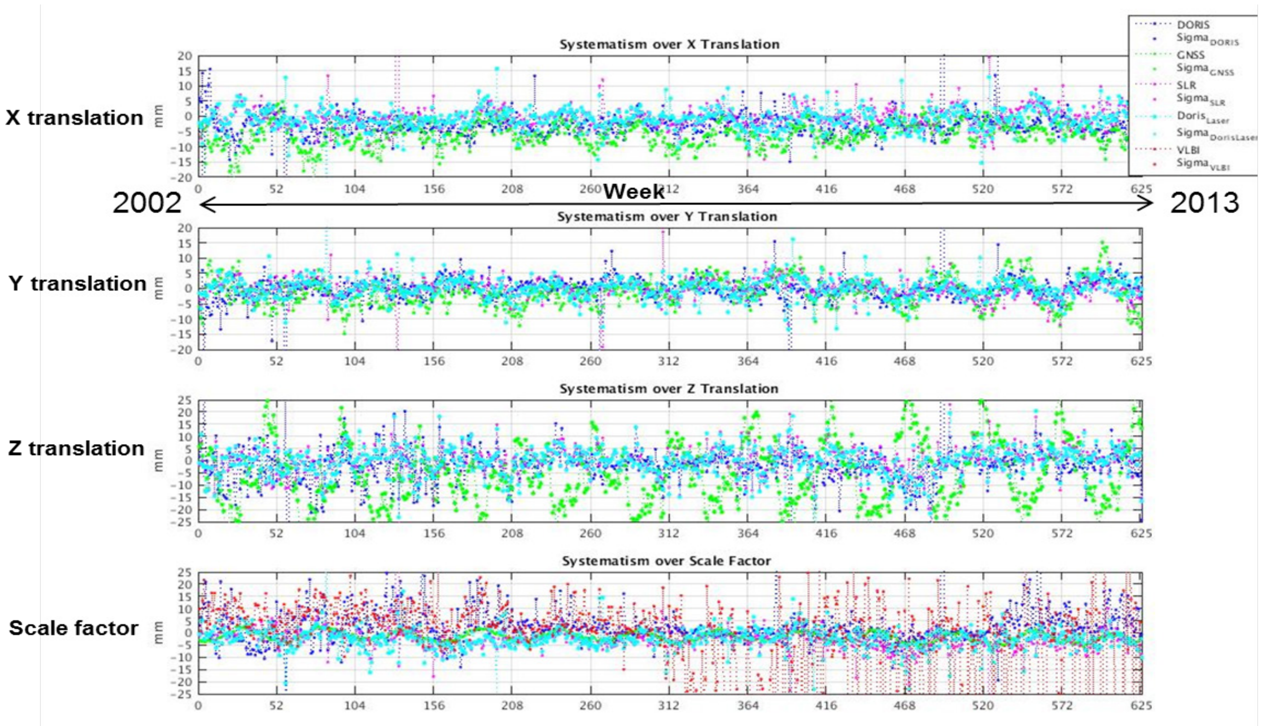

Fig. 5: Systematic effects in translation and scale factor weekly estimated over the 625 weeks 2002–2013

tion. This development closes the COL activities presented at the last meeting on 19th February 2016 at BKG Frankfurt am Main.

GRGS Combination Centre pursues this improvement in combination technique and studies the EOP determination by GNSS and VLBI combination from NEQ produced by different analysis centres in SINEX format. EOP solutions will be compared to the C04 series for evaluation and for testing the improvement in their determination.

References 2015

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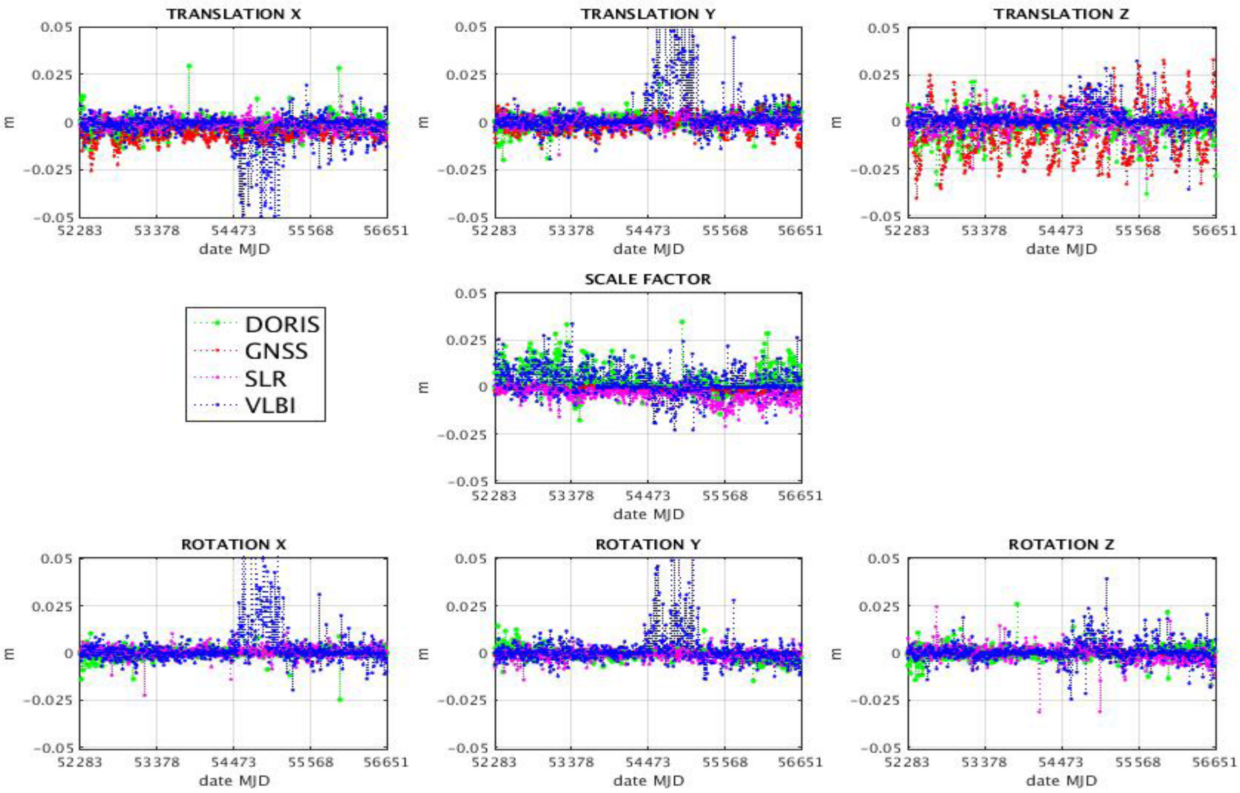

Fig. 6: Transformation parameters for DORIS, GNSS, SLR and VLBI 1p/week over 2002–2013 period

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