CNES/GRGS gravity field solutions from GRACE: RL03-v2

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Summary

- CNES/GRGS gravity fields from GRACE: RL03-v2
  - Data processing
  - Inversion strategy for monthly models
  - Mean gravity field model generation
  - Extrapolation for orbit processing
  - Model quality
  - Model upgrading strategy
Data processing

GRACE (L-1B “Version2” data)
- K-Band Range-Rate data ($\sigma_{\text{apriori}} = .1 \, \mu m$)
- Accelerometer / attitude / thrusters data
- **GPS data** (1-day arcs, $\sigma_{\text{code}} = .8 \, m$, $\sigma_{\text{phase}} = 20 \, mm / 30s \, \text{resolution}$)
  (actually: $\sigma_{2002-2003} = 8 \, mm/30 \, s$, $\sigma_{2003-2013} = 20 \, mm/300 \, s$, $\sigma_{2013-2015} = 8 \, mm/30 \, s$)

SLR
- Lageos1/2 data (10-day arcs, $\sigma_{\text{apriori}} = 6 \, mm$)
- **Starlette/Stella data** (5-day arcs, $\sigma_{\text{apriori}} = 10 \, mm$)

Physical parameters present in the normal equations
- Gravity spherical harmonic coefficients complete to degree and order 175 (truncated to 30 for LAGEOS and **40 for GPS** data)
- Ocean tides s. h. coefficients for 14 tidal waves with maximum degree/order $\leq 30$
Models used (v0 → v2)

### Dynamical models

<table>
<thead>
<tr>
<th>Category</th>
<th>Details</th>
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</thead>
<tbody>
<tr>
<td>Gravity</td>
<td><em>EIGEN-GRGS.RL02</em> → <em>EIGEN-6S2</em></td>
</tr>
<tr>
<td>Ocean tide</td>
<td><em>FES2004 (degree 80)</em> → <em>FES2012 (Legos)</em></td>
</tr>
<tr>
<td>Atmosphere</td>
<td>3-D ECMWF pressure grids / 6hrs → <em>ERA-interim / 3hrs</em></td>
</tr>
<tr>
<td>Ocean mass model</td>
<td><em>MOG2D (non-IB) / 6hrs</em> → <em>TUGO (Legos) / 3hrs</em></td>
</tr>
<tr>
<td>Atmospheric tides</td>
<td>→ <em>Not necessary any more</em></td>
</tr>
<tr>
<td>3rd body</td>
<td><em>Sun, Moon, 6 planets (DE405)</em></td>
</tr>
<tr>
<td>Solid Earth tides</td>
<td><em>IERS Conventions 2010</em></td>
</tr>
<tr>
<td>Pole tides</td>
<td><em>IERS Conventions 2010</em></td>
</tr>
<tr>
<td>Non gravitational</td>
<td><em>Accelerometer data (+biases and scale factors)</em></td>
</tr>
</tbody>
</table>

### Geometrical models

<table>
<thead>
<tr>
<th>Category</th>
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<tbody>
<tr>
<td>SLR stations</td>
<td><em>ITRF2008 coordinates</em> → <em>updated</em></td>
</tr>
<tr>
<td>GPS</td>
<td><em>IGS orbits and CODE clock</em> → <em>IGS Repro-1 orbits and clocks</em></td>
</tr>
</tbody>
</table>

### Other models

<table>
<thead>
<tr>
<th>Category</th>
<th>Details</th>
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<tbody>
<tr>
<td>Hydrology</td>
<td>Taken into account by the a priori gravity field</td>
</tr>
<tr>
<td>Glacial Isostatic Adjustment</td>
<td></td>
</tr>
</tbody>
</table>
**Interest of truncated SVD**

- **Inversion technique used for RL03: truncated Singular Value Decomposition (SVD)**
  - It is more efficient to solve well chosen linear combinations of coefficients (by truncated SVD) than to solve indistinctly the coefficients (by Cholesky decomposition).
  - Demonstration with a normal matrix up to d/o 80:
    1) Solving for the first 2601 components of the canonical basis (i.e. spherical harmonic coefficients up to degree/order 50)
    2) Solving for the first 2601 components of the basis made by the eigenvectors of the normal matrix
1) Cholesky decomposition

Equivalent Water Heights comparison

Cholesky Inversion up to degree and order 50: 2501 parameters

Reference: Mean field

Degree 2 to 60

min -184.81 cm / max 168.34 cm / weighted rms 34.56 cm / oceans 37.61 cm
2) Truncated SVD

Equivalent Water Heights comparison

SVD solution: minimisation in the direction of the 2601 most significant eigenvectors

Reference: Mean field

Degree 2 to 60

min ~206.01 cm / max 58.90 cm / weighted rms 10.72 cm / oceans 6.60 cm
Trying to solve the problems at the poles

Since SVD does not solve sectorial coefficients due to a lack of information, we need to introduce decent a-priori sectorial coefficients before using SVD.

So we tried to establish a 2-step inversion in RL03-v2.

First step: Cholesky inversion with constraints to obtain good sectorial coefficients.

Second step: Truncated SVD inversion starting with the first step solution.

Results

The 2-step inversion improves the solutions mainly at the poles.
Equivalent Water Heights comparison
T36.decade.22S92.0G_ONLY.V1.RELQ3EQ_v1.srd2500.shc
Reference: CHAMP_MOYEN_RE03.par_cuml_EgN_v2

Degree 2 to 60

min -198.94 cm / max 62.61 cm / weighted rms 10.41 cm / oceans 6.21 cm

Equivalent Water Heights (cm)
RL03-v2

Equivalent Water Heights comparison
T36.decade.22992.0.GONLY.VI_RL03EQV1_k18_chol80.svdx2500.shc
Reference: CHAMP_MOYEN_RL03.par_cumul_EQN_v2
Degree 2 to 80
min ~206.60 cm / max 55.46 cm / weighted rms 10.18 cm / oceans 5.66 cm
Mean model generation

- Mean Models generated from time series
  - Fitting each series of monthly coefficients by a set of 6 parameters
  - Used for operational computation (i.e. altimetric orbit processing) or TRF processing (i.e. ITRF2014)
  - In order to better match with GRACE observations, gravity field models have become more complex. They contain now:
    - Yearly bias and slope: piecewise linear function except in case of...
    - Jumps caused by big earthquakes (3 so far: Sumatra, Concepcion and Tohoku)
    - Annual and semi-annual sine/cosine functions (with continuity constraints at hinge epochs)
  
  ... it means 600 000 coefficients for a 80x80 s. h. model
Normalized $S(10,01)$ coefficient

From RL02 10-day series

GRGS RL02 time series
Normalized $S(10,01)$ coefficient

From RL03 monthly series
From RL03-v2 mean model with bias, drift per year, annual and semi-annual periodic terms per year
Mean gravity field models

The links below give access to the models. For a description of how the models are built, go to the tabs "Release 01", "Release 02" or "Release 03".

Associated with Release 03:

- **EIGEN-GRGS.RL03.MEAN-FIELD** (based on 28 years of LAGEOS data, 10 years of GRACE data and 3 years of GOCE data)
- **Reference field_for_RL03-v1_grids**: The geoid and EWH grids and images are computed by difference of the RL03-v1 solutions to a static reference mean field, which is an arbitrary reference. In the case of the RL03-v1 grids and images, we have used Reference_field_for_RL03-v1_grids. This static mean field is close to the actual value of the Earth’s gravity field at the date 2008.0

- **EIGEN-GRGS.RL03-v2.MEAN-FIELD** (based on 28 years of LAGEOS data, 12 years of GRACE data and 3 years of GOCE data)
- **EIGEN-GRGS.RL03-v2.MEAN-FIELD.mean_slope_extrapolation** (identical to EIGEN-GRGS.RL03-v2.MEAN-FIELD, except that the null slope on extrapolation is replaced by the average slope of the signal over the period 2003.0 - 2014.0)

Associated with Release 02:

- **EIGEN-GRGS.RL02.MEAN-FIELD** (based on 4.5 years of data)
- **EIGEN-GRGS.RL02bis.MEAN-FIELD** (update based on 8 years of data)
- **EIGEN-6S2** (proposal for ITRF2013 standards)
- **EIGEN-6S2.extended** (this field is no longer available, there was an error in the TVG part for the years 2012-2013. It is replaced by EIGEN-6S2.extended.v2)
- **EIGEN-6S2.extended.v2** (same as EIGEN-6S2, except that the TVG part has been extended to end of 2013 for the needs of the ITRF2013 computation)

Associated with Release 01:

- **EIGEN_GL04S**
- **EIGEN_GL04S_ANNUAL**
- **EIGEN_GL04C**
FIRST EIGEN_03series.v2.PWL_PER_ANN.mean_slope.dg_300

CMMT Extrapolation = mean slopes over 2003.0 - 2014.0

EARTH 0.3986004415E+15 0.6378136460E+07
SHM 300 300 2.00 fully normalized exclusive permanent tide

G_BIAS 2 0 -0.484165442874E-03 0.000000000000E+00 1.3920E-11 0.0000E+00 19500101.0000 19850101.1751 yynn
GDRIFT 2 0 0.000000000000E+00 0.000000000000E+00 0.0000E+00 0.0000E+00 19500101.0000 19850101.1751 mnnn

G_BIAS 2 0 -0.484165442874E-03 0.000000000000E+00 1.3920E-11 0.0000E+00 19850101.1751 19860101.0000 yynn
GDRIFT 2 0 0.124657017393E-10 0.000000000000E+00 2.2600E-11 0.0000E+00 19850101.1751 19860101.0000 yynn

GCOS1A 2 0 0.387007395388E-10 0.000000000000E+00 0.1117E-11 0.0000E+00 19500101.0000 20030101.0000 yynn
GSIN1A 2 0 0.591814852349E-10 0.000000000000E+00 0.1101E-11 0.0000E+00 19500101.0000 20030101.0000 yynn
GCOS2A 2 0 0.393538776211E-10 0.000000000000E+00 0.1017E-11 0.0000E+00 19500101.0000 20030101.0000 yynn
GSIN2A 2 0 -0.219462790927E-10 0.000000000000E+00 0.1044E-11 0.0000E+00 19500101.0000 20030101.0000 yynn

GCOS1A 2 0 -0.484165227624E-03 0.000000000000E+00 0.2330E-10 0.0000E+00 20030101.0000 20040101.0000 yynn
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GCOS2A 2 0 -0.384911295545E-10 0.000000000000E+00 0.1098E-10 0.0000E+00 20030101.0000 20040101.0000 yynn
GSIN2A 2 0 -0.722385315629E-10 0.000000000000E+00 0.1354E-10 0.0000E+00 20030101.0000 20040101.0000 yynn
GCOS2A 2 0 -0.766906872209E-11 0.000000000000E+00 0.8906E-11 0.0000E+00 20030101.0000 20040101.0000 yynn
GSIN2A 2 0 -0.313633906172E-10 0.000000000000E+00 0.1522E-10 0.0000E+00 20030101.0000 20040101.0000 yynn

GCOS1A 2 0 -0.484165276861E-03 0.000000000000E+00 0.1476E-10 0.0000E+00 20040101.0000 20050101.0000 yynn
GSIN1A 2 0 -0.772123828542E-10 0.000000000000E+00 0.2719E-10 0.0000E+00 20040101.0000 20050101.0000 yynn
GCOS2A 2 0 -0.446978163033E-10 0.000000000000E+00 0.4782E-10 0.0000E+00 20040101.0000 20050101.0000 yynn
GSIN2A 2 0 -0.331550995538E-10 0.000000000000E+00 0.9492E-10 0.0000E+00 20040101.0000 20050101.0000 yynn
GCOS2A 2 0 -0.103868129375E-11 0.000000000000E+00 0.4411E-11 0.0000E+00 20040101.0000 20050101.0000 yynn
GSIN2A 2 0 -0.159947020906E-10 0.000000000000E+00 0.6033E-11 0.0000E+00 20040101.0000 20050101.0000 yynn

GCOS1A 2 0 -0.484165332544E-03 0.000000000000E+00 0.1854E-09 0.0000E+00 20140615.0917 20150630.0000 yynn
GSIN1A 2 0 -1.147311624901E-10 0.000000000000E+00 0.4825E-11 0.0000E+00 20140615.0917 20150630.0000 yynn
GCOS2A 2 0 -0.322262028125E-10 0.000000000000E+00 0.2667E-11 0.0000E+00 20140615.0917 20150630.0000 yynn
GSIN2A 2 0 -0.480638590637E-10 0.000000000000E+00 0.2981E-11 0.0000E+00 20140615.0917 20150630.0000 yynn
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GSIN2A 2 0 -0.174442524168E-10 0.000000000000E+00 0.2777E-11 0.0000E+00 20140615.0917 20150630.0000 yynn
J2 behaviour

- J2 monthly variations are extended from 1986 till now
  - From LAGEOS, Starlette and Stella data
  - Need to be consistent with the 18.6 yrs ocean tide model
    055.565 (Om1): $C_{20}^+ = 0.5406 \text{ cm}$, $\epsilon_{20}^+ = 270 \text{ deg}$.

- www.thegraceplotter.com
Coefficient extrapolation

- **Extrapolated coefficients**
  - Mean drift, mean annual and semi-annual periodic terms from the first (backward) and last (forward) determined biases
  - Before 1986 for 2-degree terms determined from Lageos data
  - Before August 2002 for all other terms up to degree/order 80
  - After April 2015 until presently for all terms

*S(10,1) within the GRACE period*  
*S(10,1) outside the GRACE period*  

_Continuity constraints applied_
The new RL03-v2 model reduces the geographically correlated radial orbit drift rate, from more than 1 mm/yr (for the RL02bis mean model) to less than 0.6 mm/y over ~7 years, with respect to Jason-2 GDR-E reduced-dynamic orbits (from GPS+DORIS).

Jason-2 SLR residuals:
- RL02: 1.36 cm rms
- RL03-v2: 1.29 cm rms
- RL03-v2 + C31 adjusted: 1.27 cm rms

Radial orbit drift rate
Scale: -1 / +1 mm/yr [A. Couhert & al., 2015]
**Perspectives**

- **Next RL03-v3 model**
  - Improving the inversion process (Cholesky + SVD in a 2-step procedure)
  - Adapting the relative weights (between GPS and KBR)
  - Using more satellite data (Starlette, Stella, Jason)
  - Increasing the temporal resolution (back to 10-days?)
  - Using improved dealiasing models such as ocean tides (FES2014)
Delivery strategy

- Mean models could be updated each year:
  - RL03-v3 should be ready for the end of the year
  - The mean RL02-v3 model will contain extrapolated terms from mid-2015
  - The completion (with adjusted terms) from 2015 till mid-2016 can be expected for end 2016
  - Updated mean models could be delivered annually at the end of year