3.7.2 Working Group on Combination at the Observation Level

Overview

The Working Group on Combination at the Observation Level (WG COL) reviewed the interest in combining techniques at the observation level for EOP and reference frames. Its main goal was to bring together groups capable to do combinations on the observation level and to improve the homogeneity, precision and resolution of the products. After 5 years of activities, beginning the 22th October 2009 at the Centre for Space Research of Warsaw in Poland, the working group concluded its efforts during the last meeting on the 19th February 2016 at BKG, Frankfurt am Main, Germany. The WG COL activities has been transferred to the PLATO/IAG-GGOS group (Performance Simulations and Architectural Trade-Offs), organized by Daniela Thaller and Richard Gross, for further considerations on the combination technique.

Summary of combination presented during the 19th February 2016 meeting

The WG COL contributed to the ITRF2014 realization by combining geodetic techniques (DORIS, GNSS, SLR, and VLBI) at the Normal Equation level. Quasar coordinates, Earth Orientation Parameters solutions (EOP) and station positions have been produced at a weekly basis in SINEX format, spanning twelve years from January 4th, 2002 to December 28th, 2013 (625 weeks) and delivered to IGN for comparisons. The Normal Equations processed for each techniques are collected in Table 1 and parameters to estimate are presented in Table 2 with some added parameters for further analyses.

Table 1: *GRGS Normal Equations 2002–2013 processed and parameters for each technique*

GNSS: CNES-CLS Toulouse	DORIS: CNES-CLS Toulouse	SLR: IMCCE GRGS Paris	VLBI: OB LAB Bordeaux
4372 daily NEQ, 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 using the Doppler signals**: **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 using the Laser reflectors:** **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 arc length spanning 9d for the SLR 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

One of the COL WG goals concerns the determination of the CRF, the TRF and the EOP parameters simultaneously and consistently by GNSS, DORIS, SLR and VLBI combination at the normal equation level.

Concerning the quasar coordinate corrections versus ICRF-2 in right ascension (RS_RA) and declination (RS_DE) for all quasars estimated between 2002 and 2013, Fig. 1 shows a discrepancy of 722 μas and 791 μas respectively and rotation parameters R1, R2, R3 of the celestial network (w.r.t. ICRF-2) have the estimated values of 98 μas, 20 μas and 153 μas respectively.

For the Earth rotation parameters, pole and UT1–UTC corrections w.r.t. IERS 08 C04 are plotted in Fig. 2 and exhibits an annual and semi-annual periodic signals in the polar motion (x, y) with a discrepancy of 51 μas and 37 μas respectively and 26 μs for the UT1–UTC.

Concerning the nutation offsets issued only from VLBI observations, the quality of determination is not at the level of the IVS series. Estimations at 12h UTC are shown in Fig. 3 compared with the IERS 08 C04 series. The discrepancies in RMS are 367 μas and 348 μas for dX and dY respectively. Investments are in progress to complete the VLBI observations processing by GINS software used at GRGS.

Table 2: *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

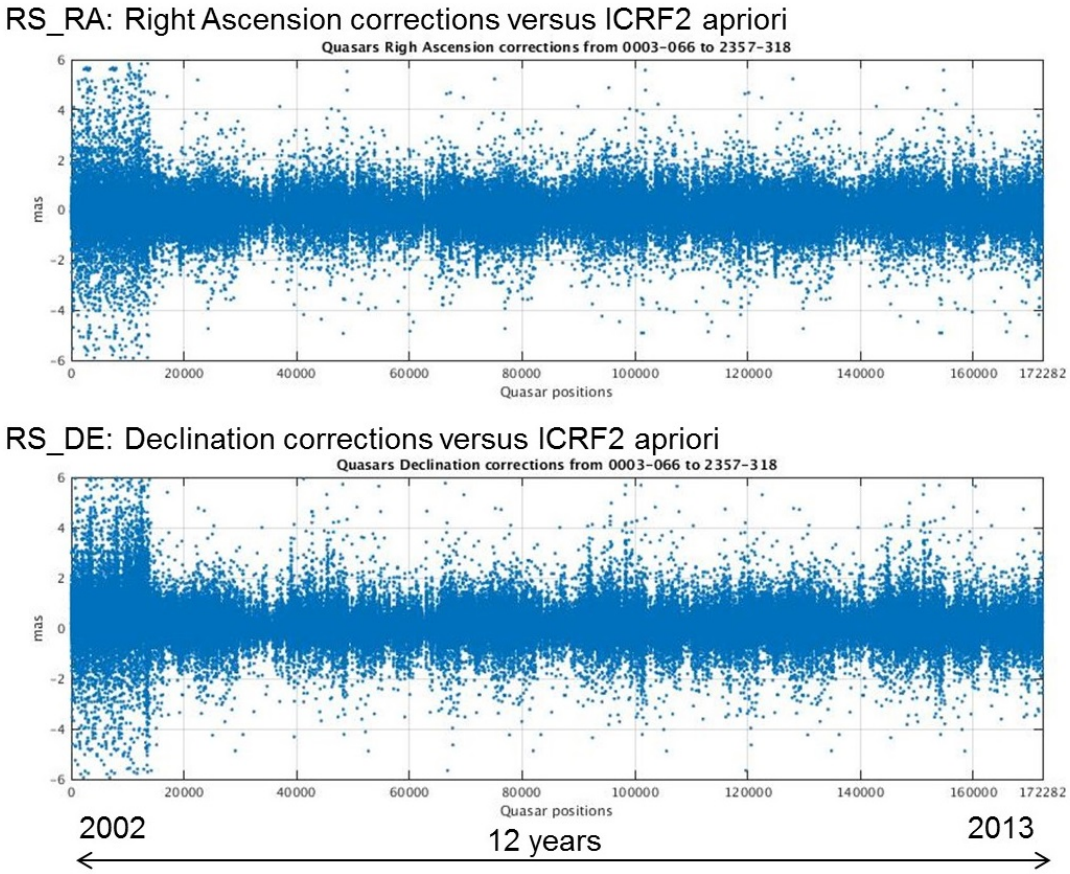

Fig. 1: *Quasar coordinates corrections w.r.t. ICRF-2 from 2002 to 2013 – ĩ00 quasars estimated at a weekly basis*

For the stations positions of all techniques determined at a weekly basis we apply preliminary averages set in Table 3.

Analyses of collocated stations obtained by this combination of four techniques are Ny-rAlesund site with the DORIS domes 10317S005, GPS domes 10317M005 and VLBI domes 10317S003, Wettzell (Bad Koetzting) site with GPS domes 14201M010, SLR domes 14201S018 and VLBI domes 14201S004 and Kokee Park site with DORIS domes 40424S009, GPS domes 40424M004 and VLBI domes 40424S007. These positions are estimated with their respective tropospheric bias parameters. Fig. 4, 5, 6 show the corrections w.r.t. Cartesian coordinates a-priori for Ny-Ålesund, Wettzell/Bad Koetzting and Kokee Park respectively with their differences, rates and the RMS3D estimated per techniques from the combination solutions over twelve years of observations. The differences calculated from the estimated positions are compatible with their respective local ties extracted from the SINEX files containing the co-location sites used in the ITRF2008 combination.

The systematic effects absorbed by Helmert parameters added for each technique have been weekly estimated. Fig. 7 shows the translations and scale for the satellite techniques and scale for VLBI over twelve

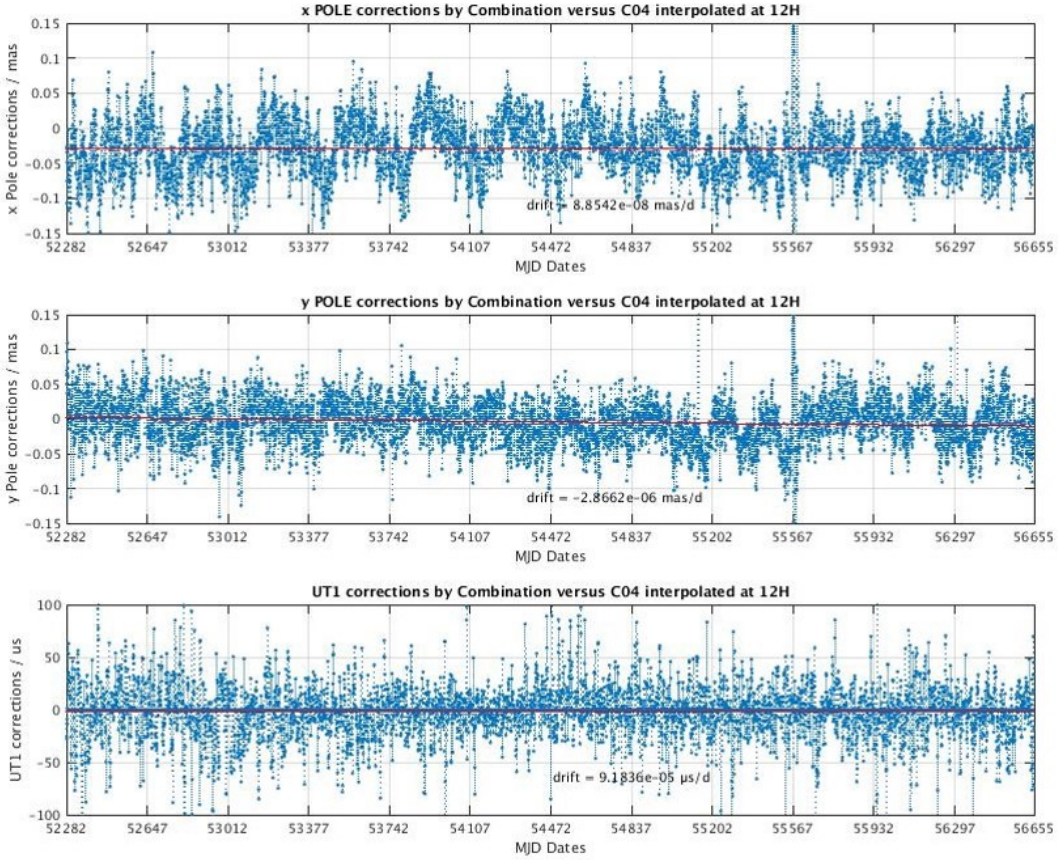

Fig. 2: *x and y Pole coordinates corrections and UT1-UTC corrections w.r.t. IERS 08 CO4 series interpolated at 12h UTC – 4370 samples over 2002–2013 with 1pt/day at 12h UTC*

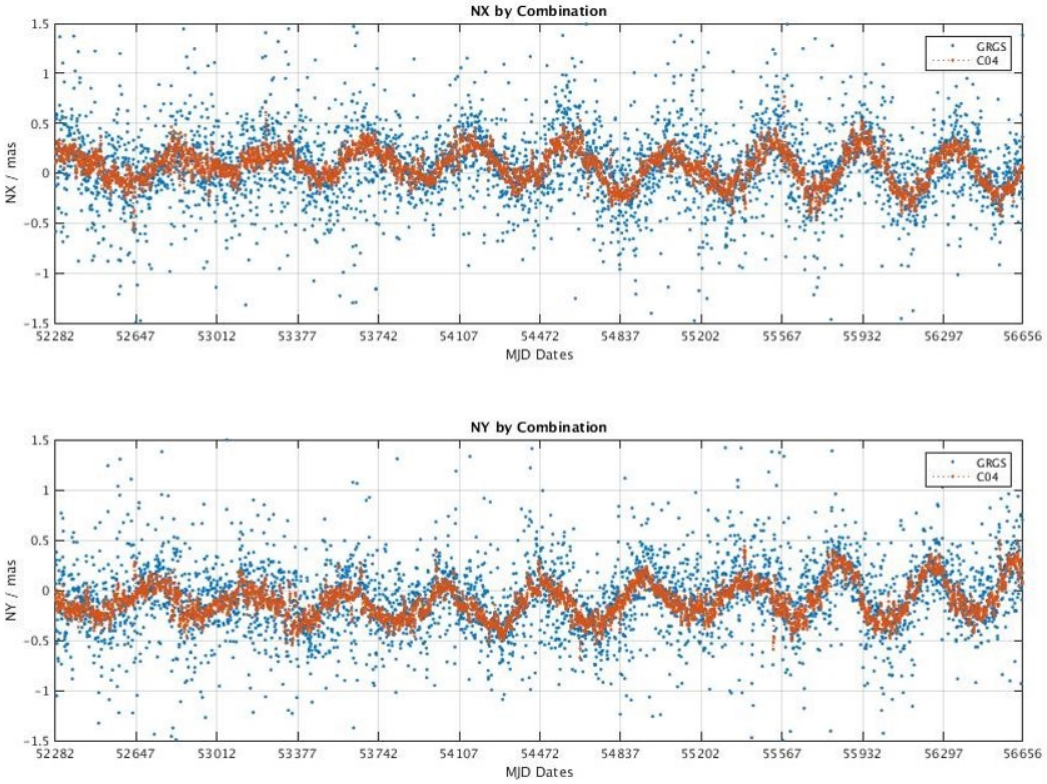

Fig. 3: *Nutation offset corrections w.r.t. IERS 08 CO4 series interpolated at 12h UTC – 4370 samples over 2002–2013 with 1pt/day at 12h UTC*

Table 3: *Doris, GPS, SLR, VLBI Stations considered and pre-processing applied*

	DORIS	GNSS	SLR	VLBI	Total
Number of Station	50	204	26	14	294
Observation frequency	Weekly	Daily	Weekly	Per session R1 R4, each week	~900 parameters per week
Processing		Weekly average	SLR stations measured by DORIS satellites are separated to SLR stations measured by SLR satellites	Weekly average	Systematic effects per technique (17) & 7 minimal constraints per techniques (35)

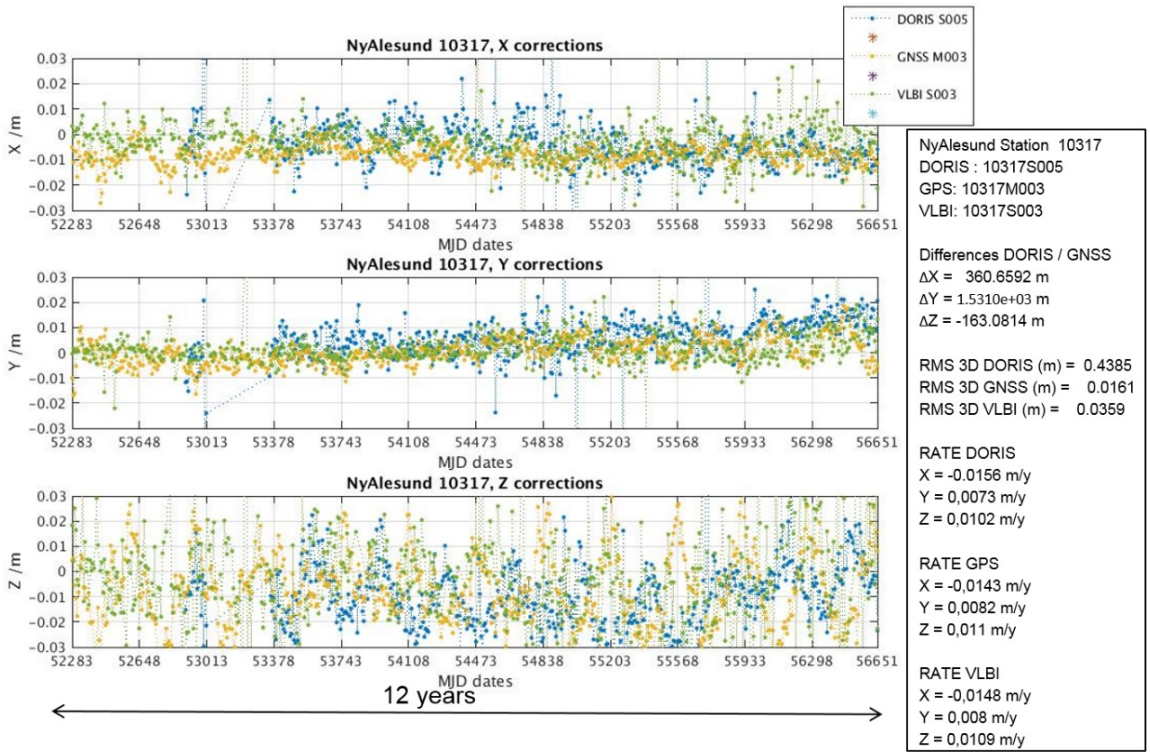

Fig. 4: *Ny-Ålesund Cartesian coordinate corrections w.r.t. ITRF2008 for DORIS, GPS & VLBI collocated stations*

years of observations. Table 4 shows the mean and standard deviation for each Helmert parameters in mm. We note that no bias is observed for the SLR origin either from the Doris satellites using Laser reflectors nor SLR satellites. The origin for all Doris satellites (with or without Laser reflectors) has -2 mm of bias over x and z components compatible with the null bias considering the associated discrepancies estimated to more than 1.2 cm.

Concerning the application of minimal constraints, the seven transformation parameters – 3 translations, 1 scale factor, 3 rotations – for each technique applied to their respective reference networks have been plotted in Fig. 8, and Table 5 collects the mean and standard deviation for the DORIS, GPS, SLR and VLBI techniques.

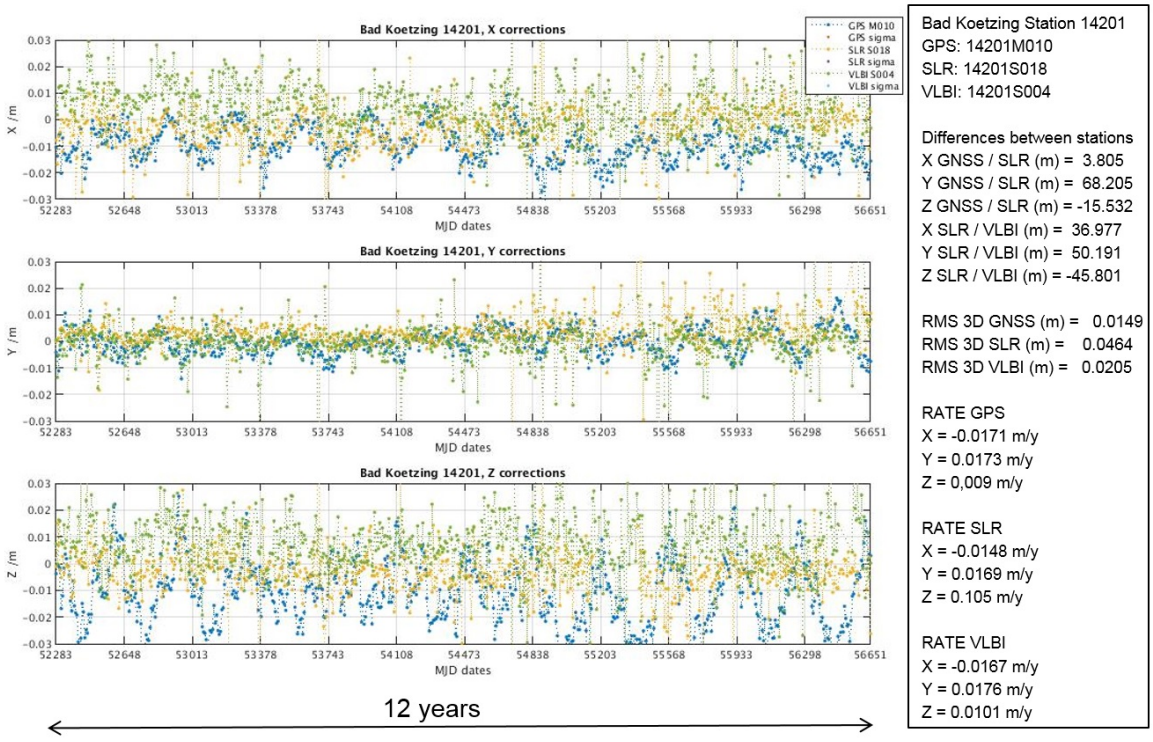

Fig. 5: *Wettzell (Bad Koetzting) Cartesian coordinate corrections w.r.t. ITRF2008 for GPS, SLR & VLBI collocated stations*

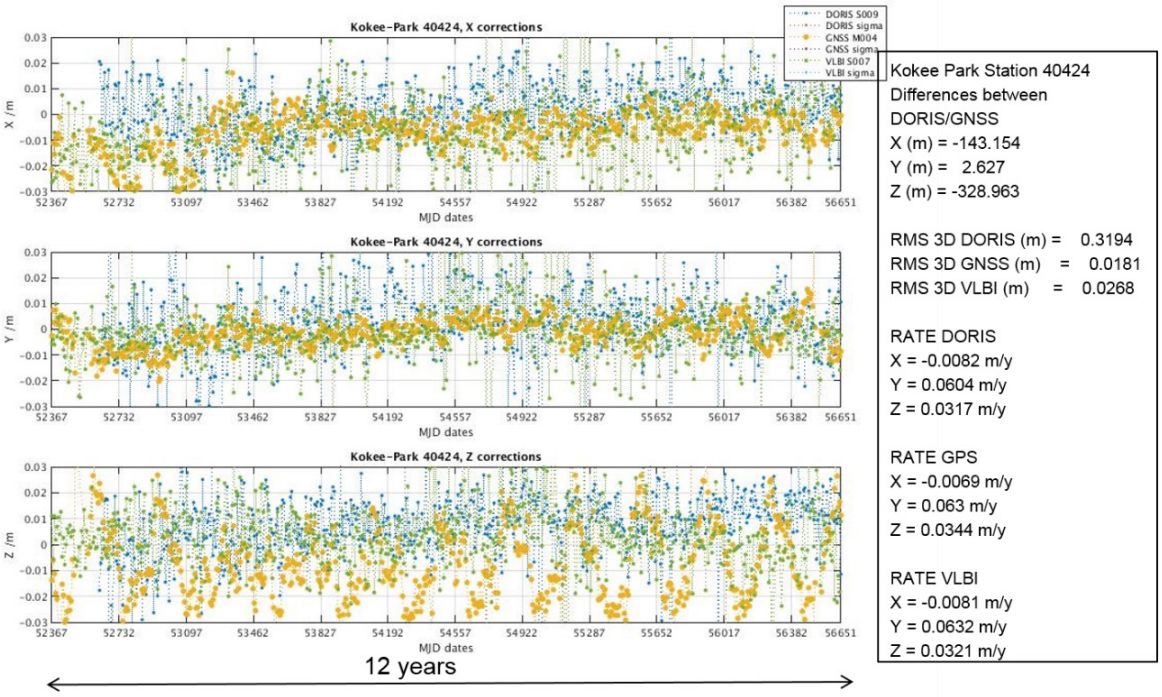

Fig. 6: *Kokee Park Cartesian coordinate corrections w.r.t. ITRF2008 for GPS, SLR & VLBI collocate stations*

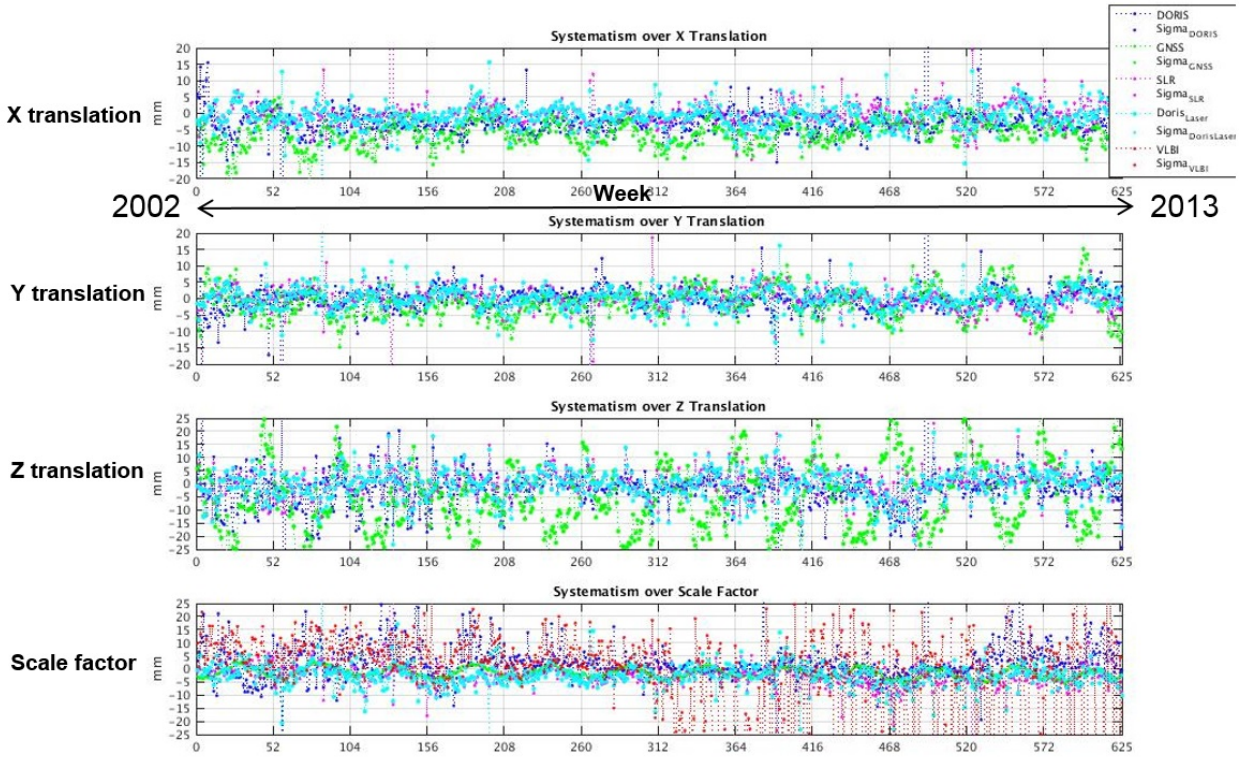

Fig. 7: *Systematic effects on station networks for DORIS, GPS, SLR and VLBI*

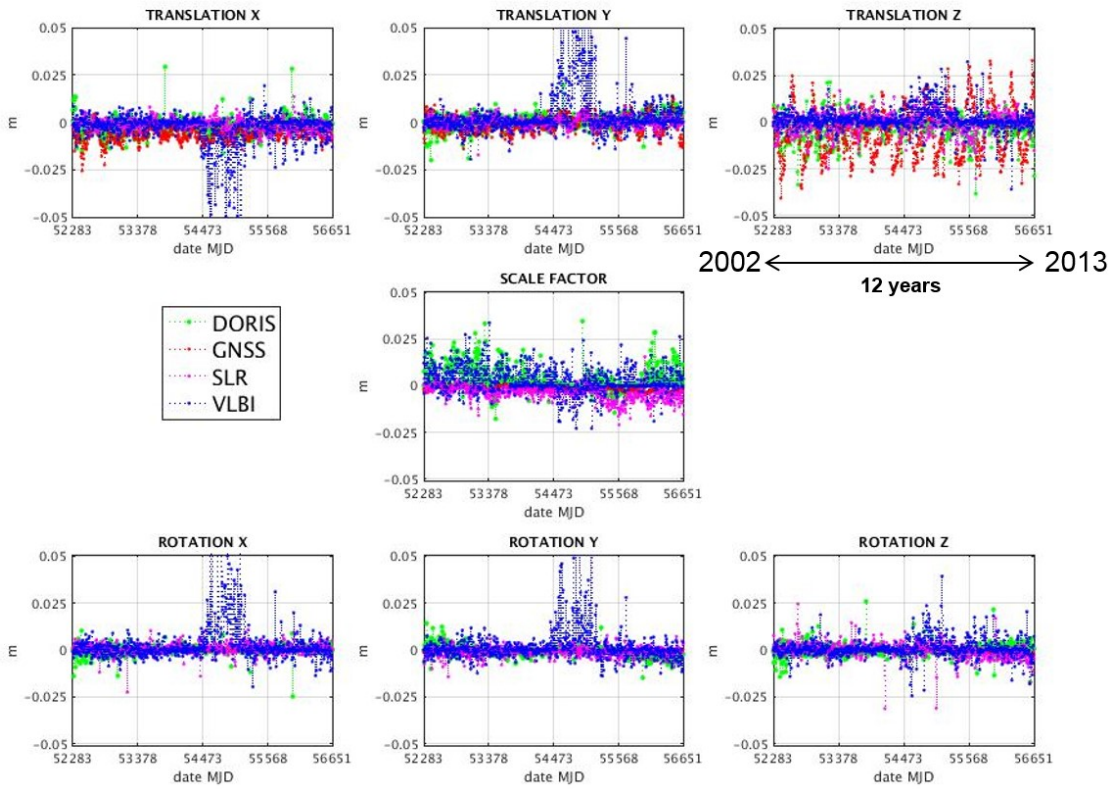

Fig. 8: *Transformation parameters – 3 translations, 1 scale factor, 3 rotations – for DORIS, GPS, SLR and VLBI techniques over 2002–2013 period*

Table 4: *Mean and standard deviation for the Systematic effects estimated for each technique over the 2002–2013 period*

Networks	DORIS		SLR by DORIS satellites		GNSS		SLR by 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**

Table 5: *Mean and standard deviation of transformation parameters weekly estimated for DORIS, GPS, SLR and VLBI techniques*

	TX 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**

Conclusion

The method developed to combine normal equations from astro-geodetic techniques by the COL WG has proved its capability to perform consistently CRF-EOP-TRF solutions at a weekly basis. During the campaign of generation the new terrestrial reference frame ITRF2014, the COL WG has generated weekly solutions and delivered files in SINEX format over 12 years, 2002–2013.

The results for Quasar positions simultaneously estimated with station coordinates at a weekly basis show a discrepancy of about 700 μas versus ICRF2, for the Pole coordinates compared to IERS 08 C04: rms(xp_corr) = 51 μas, rms(yp_corr) = 37 μas shows an annual periodic term, for UT versus C04: rms(UT_corr) = 26 μs & LOD is comparable to C04, for Nutation offset issue only from VLBI technique shows a large discrepancy versus C04 du to the processing on the VLBI observables not suitable for this combination (improvement is in progress for using VLBI NEQ from GINS software in order to combine them with over techniques). For the station coordinates we show an annual effect w.r.t. ITRF2008 a-priori probably due to the atmospheric loading not included in the model of station displacements, with discrepancies at the cm level. The systematic effects exhibit an annual oscillation for all techniques at 1.5 cm level for DORIS, 5 mm level for SLR by DORIS satellites, 1.4 cm for Z components of GNSS, 1 cm level for SLR by SLR satellites and 2.6 cm for scale factor of VLBI network. The transformation parameters show a large discrepancy for VLBI on translations and rotations at 5 cm level during the 2008-2010 period probably due to the VLBI network containing seismic stations, annual oscillation on translations for GNSS network at 6 mm level for TX and TZ, 1 mm for TY, scale factor for SLR is at a level of 4 mm with 6 mm of discrepancy.

Further investigations have to consider to take benefits of this COL WG efforts on doing this combination procedure. First concern the comparison of EOP and station solutions with ITRF2014, the analysis on mutualisation of tropospheric parameters and on mutualisation of orbital parameters for multi-techniques satellites.

Jean-Yves Richard