COL / E-GRASP meeting
19 February 2016 – BKG/Frankfurt

9:00 – 9:30: welcome (D Thaller)
9:30 – 10:30: summarizing final COL activities
   • Summarizing COL activities (R. Biancale)
   • GRGS (J.-Y. Richard/OP)
   • DGFI (D. Angermann/TUM)
   • others
10:30 – 11:00: preparing the future of COL
Break
11:15 – 11:30: E-GRASP/Eratosthenes EE9 proposal (R. Biancale)
11:30 – 12:00: mission scenarios
   • orbit simulation (A. Pollet/IGN)
   • VLBI simulation (S. Glaser/GFZ)
Lunch
13:30 – 15:00: E-GRASP/Eratosthenes payload
   • GNSS receiver
   • DORIS receiver (CNES)
   • VLBI transmitter (JPL)
   • USO
   • SLR (GFZ)
   • μSTAR (ONERA)
   • T2L2 (OCA)
15:00 – 16:00: E-GRASP/Eratosthenes proposal organization
16:00 – 16:30: conclusive remarks
After 6 years of COL activities…

1) reviewing the approach of the various groups
   and their capability to process two or more techniques.

2) elaborating benchmarks
   to intercompare results between groups from the same data set.

3) ensuring SINEX compatibility
   between techniques and with the international technique services and IERS.

4) establishing common processing standards
   for all techniques in order to guarantee homogeneity and consistency.

5) optimizing and unifying parameterization
   for instance for tropospheric parameters in order to minimize globally the degree of
   freedom of the whole inverse system.

6) studying the appropriate weighting between techniques
   and the use of local ties or identical satellites tracked by several techniques.

7) studying stabilization methods
   and looking for high temporal resolution of parameters.

8) evaluating and comparing results
   to search for compatibility between groups.

9) organizing routine operations
   for a new TRF realization, either in the framework of the next ITRF or as ITRF assessment.
COL objectives

COL-WG major tasks will be to study methods and advantages of combining techniques at the observation level, searching for an optimal strategy to solve for geodetic parameters.

Demonstration is based on weekly combined modified SINEX files (actually containing unconstrained normal equations of station coordinates, Earth rotation parameters, nutation parameters and quasar coordinates) from all space geodetic techniques together (SLR/LLR, GNSS, VLBI, DORIS).

Combination at the observation level can be considered as equivalent to the normal equation level under the condition that all common parameters must be combined together (like tropospheric parameters).

At least most of the works have been done at this NEq level.

Adjusted PM from combined DORIS-SLR data on a Jason2 7-day arc in August 2008
Basic principle of Combination

1. Merging all sources of pertinent space information

2. Searching for homogeneity through the same a priori models:
   - Geodetic and geophysical
   - But technique dependent modelling (centre of phase, empirical…)

3. Improving resolution through the same parameterization:
   - Daily or sub-daily EOP (Xp, Yp, UT1); need of LOD?
   - Daily nutation
   - Weekly stations coordinates
   - Quasar coordinates
   - Tropospheric parameters

4. Helping de-correlation through additional constraints between techniques
   - Helmert’s constraints
   - Ties
Tasks (2011)

- **Processing with updated and homogenized standards and parameters** to be finalized over the same 3-weeks period (10-30 August 2008 / CONT08)

- Extension to the **CONT11** campaign (15-29 September 2011)

- Provide on the forum the **list of stations** used (for DORIS, VLBI, SLR, and GNSS)

- **New set of data**: LEO satellites, in particular Jason-2 with multi-technique (SLR, DORIS, GPS) or GRACE-A/B (SLR, GPS). To be provided by some groups on a volunteer basis

- Include LLR for dynamic realization of the celestial reference frame, complementary to kinematic realization of VLBI to contribute to long-term monitoring of nutation as well as pole and UT

- Increase EOP parameterization frequency (from 1d to 3 hrs)
## COL Analysis Centres

<table>
<thead>
<tr>
<th>groups</th>
<th>software packages</th>
<th>techniques</th>
<th>NEq</th>
<th>product</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIUB/BKG</td>
<td>BERNESE</td>
<td>GNSS</td>
<td>SLR</td>
<td>X</td>
</tr>
<tr>
<td>DGFI</td>
<td>DOGS-OC</td>
<td>SLR</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>BERNESE/DOGS-RI</td>
<td>G…</td>
<td></td>
<td>V…</td>
</tr>
<tr>
<td>ESOC</td>
<td>NAPEOS</td>
<td>DORIS</td>
<td>GNSS</td>
<td>SLR</td>
</tr>
<tr>
<td>GFZ</td>
<td>EPOS</td>
<td>D…</td>
<td>GNSS</td>
<td>SLR</td>
</tr>
<tr>
<td>GRGS</td>
<td>GINS</td>
<td>DORIS</td>
<td>GNSS</td>
<td>SLR</td>
</tr>
<tr>
<td>GSFC</td>
<td>GEODYN</td>
<td>D…</td>
<td>G…</td>
<td>S…</td>
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<tr>
<td></td>
<td>CALC-SOLVE</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>ASI</td>
<td>BERNESE/GEODYN</td>
<td>G…</td>
<td>SLR</td>
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<tr>
<td>TUW</td>
<td>VIEVS</td>
<td></td>
<td></td>
<td>VLBI</td>
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<tr>
<td>UB</td>
<td>GEODYN</td>
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</tbody>
</table>

## COL Combination Centres

- DGFI
  - DOGS-CS
- GRGS
  - DYNAMO
Activities in the COL-WG (2014)

- to continue to homogenize processing in the COL ACs over CONT08 and CONT11 3-week periods
- to look at high resolution ERP (3hrs)
- to unify all common parameters (e.g. troposphere) solving for EOP, TRF, CRF
- to check different kinds of constraints in global treatments (TRF/CRF nnr, retrograde diurnal pole, Helmert’s systematisms…)
- to study the impact of ground and space ties (Jason2, GRACE…)
- to progress in multi-technique processing directly at the level of observation (ESOC, GRGS…)
- to maintain a forum site (at OP) for data exchange and discussion: http://grgs.obspm.fr/forum/
- to submit long term combinations in the ITRF2014 framework (GRGS, AIUB/BKG, ESOC, GSFC…)
Future of COL

• Very depending on motivation and resources of the ACs and CCs
• Still need of homogenizing technique processing and upgrading several software packages to be really at the observation level
• Demonstrations on VLBI-CONT periods as well as in the ITRF2014 framework are not complete
• COL results must yet be assessed
• Combination at the observation level activities should be updated in the framework of GRASP-like satellite missions
Modelling
<table>
<thead>
<tr>
<th>Gravitational Dynamic</th>
<th>DORIS</th>
<th>GNSS</th>
<th>SLR</th>
<th>VLBI</th>
<th>COL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geopotential</td>
<td>EIGEN-6S2 up to degree 95 including time variable terms up to degree 50 (bias &amp; drift per yr from 2002 to 2012, periodic 18.6, 1, 0.5 yrs)</td>
<td>EIGEN-6S2 up to degree 12</td>
<td>EIGEN-6S2 up to degree 30 (for LAGEOS)</td>
<td></td>
<td>Static gravity field model is based on EIGEN-GRGS.RL02, tide-free, complete to degree and order 2 up to 160 [ftp://hpiers.obspm.fr/iers/eop/grgs/Models/Gravity_Field/]</td>
</tr>
<tr>
<td>Third-body</td>
<td>JPL DE421</td>
<td>JPL DE421</td>
<td>JPL DE421</td>
<td>JPL DE421</td>
<td>JPL DE405</td>
</tr>
<tr>
<td>Solid Earth Tides</td>
<td>IERS 2010 standards</td>
<td>IERS 2010 standards</td>
<td>IERS 2010 standards</td>
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<td>IERS 2010 standards</td>
</tr>
<tr>
<td>Ocean Tides</td>
<td>FES 2012 (32 principal waves, + 60 admittance waves) up to degree 50</td>
<td>FES 2012 (32 principal waves, + 60 admittance waves) up to degree 12</td>
<td>FES 2012 (32 principal waves, + 60 admittance waves) up to degree 20</td>
<td></td>
<td>FES 2004 [ftp://hpiers.obspm.fr/iers/eop/grgs/Models/Ocean_Tide_Loading/]</td>
</tr>
<tr>
<td>Atmospheric gravity</td>
<td>3hr ERA-interim / ECMWF up to degree 50</td>
<td>3hr ERA-interim / ECMWF up to degree 12</td>
<td>3hr ERA-interim / ECMWF up to degree 20</td>
<td></td>
<td>none (integrated into the geopotential)</td>
</tr>
<tr>
<td>Non tidal oceanic gravity</td>
<td>TUGO R12 up to degree 50</td>
<td>TUGO R12 up to degree 12</td>
<td>TUGO R12 up to degree 20</td>
<td></td>
<td>none (integrated into the geopotential)</td>
</tr>
<tr>
<td>Atmospheric tides</td>
<td>none (considered through the ECMWF atmospheric data)</td>
<td>none</td>
<td>none</td>
<td></td>
<td>Ray &amp; Ponte 2003 [ftp://hpiers.obspm.fr/iers/eop/grgs/Models/Atmospheric_Tide/]</td>
</tr>
<tr>
<td>Earth pole tide</td>
<td>IERS2010 standards</td>
<td>IERS2010 standards</td>
<td>IERS2010 standards</td>
<td></td>
<td>IERS2010 standards</td>
</tr>
<tr>
<td>Ocean Pole Tide</td>
<td>Desai 2002 up to degree 12</td>
<td>Desai 2002 up to degree 12</td>
<td>Desai 2002 up to degree 12</td>
<td></td>
<td>Desai 2002 up to degree 12</td>
</tr>
<tr>
<td>Non Gravitational Dynamic</td>
<td>DORIS</td>
<td>GNSS</td>
<td>SLR</td>
<td>VLBI</td>
<td>COL</td>
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<tr>
<td>Atmospheric drag</td>
<td>DTM94 (with Am indices) Spots, Envisat, Cryosat2, HY-2A: one coef/4 hrs (one/1hr in high solar activity periods); Topex, Jasons: one coef/half day</td>
<td></td>
<td>None for Lageos</td>
<td></td>
<td>JB2008</td>
</tr>
<tr>
<td>Solar radiation pressure</td>
<td>one coef/day strongly constrained (1.e-4) to: 0.98 for Topex; 1.15 for Spot-2; 1.16 for Spot-3/-4; 1.17 for Spot-5; 1.29 for Envisat; 0.97 for Jason-2; 0.85 for Cryosat-2; 0.86 for HY-2A</td>
<td>one coefficient adjusted per day?</td>
<td>one scale coefficient adjusted per arc</td>
<td></td>
<td>applied</td>
</tr>
<tr>
<td>Albedo + infra-red</td>
<td>interpolated from grids issued from ECMWF 6hr 4.5° grids</td>
<td>interpolated from grids issued from ECMWF 6hr 9° grids</td>
<td>interpolated from grids issued from ECMWF 6hr 9° grids</td>
<td></td>
<td>applied</td>
</tr>
<tr>
<td>Satellite emissivity</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td></td>
<td>none</td>
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<tr>
<td>Relativity</td>
<td>Schwarzschild model + Lense-Thirring + geodetic precession</td>
<td>Schwarzschild model + Lense-Thirring + geodetic precession</td>
<td>Schwarzschild model + Lense-Thirring + geodetic precession</td>
<td>IERS 2010 standards</td>
<td>Schwarzschild model + Lense-Thirring + geodetic precession</td>
</tr>
<tr>
<td>Hill/empirical</td>
<td>once/rev along-&amp; cross-track per x day</td>
<td>once/rev along-&amp; cross-track per x day</td>
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</tr>
<tr>
<td>Geometry</td>
<td>DORIS</td>
<td>GNSS</td>
<td>SLR/LLR</td>
<td>VLBI</td>
<td>COL</td>
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<tr>
<td>Pole &amp; UT1</td>
<td>daily EOPC04_i08</td>
<td>daily EOPC04_i08</td>
<td>daily EOPC04_i08</td>
<td>daily EOPC04_i08</td>
<td>EOPC04 initial values interpolated (Lagrange polynomial method) with 3hr time intervals</td>
</tr>
<tr>
<td>Solid Earth tidal displacement</td>
<td>IERS 2010 standards</td>
<td>IERS 2010 standards</td>
<td>IERS 2010 standards</td>
<td>IERS 2010 standards</td>
<td>IERS 2010 standards</td>
</tr>
<tr>
<td>Ocean loading</td>
<td>FES2012</td>
<td>FES2012</td>
<td>FES2012</td>
<td>FES2012</td>
<td>Ocean tide loading models per stations are obtained from Scherneck's ocean loading site and provided in the BLQ format according to the IERS Standards 2010</td>
</tr>
<tr>
<td>Non tidal atmospheric loading</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Ocean pole tide displacement</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Propagation &amp; Systems</td>
<td>DORIS</td>
<td>GNSS</td>
<td>SLR/LLR</td>
<td>VLBI</td>
<td>COL</td>
</tr>
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</tr>
<tr>
<td>Troposphere</td>
<td>GPT/GMF modelling from Boehm et al. (2006). One zenith delay/pass + one daily tropospheric gradient per station in North &amp; East directions</td>
<td>GPT/GMF modelling from Boehm et al. (2006). One zenith delay/2hr in PWL mode + one daily tropospheric gradient per station in North &amp; East directions</td>
<td>Mendes-Pavlis: (zenith delay &amp; mapping Function)</td>
<td>GPT/GMF modelling from Boehm et al. (2006). One zenith delay/2hr + one daily tropospheric gradient per station in North &amp; East directions</td>
<td>GPT/GMF for radio-electrical waves and Mendes-Pavlis for SLR. One zenith delay/2hr or pass + one daily tropospheric gradient per station in North &amp; East directions</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>2nd order corrections using IGS TEC values and igrf2011 magnetic field model</td>
<td>(2nd order corrections using IGS TEC values and igrf2011 magnetic field model) not effective</td>
<td>none</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>Satellite system</td>
<td>Centre of mass / Phase centre vector from macro model + attitude law No phase law applied</td>
<td>Centre of mass offsets / Phase centre corrections from file: igs08_<a href="http://www.atx">www.atx</a></td>
<td>Centre of mass corrections from G. Appleby</td>
<td>Centre of mass corrections from G. Appleby</td>
<td>Centre of mass corrections from G. Appleby</td>
</tr>
<tr>
<td>Elevation cut-off</td>
<td>12 degrees Down weighting law for elevation &lt;= 20 deg; Weight of the observation is multiplied by the factor elevation**2/400 with elevation in degrees</td>
<td>10 degrees</td>
<td>10 degrees</td>
<td>12 degrees</td>
<td>12 degrees</td>
</tr>
</tbody>
</table>
## Parameterizations for the COL campaign

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Parameters to be estimated</th>
<th>Initial values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole, UT1-UTC or UT1-TAI</td>
<td>XPO, YPO, UT : PWL @ {00, 03, 06, 09, 12, 15, 18, 21, 24} hr</td>
<td>IERS EOP 08-C04 (tables available on the Forum Multi-technic Combination <a href="http://grgs.obspm.fr/forum/">http://grgs.obspm.fr/forum/</a>)</td>
</tr>
<tr>
<td>Pole Rate</td>
<td>XPOR, YPOR 1pt/day @ 12hr</td>
<td>Set to 0</td>
</tr>
<tr>
<td>LOD</td>
<td>LOD 1pt/day @ 12hr</td>
<td>Set to 0</td>
</tr>
<tr>
<td>Nutation angles</td>
<td>NUT_X, NUT_Y : PWL @ 0hr corrections to the model IAU2000</td>
<td>IERS EOP 08-C04</td>
</tr>
<tr>
<td>Station coordinates</td>
<td>SX, SY, SZ at mid epoch</td>
<td>ITRF2008</td>
</tr>
<tr>
<td>Radio sources coordinates</td>
<td>RS_RA, RS_DE 1pt/week</td>
<td>ICRF2</td>
</tr>
<tr>
<td>Zenithal Tropospheric Delay Wet component &amp; Horizontal gradients</td>
<td>TROWET @ {00, 02, 04, … 24} hr: Adjustment of the wet component to the model</td>
<td>GPT/GMF model for radio waves &amp; Mendes/Pavlis for optical waves</td>
</tr>
</tbody>
</table>
Combination at the observation level vs. NEq level

Example: Jason2 - 7 day arc over the period: 17/8/2008 – 23/8/2008

<table>
<thead>
<tr>
<th>Technique</th>
<th>Nb of observ.</th>
<th>Residuals</th>
<th>Orbit # rms</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLR</td>
<td>2216/224</td>
<td>4.1cm</td>
<td>12.1cm</td>
</tr>
<tr>
<td>DORIS</td>
<td>109884/52825</td>
<td>.346mm/s</td>
<td>10.6cm</td>
</tr>
<tr>
<td>SLR + DORIS</td>
<td>2247/193</td>
<td>4.2cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td>109614/53095</td>
<td>.352mm/s</td>
<td></td>
</tr>
</tbody>
</table>

- difference in data editing
- difference in orbits
- almost no difference in ERP

Observation level

\[
\sum \frac{\partial Q_{i}^{\text{calc}}}{\partial p_k} \left( \sum_{j=1}^{n} \frac{\partial Q_{i}^{\text{calc}}}{\partial p_j} \Delta p_j - \Delta Q_i \right) = 0
\]

\( \forall k = 1, n \)

NEq level

\[
\Delta Q_i = Q_{i}^{\text{obs}} - Q_{i}^{\text{calc}} = \sum_{j=1}^{n} \frac{\partial Q_i}{\partial p_j} \Delta p_j
\]
Technique of EOP interpolation

Piece-wise linear Offset+Drift
\(2n\) parameters
no continuity at boundaries
continuity constraints reduce #parameters to \(n+1\)

Piece-wise linear Polygon
\(n+1\) parameters
“real” continuity at boundaries
no continuity constraints needed
not distinguishable from “offset-only” in SINEX

Densified piece-wise linear Polygon
\(4n+1\) parameters
“real” continuity achieved
no continuity constraints needed
not distinguishable from “offset-only” in SINEX
Technique of EOP interpolation

Piece-wise linear **Offset+Drift**
- $2n$ parameters
- no continuity at boundaries
- continuity constraints reduce #parameters to $n+1$

Piece-wise linear **Polygon**
- $(n+1)$ parameters
- “real” continuity at boundaries
- no continuity constraints needed
- not distinguishable from “offset-only” in SINEX

Densified piece-wise linear **Polygon**
- $4n+1$ parameters
- “real” continuity achieved
- linearity conditions by segment
- not distinguishable from “offset-only” in SINEX

Seitz, Thaller - Workshop on Combination on Observation Level, 21./22.10.09, Warsaw
Example of EOP undersampling
GPS - from 6 hr to 1 day

\[
\begin{align*}
P_j(6h) &= \frac{3}{4} P_j(0h) + \frac{1}{4} P_{j+1}(0h) \\
P_j(12h) &= \frac{1}{2} P_j(0h) + \frac{1}{2} P_{j+1}(0h) \\
P_j(18h) &= \frac{1}{4} P_j(0h) + \frac{3}{4} P_{j+1}(0h)
\end{align*}
\]

by linearity constraints:

=> One can densify the EOP parameterization (to 3hr for instance) to be closer to the temporal data distribution (mainly for VLBI) and apply linearity constraints afterwards if needed.
COL FORUM

http://grgs.obspm.fr/forum/

Discussion for GRGS processing

GINS/DYNAMO, Software, Formats...

http://grgs.obspm.fr/forum/

Combinations Series available at http://hpiers.obspm.fr/iers/eop/grgs/

Exchanges with DGFI, ORB, Ukrainian Observatory MAO … For SINEX Matrix
GRGS Solutions EOP, TRF, CRF by multi technique Combination DORIS, GPS, SLR, VLBI at normal equation level, period 2002-2013

Jean-Yves Richard(1), Daniel Gambis(1), Christian Bizouard(1), Sébastien Lambert(1), Olivier Becker(1), Teddy Carlucci(1)
Sylvain Loyer(2), Laurent Soudarin(2), Géraldine Bourda(3), Antoine Bellanger(3), Florent Deleflie(4), David Coulot(4,5), Arnaud Pollet(5), Jean-Michel Lemoine(7), Richard Biancale(7), Jean-Charles Marty(7), Felix Perozanz(7)

(1) Observatoire de Paris - SYRTE – GRGS
(2) CNES / CLS, Toulouse
(3) Observatoire de Bordeaux, LAB
(4) IMCCE – GRGS Paris
(5) IGN – LAREG – GRGS
(7) CNES – OMP – DTP – GRGS Toulouse

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GRGS Solutions EOP, TRF, CRF by multi technique Combination DORIS, GPS, SLR, VLBI at normal equation level, period 2002-2013

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## GRGS Normal Equations: 2002-2013 period

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td><strong>Pole</strong>: PX, PY 1pt/d @12:00</td>
<td><strong>Pole</strong>: PX, PY, UT1-TAI 4pt/d @ 00,06,12,18:00 <strong>Nutation</strong>: NX, NY 2pt/d @ 00, 12:00 <strong>Stations</strong>: SX, SY, SZ 1p/week @ 12:00 <strong>Tropospheric MZB</strong> (Zenith Tropospheric Delay) 12pt/d @ 02h <strong>MGE, MGN</strong> East &amp; North Gradients 1pt/d</td>
<td><strong>Pole</strong>: PX, PY 4pt/d @ 00,06,12,18:00 <strong>UT1-TAI</strong>: PT 4pt/d @ 00,06,12,18:00 <strong>Nutation</strong>: NX, NY 2pt/d @ 00:00, 12:00 <strong>Stations</strong>: SX, SY, SZ 1p/week @12:00 <strong>Station range Bias</strong> MRB 1/w/station</td>
<td><strong>Pole</strong>: PX, PY 4pt/d @ 00,06,12,18:00 <strong>UT1-TAI</strong>: PT 4pt/d @ 00,06,12,18:00 <strong>Nutation</strong>: NX, NY 4pt/d @ 00,06,12,18:00 <strong>Stations</strong>: SX, SY, SZ 1p/week @12:00 <strong>Quasars</strong>: QRA, QDE 1pt/week <strong>Tropospheric zenithal delays</strong> MZB 12pt/d @ 02h (01,03,05,07,09,11,13,15,17,19, 21,23)</td>
</tr>
<tr>
<td><strong>Pole Rates</strong>: PXR, PYR 1pt/d @12:00</td>
<td><strong>Pole Rates</strong>: PXR, PYR 1pt/d @12:00</td>
<td><strong>Pole Rates</strong>: PXR, PYR 1pt/d @12:00</td>
<td><strong>Pole Rates</strong>: PXR, PYR 1pt/d @12:00</td>
</tr>
<tr>
<td><strong>LOD</strong> 1pt/d @12:00</td>
<td><strong>LOD</strong> 1pt/d @12:00</td>
<td><strong>LOD</strong> 1pt/d @12:00</td>
<td><strong>LOD</strong> 1pt/d @12:00</td>
</tr>
<tr>
<td><strong>Stations</strong> coordinates SX, SY, SZ 1pt/d</td>
<td><strong>Stations</strong> coordinates SX, SY, SZ 1pt/week @12:00</td>
<td><strong>Stations</strong> coordinates SX, SY, SZ 1pt/week @12:00</td>
<td><strong>Stations</strong> coordinates SX, SY, SZ 1p/week @12:00</td>
</tr>
</tbody>
</table>

* Added parameters for further studies which are reduced or eliminated for this step of development.
Radiosources estimation versus ICRF2

~100 quasars estimated at weekly bases

RS_RA: Right Ascension corrections versus ICRF2 apriori

RS_DE: Declination corrections versus ICRF2 apriori

2002  12 years  2013

Mean on RS_RA corrections : /mas 0.0343
Mean on RS_DE corrections : /mas 0.1334
RMS on RS_RA corrections : /mas 0.7221
RMS on RS_DE corrections : /mas 0.7907

Non Rotation parameters:
R1 : /mas 0.0982
sigma R1 : /mas 212.7201
R2 : /mas 0.0198
sigma R2 : /mas 186.2675
R3 : /mas 0.1537
sigma R3 : /mas 154.2918
Pole coordinates estimation versus C04 interpolated @12H

Number of daily determination @12H: 4370
Number of redundant dates removed: 413
Any outliers removed

Mean $x_p$ C04 - GRGS (mas) = -0.0294
Mean $y_p$ C04 - GRGS (mas) = -0.0042

RMS difference $x_p$ C04 - GRGS (mas) = 0.0512
RMS difference $y_p$ C04 - GRGS (mas) = 0.0373

Mean UT1 C04 - GRGS ($\mu$s) = -1.9881
RMS difference UT1 C04 - GRGS ($\mu$s) = 26.3918

2002  12 years  2013
UT1 corrections & LOD compared with C04 interpolated @12h

Number of keeping daily UT1: 4369
Number of redundant dates removed: 413, any outliers removed
Mean UT1 C04 - GRGS: /µs -1.9574
RMS difference UT1 C04 - GRGS: /µs 26.282

GRGS LOD from GPS LOD @12h

Qualitatively compared with C04 LOD @0h

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Nutation corrections $dX$, $dY$ versus C04 series interpolated @12h

Number of keeping points: 4369
Number of redondante dates removed: 413
Any outliers removed

Mean $dX$ corrections with C04 apriori: /mas 0.0039
Mean $dY$ corrections with C04 apriori: /mas 0.0195
RMS $dX$ corrections with C04 apriori: /mas 0.3670
RMS $dY$ corrections with C04 apriori: /mas 0.3482

2002 12 years 2013
# Stations for DORIS GPS SLR VLBI techniques

<table>
<thead>
<tr>
<th></th>
<th>DORIS</th>
<th>GNSS</th>
<th>SLR</th>
<th>VLBI</th>
<th>Total</th>
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</thead>
<tbody>
<tr>
<td>Number of Station</td>
<td>50</td>
<td>204</td>
<td>26</td>
<td>14</td>
<td>294</td>
</tr>
<tr>
<td>Observation frequency</td>
<td>Weekly</td>
<td>Daily</td>
<td>Weekly</td>
<td>Per session R1 R4, twice per week</td>
<td>~900 parameters per week</td>
</tr>
<tr>
<td>Processing</td>
<td>Mean equation over each week</td>
<td>SLR stations measured by DORIS satellites are separated to SLR stations measured by SLR satellites</td>
<td>Mean equation over each week</td>
<td>Systematic effects per technique (17) &amp; minimal constraints per techniques (35)</td>
<td></td>
</tr>
</tbody>
</table>

**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 |
### Stations

<table>
<thead>
<tr>
<th>Stations</th>
<th>DORIS Doppler</th>
<th>GNSS 10003M009</th>
<th>SLR 10002S002</th>
<th>VLBI</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRASSE, France</td>
<td>10002S018</td>
<td>10003M009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Toulouse, France</td>
<td>10003S005</td>
<td>10003M009</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reykjavik, Iceland</td>
<td>10202S003</td>
<td>10202S003</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Ny-Alesund, Norway</strong></td>
<td><strong>10317S005</strong></td>
<td><strong>10317M003</strong></td>
<td><strong>10317S003</strong></td>
<td></td>
</tr>
<tr>
<td>Metsahovi, Finland</td>
<td>10503S015</td>
<td>10503M005</td>
<td></td>
<td></td>
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<tr>
<td>Kitab, Uzbekistan</td>
<td>12334S006</td>
<td>12334S006</td>
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<tr>
<td><strong>Bad Koetzting, Germany</strong></td>
<td><strong>14201S009</strong></td>
<td><strong>14201M010</strong></td>
<td><strong>14201S018</strong></td>
<td><strong>14201S004</strong></td>
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<tr>
<td>Wuhan, P.R. China</td>
<td>21602S005</td>
<td>21602S005</td>
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<tr>
<td>Libreville, Gabon</td>
<td>32809S004</td>
<td>32809M002</td>
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<tr>
<td>Algonquin Park, Canada</td>
<td>40104S002</td>
<td>40104S002</td>
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<tr>
<td>Fairbanks, United Stat</td>
<td>40408S005</td>
<td>40408M001</td>
<td></td>
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<tr>
<td><strong>Kokee Park, Waimea, USA</strong></td>
<td><strong>40424S009</strong></td>
<td><strong>40424M004</strong></td>
<td><strong>40424S007</strong></td>
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<td>Westford, USA</td>
<td>40440S020</td>
<td>40440S020</td>
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<tr>
<td>Greenbelt, United Stat</td>
<td>40451S176</td>
<td>40451M123</td>
<td>40451M105</td>
<td></td>
</tr>
<tr>
<td>Laguna Mountains, USA</td>
<td>40497S009</td>
<td>40497M004</td>
<td>40497M001</td>
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<tr>
<td>Ensenada, Mexico</td>
<td>41609S002</td>
<td>40508M002</td>
<td></td>
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<tr>
<td>San Juan, Argentina</td>
<td>41508S003</td>
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<tr>
<td>Fortaleza, Brazil</td>
<td>41602S002</td>
<td>41602S002</td>
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<tr>
<td>Easter Island, Chile</td>
<td>41703S009</td>
<td>41703M007</td>
<td></td>
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<tr>
<td>Santiago, Chile</td>
<td>41705S009</td>
<td>41705M003</td>
<td>41705M003</td>
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<tr>
<td>Concepcion, Chile</td>
<td>41719S002</td>
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<td>41719M001</td>
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<td>Puerto Ayora, Ecuador</td>
<td>42005S001</td>
<td>42005M002</td>
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<td>Lima II, Peru</td>
<td>42202S007</td>
<td>42202S007</td>
<td></td>
<td>42202M003</td>
</tr>
<tr>
<td>Thule Airbase, Greenland</td>
<td>43001S005</td>
<td>43001M002</td>
<td></td>
<td></td>
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<tr>
<td>YARRAGADEE, Australia</td>
<td>50107S011</td>
<td>50107M001</td>
<td></td>
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<tr>
<td>Canberra, Australia</td>
<td>50119S004</td>
<td>50119M001</td>
<td>50119M002</td>
<td>50119S003</td>
</tr>
<tr>
<td>Waitangi, New Zealand</td>
<td>50207S001</td>
<td>50207M001</td>
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<td></td>
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<tr>
<td>Port aux Francais, Ker TAHITI</td>
<td>91201S005</td>
<td>91201M002</td>
<td>92201M007</td>
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<tr>
<td>Antarctic base of Dum</td>
<td>91501S003</td>
<td>91501M001</td>
<td></td>
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<tr>
<td>NOUMEA, FRANCE</td>
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<td>92701M005</td>
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<td></td>
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<tr>
<td>Kourou, French Guyana</td>
<td>97301S004</td>
<td>97301M210</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Le Tampon, France</td>
<td>97401S002</td>
<td>97401M003</td>
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</tr>
</tbody>
</table>

### Selection of 3 stations with commun tropospheric parameters

Station Corrections Ny-Alesund versus ITRF2008 – tropospheric parameters independently estimated

NyAlesund 10317, X corrections

NyAlesund 10317, Y corrections

NyAlesund 10317, Z corrections

Differences DORIS / GNSS
X = 360.6592 m
Y = 1.5310e+03 m
Z = -163.0814 m

RMS 3D DORIS (m) = 0.4385
RMS 3D GNSS (m) = 0.0161
RMS 3D VLBI (m) = 0.0359

RATE DORIS
X = -0.0156 m/y
Y = 0.0073 m/y
Z = 0.0102 m/y

RATE GPS
X = -0.0143 m/y
Y = 0.0082 m/y
Z = 0.011 m/y

RATE VLBI
X = -0.0148 m/y
Y = 0.008 m/y
Z = 0.0109 m/y

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Station corrections Bad-Koetzing versus ITRF2008 – tropospheric parameters independently estimated

Bad Koetzing Station 14201
GPS: 14201M010
SLR: 14201S018
VLBI: 14201S004

Differences between stations
X GNSS / SLR (m) = 3.805
Y GNSS / SLR (m) = 68.205
Z GNSS / SLR (m) = -15.532
X SLR / VLBI (m) = 36.977
Y SLR / VLBI (m) = 50.191
Z SLR / VLBI (m) = -45.801

RMS 3D GNSS (m) = 0.0149
RMS 3D SLR (m) = 0.0464
RMS 3D VLBI (m) = 0.0205

RATE GPS
X = -0.0171 m/y
Y = 0.0173 m/y
Z = 0.009 m/y

RATE SLR
X = -0.0148 m/y
Y = 0.0169 m/y
Z = 0.105 m/y

RATE VLBI
X = -0.0167 m/y
Y = 0.0176 m/y
Z = 0.0101 m/y

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Station Corrections Kokee-Park versus ITRF2008 – tropospheric parameters independently estimated

Kokee Park Station 40424
Differences between
DORIS/GNSS
X (m) = -143.154
Y (m) =  2.627
Z (m) = -328.963

RMS 3D DORIS (m) = 0.3194
RMS 3D GNSS (m)  = 0.0181
RMS 3D VLBI (m)   = 0.0268

RATE DORIS
X = -0.0082 m/y
Y =  0.0604 m/y
Z =  0.0317 m/y

RATE GPS
X = -0.0069 m/y
Y =  0.063 m/y
Z =  0.0344 m/y

RATE VLBI
X = -0.0081 m/y
Y =  0.0632 m/y
Z =  0.0321 m/y
Systematic effects on station networks for DORIS, GNSS, SLR by Laser satellites & by DORIS satellites and VLBI techniques

<table>
<thead>
<tr>
<th>Networks</th>
<th>DORIS</th>
<th>SLR by DORIS satellites</th>
<th>GNSS</th>
<th>SLR by SLR satellites</th>
<th>VLBI</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Rms</td>
<td>Mean</td>
<td>Rms</td>
<td>Mean</td>
</tr>
<tr>
<td>TX (mm)</td>
<td>-2,8</td>
<td>16,0</td>
<td>0,0</td>
<td>3,9</td>
<td>-6,1</td>
</tr>
<tr>
<td>TY (mm)</td>
<td>0,0</td>
<td>16,5</td>
<td>0,0</td>
<td>3,9</td>
<td>-1,2</td>
</tr>
<tr>
<td>TZ (mm)</td>
<td>-1,9</td>
<td>12,4</td>
<td>0,0</td>
<td>6,1</td>
<td>-5,7</td>
</tr>
<tr>
<td>Scale (mm)</td>
<td>2,5</td>
<td>17,0</td>
<td>-2,4</td>
<td>5,4</td>
<td>-1,6</td>
</tr>
</tbody>
</table>

Weekly estimate d over 625 weeks from 2002 January 4th to 2013 December 28th
Transformation parameters for DORIS GNSS SLR VLBI networks 2002-2013 period

<table>
<thead>
<tr>
<th></th>
<th>TX mm</th>
<th>TY mm</th>
<th>TZ mm</th>
<th>Sc mm</th>
<th>RX µas</th>
<th>RY µas</th>
<th>RZ µas</th>
</tr>
</thead>
<tbody>
<tr>
<td>DORIS</td>
<td>-2,0 ± 4,6</td>
<td>0,0 ± 3,7</td>
<td>-2,8 ± 7,2</td>
<td>-3,2 ± 7,1</td>
<td>0,2 ± 2,4</td>
<td>-1,0 ± 3,0</td>
<td>0,0 ± 3,1</td>
</tr>
<tr>
<td>GNSS</td>
<td>-6,3 ± 7,4</td>
<td>-1,1 ± 4,6</td>
<td>-5,5 ± 14,5</td>
<td>-1,7 ± 2,1</td>
<td>-0,07 ± 0,3</td>
<td>-0,4 ± 0,6</td>
<td>-0,2 ± 0,9</td>
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<tr>
<td>SLR</td>
<td>-1,1 ± 3,3</td>
<td>0,2 ± 2,7</td>
<td>-0,2 ± 5,5</td>
<td>4,0 ± 5,6</td>
<td>0,7 ± 2,8</td>
<td>-0,9 ± 2,8</td>
<td>-0,3 ± 4,2</td>
</tr>
<tr>
<td>VLBI</td>
<td>-4,0 ± 11,7</td>
<td>3,8 ± 12,2</td>
<td>1,6 ± 5,9</td>
<td>3,1 ± 7,8</td>
<td>2,8 ± 10,5</td>
<td>1,7 ± 8,6</td>
<td>0,8 ± 5,4</td>
</tr>
</tbody>
</table>
Conclusion

Method
• Algorithms developed to process DORIS GNSS SLR and VLBI techniques are usable to perform combination
• Weekly Normal Equations combined over 2002-2013 are generated in Sinex format and delivery to IGN for analysis and comparison with ITRF2014 realization

Results
• Quasars positions simultaneously estimated with stations coordinates at the weekly bases shows a discrepancy of about 700 µas versus ICRF2.
• Pole compared to C04: rms(xp_corr)=51µas, rms(yp_corr)=37µas shows an annual periodic term
• UT versus C04: rms(UT_corr)=26µs & LOD is comparable to C04
• Nutation issue meanly from VLBI shows a large discrepancy versus C04 due to nutation format every 12h introduced into GRGS VLBI
• Station coordinates shows annual periodic variations versus ITRF2008 apriori & discrepancies at a cm level have to compare with other realization (IVS, IGS, ILRS, IDS)
• Systematic effects exhibits annual oscillation for all techniques at 1.5 cm level for DORIS, 5mm level for SLR by DORIS satellites, 1.4cm for Z components of GNSS, 1cm level for SLR by SLR satellites and 2.6 cm for scale factor of VLBI network
• Transformation parameters show large discrepancy for VLBI on translations and rotations at 5cm level during the 2008-2010 period, annual oscillation on translations for GNSS network at 6mm level for TX and TZ, 1mm for TY, scale factor for SLR is at a level of 4mm with 6mm of discrepancy

Further investments
• Analysis of EOP, CRF and TRF solutions from GRGS combination has to be more deeply performed to conclude on the quality achieved
• Comparison of EOP and Stations solutions with ITRF2014
• Analyses on mutualisation of tropospheric parameters (VLBI, GPS, DORIS) over 2009
• Analyses on mutualisation of orbital parameters for multi-techniques satellites

Communication
• Paper on GRGS multi techniques combination at normal equation level is writing to summarize this development
COL-GRGS communications

- Richard J.Y., Gambis D., R. Biancale, 2010, Combination of Space Geodetic Techniques at the Normal Equation Level, Geophysical Research Abstracts, Vol. 12, EGU2010-2333
- Richard J.Y., Gambis D., Bizouard Ch, 2011, Earth rotation parameters determined over CONT08 VLBI campaign by the GRGS from the combination of space geodetic techniques, in Proc. Journées Systèmes de Référence 2010, N. Capitaine (ed.), pp219-220
- Richard J.-Y., Gambis D., Biancale R., Bizouard C. “Earth rotation parameters determined over CONT08 VLBI campaign by the GRGS from the combination of space geodetic techniques”. REFAG 2010, Poster, Marne La Vallée, Octobre 2010
- Richard J.Y., Gambis D., Multi-Technique Combinations of Geodetic Observations at the level of Normal Equations, IDS Analysis Working Group, Venice, Sept. 2012
- Richard J.Y., Biancal R., Bizouard C., Gambis D., Systematic Effects in Multi-Technique Combination, EGU-2013, Vienne, 7-12 April 2013

Article à referee
Gambis D., Richard J-Y., Biancal R., Bizouard C. Why combining at the Observation Level?, REFAG 2010, IAG series 2013
### Recomended Models for GRGS

<table>
<thead>
<tr>
<th>Category</th>
<th>Details</th>
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</thead>
<tbody>
<tr>
<td><strong>Reference System</strong></td>
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</tr>
<tr>
<td>Earth reference system</td>
<td>IGB08 for GNSS &amp; DORIS, ITRF2008 for SLR VTRF2008 for VLBI</td>
</tr>
<tr>
<td>Celestial reference system</td>
<td>inertial J2000</td>
</tr>
<tr>
<td>Polar motion &amp; UT1</td>
<td>IERS C04 08</td>
</tr>
<tr>
<td>Precession/nutation</td>
<td>IERS 2010 using NRO origin</td>
</tr>
<tr>
<td><strong>Displacement of reference points</strong></td>
<td></td>
</tr>
<tr>
<td>Solid Earth tidal displacement</td>
<td>IERS2010 Conventions</td>
</tr>
<tr>
<td>Tidal ocean loading</td>
<td>FES2012</td>
</tr>
<tr>
<td>Tidal atmospheric loading</td>
<td>S1/S2 Ray &amp; Ponte (2003)</td>
</tr>
<tr>
<td>Non tidal atmospheric loading</td>
<td>none</td>
</tr>
<tr>
<td>Solid pole tide displacement</td>
<td>IERS2010 Conventions</td>
</tr>
<tr>
<td><strong>Gravity</strong></td>
<td></td>
</tr>
<tr>
<td>Gravity field (static)</td>
<td>EIGEN-6S2</td>
</tr>
<tr>
<td>Gravity field (time varying)</td>
<td>EIGEN-6S2 up to degree 12 including time variable terms up to degree 12 (bias &amp; drift per yr from 2002 to 2012, periodic 18.6, 1, 0.5yrs)</td>
</tr>
<tr>
<td>Solid Earth tides</td>
<td>IERS2010 conventions</td>
</tr>
<tr>
<td>Ocean tides</td>
<td>FES 2012 (32 principal waves, + 60 admittance waves) up to degree 12</td>
</tr>
<tr>
<td>Atmospheric gravity</td>
<td>SRI ERA-interim / ECMWF up to degree 12 for GNSS</td>
</tr>
<tr>
<td>Non tidal oceanic gravity</td>
<td>TUGO R12 up to degree 12 for GNSS, 50 for DORIS</td>
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<tr>
<td>Atmospheric tides</td>
<td>none (considered through the ECMWF atmospheric data)</td>
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<td>Earth pole tide</td>
<td>IERS2010 conventions</td>
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<td>Ocean pole tide</td>
<td>Desai 2002 up to degree 12</td>
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<tr>
<td>Third bodies</td>
<td>Sun, Moon, Mars, Venus, Jupiter, Saturn, Uranus and Neptune ephemeris : DE421 (JPL)</td>
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<tr>
<td><strong>Troposphere</strong></td>
<td></td>
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<tr>
<td>Troposphere Model</td>
<td>GPT2/VMF1</td>
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<tr>
<td>Troposphere correction</td>
<td>one zenith delay/2hour (wet tropo scale factor adjusted) + one daily tropospheric gradient per station &amp; per day in North &amp; East directions</td>
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<td><strong>Ionosphere</strong></td>
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<td><strong>Atmospheric drag</strong></td>
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</tr>
<tr>
<td><strong>Relativity</strong></td>
<td></td>
</tr>
</tbody>
</table>

COL meeting frankfurt 2016
Systematic effects estimated on DORIS station network

TX (m) mean amplitude & rms : -0.0028  0.0160
TY (m) mean amplitude & rms : -2.5152e-05  0.0165
TZ (m) mean amplitude & rms : -0.0019  0.0124
SC (m) mean amplitude & rms :  0.0025  0.0170
Systematic effects estimated on SLR station network measured over DORIS satellites

TX (m) mean amplitude & rms : 8.8528e-04  0.0039
TY (m) mean amplitude & rms : 6.6362e-05  0.0039
TZ (m) mean amplitude & rms : -3.2842e-04  0.0061
SC (m) mean amplitude & rms : -0.0024  0.0054

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Systematic effects estimated on GNSS station network

TX (m) mean amplitude & rms : -0.0061 0.0073
TY (m) mean amplitude & rms : -0.0012 0.0048
TZ (m) mean amplitude & rms : -0.0057 0.0143
SC (m) mean amplitude & rms : -0.0016 0.0025
Systematic effects estimated on SLR station network

TX (m) mean amplitude & rms: $-1.7552e-04$ 0.0076
TY (m) mean amplitude & rms: $-4.8732e-05$ 0.0036
TZ (m) mean amplitude & rms: $7.7599e-05$ 0.0059
SC (m) mean amplitude & rms: $-0.0025$ 0.0130
Systematic effects estimated on VLBI station network

SC (m) mean amplitude & rms : -0.0053  0.0258
Transformation parameters for DORIS network over 2002-2013
1) **review the approach of the various groups** and their capability to process two or more techniques.
   AUIB, ASI,, BKG, DGFI, ESOC, GFZ, GRGS, GSFC, TUW

2) **establishing common processing standards** for all techniques in order to guarantee homogeneity and consistency.
   List of recommended models established are established

3) **studying the appropriate weighting between techniques** and the use of local ties or identical satellites tracked by several techniques.
   Tests between fixed and Helmert algorithm are applied for NEQ stacking, DORIS satellites performing doppler and laser measurements are used

4) **optimizing and unifying parameterization** for instance for tropospheric parameters in order to minimize globally the degree of freedom of the whole inverse system.
   Tropospheric parameters are included for DORIS, GNSS and VLBI

5) **elaborating benchmarks** to intercompare results between groups from the same data set.
   Tow period are tested for combination performance evaluation: CONT08 and CON11

6) **insuring SINEX compatibility** between techniques and with the international technique services and IERS.
   File exchanges have been made using the Sinex format 2,1

7) **studying stabilization methods** and looking for high temporal resolution of parameters.
   Earth rotation parameters resolution have been processed every 6h

8) **evaluating and comparing results** to search for compatibility between groups.
   17 meetings

9) **organizing routine operations** for a new TRF realization, either in the framework of the next ITRF or as ITRF assessment.
   Developpment of routines for processing for intra and inter-techniques
Transformation parameters for GNSS network over 2002-2013
Transformation parameters for SLR network over 2002-2013
Transformation parameters for VLBI network over 2002-2013

COL meeting frankfurt 2016
Multi Techniques Combinaison at Normal Equation Level

- Celestial Reference Frame CRF, Terrestrial Reference Frame TRF & Earth Orientation Parameters EOP are estimated by combination of solutions without garanty on the consistency and model between space geodesy technics

- GRGS with the IERS working group on combination « COL » from october 2009, has performed a new approach using inter technique combination at observation level.

- Allow the consistency and homogeneity between techniques which can be processed using the same software with compatible models and similar a priori
- Allow to cancel systematic effect between techniques
- Allow to estimate periodically and simultaneously the geodetic parameters
  - Quasars coordinates
  - Terrestrial Station coordinates & rates
  - Polar motion, Rotation and Nutation
  - Tropospheric bias & gradients
  - Geocentric coordinates and low degree of gravity field

CRF Celestial Reference Frame
TRF Terrestrial Reference Frame
EOP Earth Orientation Parameters
ZTD Zenithal Time Delay
CM, C21, S21 Center of Mass, Stockes Coefficients Order 2

COL meeting frankfurt 2016
## Estimated Parameters to be compared with ITRF2014

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Estimated Parameters</th>
<th>Initial Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pole, UT1- TAI</td>
<td><strong>XPO, YPO, UT</strong>: PWL @ 12Hr (PX, PY into GINS)</td>
<td>IERS EOP 08-C04</td>
</tr>
<tr>
<td>Pole Rate</td>
<td><strong>XPOR, YPOR</strong>: 1pt/day @ 12Hr (PXR, PYR into GINS)</td>
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</tr>
<tr>
<td>LOD</td>
<td><strong>LOD</strong>: 1pt/day @ 12Hr (PTR into GINS)</td>
<td>IERS EOP 08-C04</td>
</tr>
<tr>
<td>Precession/Nutation Corrections</td>
<td><strong>NUT_ X, NUT_ Y</strong>: PWL @ 12Hr IAU2000A/2006 model corrections (dX,dY) (NX, NY dans GINS)</td>
<td>0.0</td>
</tr>
<tr>
<td>Station Coordinates</td>
<td><strong>SX, SY, SZ</strong>: 1 pt/week</td>
<td>ITRF2008</td>
</tr>
<tr>
<td>Radio sources Coordinates</td>
<td><strong>RS_RA, RS_DE</strong>: 1pt/week (QRA, QDE into GINS)</td>
<td>ICRF2</td>
</tr>
</tbody>
</table>

### 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
Normal Equation Pre-processing per techniques

- **Intra techniques**
  - NEQ Reduction: keeping EOP, Stations, Quasars, Tropospheric parameters, orbital elements & non gravitational parameters from DORIS satellites
  - Stacking of NEQs at weekly bases, synchronous to the GPS week, for DORIS satellites is applied the weighting Helmert algorithm using EOP as common parameters, for SLR satellites using stations as common parameters, for GNSS satellite constellation stacking is already done at daily bases, for VLBI R1 & R4 session are weekly stacked
  - For daily NEQs daily stations parameters are stacked at weekly bases @ mid epoch
  - Tropospheric parameters bias & gradients are synchronized every 2h interval (01h, 03h,..., 23h) and selected from a list of stations to test their positions when their tropospheric parameters are mutualized
  - For satellite techniques, at beginning of each week UT parameter is forced to the apriori
  - Introduction of stations constraints for systematic technique effects cancellation: transformation parameters (origin & scale for satellite techniques, scale for VLBI technique)
  - Introduction of polar motion constraint to cancel the diurnal retrograde oscillation for sub-daily EOP of DORIS, SLR and VLBI techniques
Combination of Normal Equations @ weekly bases

- Inter techniques
  - Weighted stacking with Helmert algorithm using the common parameters EOP@06:00 for DORIS, Laser from DORIS satellites, SLR and VLBI, Orbital elements, orbital bias and non gravitational forces of DORIS satellites are also stacked
  - Elimination of EOP outside the GPS week by forcing them with their apriori values
  - Whitening technique’s identifiers from tropospheric parameters to stack their equations for colocated stations
  - Daily Linear constraints on EOP corrections @06:00 are introduced to reduce the NEQ to EOP 1pt/d @ 12:00
  - Weighted stacking GPS + (DORIS Doppler, DORIS Laser, SLR and VLBI) by fixed weighting factor 0,99 for GNSS & 0,01 for (DORIS Doppler, DORIS Laser, SLR and VLBI)
  - Whitening blocking the retrograde diurnal oscillation on the pole coordinates to mutualize these parameters
  - Application of Non Rotation on the set of quasars (NNR)
  - Application of Minimal Constraints on core stations for each technique DORIS, GPS, SLR, VLBI (7 Helmert transformation parameters)
Constraints on combined normal équations

To inverse the combined normal equation at weekly bases for EOP, station coordinates with their zenithal tropospheric bias or clock bias and quasar coordinates determination, some constraints are applied:

• Stability constraint on
  ➢ pole coordinates ±10mas on corrections (30cm at the Earth surface)
  ➢ UT ±6.47 ms on corrections (3m at the Earth surface)
  ➢ Nutation ±47nrd (±10mas)
• Blocking the diurnal retrograde oscillation parameters AC, AS, Act, Ast with constraint on their corrections ±1frd
• Stations corrections with a loose constraint ±50m for GNSS, DORIS, VLBI and ±20m for SLR
• Minimal constraints on core stations DORIS VLBI SLR et GNSS with constraints on the final values = 0 ±10cm
• Tropospheric Bias with constraint on the corrections ±10m
• Clock Bias with constraint on corrections ±100µs
• Quasars coordinates with constraint on corrections ±100nrd
• Non rotating parameters on a quasar set NNR ±100nrd
• Corrections on the Center of Mass for DORIS satellites without constraints
Strategy of Multi-technique Combination

DORIS Systematic Effects added Stations constraints
\[ \Phi_{\text{DORIS}} = [T_X T_Y T_Z D_S]^T \]

GNSS Systematic Effects added Stations constraints
\[ \Phi_{\text{GNSS}} = [T_X T_Y T_Z D_S]^T \]

SLR Systematic Effects added Stations constraints
\[ \Phi_{\text{SLR}} = [T_X T_Y T_Z D_S]^T \]

VLBI Systematic Effects added Stations constraints
\[ \Phi_{\text{VLBI}} = [S_c]^T \]

\[ \text{Minimal Constraints} \]
\[ \Phi = [T_X T_Y T_Z D_R R_Y R_Z]^T \]

Core Networks DORIS, GPS, SLR, VLBI

Weekly constrained NEQ Inversion
\[ \delta X = (N)^{-1} \cdot [Y \; \Theta]^T \]

Combined NEQ with constraints
\[ N_{\text{combined}} + N_{c\_Q} + N_{c\_tides} + N_{c\_7CM} = N \]

\[ \text{Solution} \]

\[ \text{Parameters to estimate} \]
Pole coordinates \(x, y\)
Universal time UT1-UT2
Nutation IAU 2000A dx, dy
Stations coordinates
Quasars coordinates
Troposphere: zenithal bias

Technical Systematic effects cancelled for stations

« No Net Rotation » on Quasars
\[ \Phi_{\text{Qpur}} = [R_x R_y R_z]^T \]

EOP, Stations coordinates in combined referential, Transformation parameters Tx Ty Tz D Rx Ry Rz, Zenithal Tropospheric bias, Systematic Effects of each technique, Quasars Coordinates & rotations of celestial frame

COL meeting frankfurt 2016
Combination of techniques at CC DGFI

Manuela Seitz, Detlef Angermann, Mathis Bloßfeld

COL Working Group Meeting
BKG Frankfurt
19. February 2016
Outline

- Intention of the COL WG
- Input data
- CC DGFI combination strategy
- Results intra-technique analysis
- Results of combination
- Summary
Combination of different techniques on the observation level

Pre-requisites:
- Homogenization of different technique-specific software packages used by the 9 Analysis Centers (AC) with respect to applied models and parameterization
- Normal equations resulting from single-technique and combined analysis provided by the AC in SINEX format
- Normal equations should include all common parameters (station coordinates, EOP, troposphere parameters)

→ Combination of the normal equations by the 2 Combination Centres (CC)
Combination of different techniques on the observation level

Pre-requisites:
- Homogenization of different technique-specific software packages used by the 9 Analysis Centers (AC) with respect to applied models and parameterization
- Normal equations resulting from single-technique and combined analysis provided by the AC in SINEX format
- Normal equations should include all common parameters (station coordinates, EOP, troposphere parameters)

→ Combination of the normal equations by the 2 Combination Centres (CC)

All items are widely realized by COL
## Input data

### Data of two time periods (CONT08 and CONT11)

<table>
<thead>
<tr>
<th></th>
<th>AIUB</th>
<th>ASI</th>
<th>DGFI</th>
<th>ESOC</th>
<th>GFZ</th>
<th>GRGS</th>
<th>MAO</th>
<th>OPA</th>
<th>TUW</th>
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<td></td>
<td></td>
<td>n1</td>
<td>n9</td>
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<tr>
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<td>n3</td>
<td>n1</td>
<td>n3</td>
<td></td>
<td>n1/08</td>
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<tr>
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<td></td>
<td></td>
<td></td>
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<td>n1</td>
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<td>n3</td>
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<td></td>
<td>n1/08</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

- 18 different data sets
- 4 pre-combined (combined orbit determination)

*Seitz: Combination at the CC DGFI*
## Input data

### Data of two time periods (CONT08 and CONT11)

<table>
<thead>
<tr>
<th></th>
<th>AIUB</th>
<th>ASI</th>
<th>DGFI</th>
<th>ESOC</th>
<th>GFZ</th>
<th>GRGS</th>
<th>MAO</th>
<th>OPA</th>
<th>TUW</th>
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<tbody>
<tr>
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<td></td>
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<td>n1</td>
<td>n9</td>
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<td>n3</td>
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<td></td>
<td></td>
<td></td>
<td>n1/08</td>
</tr>
</tbody>
</table>

- 18 different data sets / only 9 can be used due to incorrect use of SINEX format or problems with statistical values (ITPI)
- Information about new models and parameterization often missed

*Seitz: Combination at the CC DGFI*
### 9 parameter types for combination

<table>
<thead>
<tr>
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</table>
### Parameterization

#### 9 parameter types for combination / 3 “basic” parameter types

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</tbody>
</table>

For some parameter types parameterization not homogeneous
Combination procedure at DGFI

**Input data**
- GPS weekly NEQ AC 1
- SLR weekly NEQ AC 1
- DORIS weekly NEQ AC 1
- VLBI sess. NEQ AC 1
- SLR+GNSS and SLR+DORIS NEQ

**Weekly combination of different techniques**
- GPS weekly NEQ
- SLR weekly NEQ
- DORIS weekly NEQ
- VLBI sess. NEQ
- SLR+GNSS and SLR+DORIS NEQ

**Datum realization:**
- Origin: SLR
- Scale: SLR+VLBI
- Orientation: NNR w.r.t. DTRF2008

Seitz: Combination at the CC DGFI
Agreement of technique-specific contributions

### GPS: RMS of transformation between AC

<table>
<thead>
<tr>
<th></th>
<th>AIUB (250)</th>
<th>GRGS (120)</th>
<th>GFZ (50)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIUB</td>
<td></td>
<td>5 mm (08)</td>
<td>10-15 mm</td>
</tr>
<tr>
<td>GRGS</td>
<td></td>
<td></td>
<td>10-15 mm</td>
</tr>
</tbody>
</table>

### VLBI: RMS and scale differences w.r.t. combined VLBI

<table>
<thead>
<tr>
<th></th>
<th>RMS [mm]</th>
<th>Scale [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DGFI</td>
<td>1-2 mm</td>
<td>0-1 mm</td>
</tr>
<tr>
<td>TUW</td>
<td>1-3 mm</td>
<td>0-1.4 mm</td>
</tr>
<tr>
<td>OPA (does not contribute to combined solution)</td>
<td>4 (08) – 13 (11) mm</td>
<td>0-7 mm</td>
</tr>
</tbody>
</table>
Agreement of technique-specific contributions

SLR: RMS of transformation w.r.t. combined SLR solution

Between 3 and 10 mm

DORIS: RMS w.r.t. DTRF2008

RMS:
2008: 10-12 mm
2011: 15 mm

Seitz: Combination at the CC DGFI
Combination of all techniques

Internal transformation: Combination w.r.t. single technique

<table>
<thead>
<tr>
<th></th>
<th>translation</th>
<th>scale</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
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</tr>
<tr>
<td>DORIS</td>
<td></td>
<td></td>
<td>10 mm</td>
</tr>
<tr>
<td>SLR</td>
<td>0-7 mm</td>
<td>0-1.5 mm</td>
<td>6 mm</td>
</tr>
<tr>
<td>VLBI</td>
<td>0-1.0 mm</td>
<td></td>
<td>7 mm</td>
</tr>
</tbody>
</table>

- Consistency of scale very high (1.5 mm)
- Realization of origin not better than 7 mm
- RMS (deformation due to combination) between 2mm for GPS and up to 10 mm for DORIS

→ Good agreements. GPS dominates the combination. DORIS slightly worse compared to the other techniques.
Combination of all techniques

External validation of datum realization:
Transformation w.r.t. DTRF2008

<table>
<thead>
<tr>
<th></th>
<th>translation</th>
<th>scale</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>0-6 mm</td>
<td>0-3 mm</td>
<td>4 mm</td>
</tr>
<tr>
<td>DORIS</td>
<td>0-10 mm</td>
<td>5-11 mm</td>
<td>10-20 mm</td>
</tr>
<tr>
<td>SLR</td>
<td>0-10 mm</td>
<td>3 mm</td>
<td>8-17 mm</td>
</tr>
<tr>
<td>VLBI</td>
<td>0-10 mm</td>
<td>0-6 mm</td>
<td>3-9 mm</td>
</tr>
</tbody>
</table>

Translation: 0 - 10 mm (also for SLR)
Scale: 0 – 11 mm (0-6 mm for SLR and VLBI)
RMS (difference in network geometry): 3 – 20 mm

→ Good agreement. In case of DORIS model differences w.r.t.
DTRF2008 (solar radiation pressure, ...)
Summary

Done by COL

– **Combination of 4 different techniques** at the observation level by homogenizing different software packages (common standards)
– **Combined orbit determination** for Jason-2 and some GPS- and GLONASS- Satellites combining SLR, GPS and DORIS observations (done by ESOC and GFZ) → unfortunately not used in final combination by CC due to SINEX format problems
– **Internal agreement** of techniques: 5 – 15 mm
– **External accuracy**:  <= 20 mm

Remaining deficiencies

– Homogenization of software packages not fully done
– Changes in software between iterations often not clearly reported
– Parameterization inhomogeneous (EOP, troposphere) and partly unclear (offset or piece-wise linear?)
– SLR range biases not homogeneous (ILRS list or all stations)
→ discrepancies between contributions are hard to analyze
Outlook

How to go forward?

- Complete homogenization of software packages
- Integration of contributions resulting from combined orbit-determination
- Investigation: What is the benefit for TRF products from the integration of current and potential future space-based combinations?
- Analysis of longer data series

→ GRASP or E-GRASP/Erathostenes will provide the opportunity for a high-precise space-based combination of all four space geodetic techniques
Thank you for your attention!

Combination of techniques at CC DGFI

Manuela Seitz, Detlef Angermann, Mathis Bloßfeld

COL Working Group Meeting
BKG Frankfurt
19. February 2016