EGSIEM

European Gravity Service for Improved Emergency Management

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Processing Standards

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Prepared by: U. Meyer

Name	Author(s)	Date	ID
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1. Introduction

This technical note serves as a record of the processing standards, models and parameters adopted for the generation of the GRACE level 2 products by EGSIEM.

In the frame of EGSIEM monthly and daily near real time Earth gravity fields are computed by the associated processing centers (AC). The monthly solutions of the different ACs are combined on the level of normal equations (NEQ).

All ACs depend on the same input data (Sect. 4.2):

- CODE GPS orbits, Earth orientation parameters (EOPs) and clock-corrections,
- GRACE L1B-RL02: KBR, ACC, SCA, GPS (or kinematic orbits derived thereof).

The processing standards concerning reference frame (Sect. 2.2) and Earth orientation (Sect. 2.3) are defined by the GPS orbits, EOPs and clock-corrections. Each AC has to follow these specifications. Errors introduced by the application of these definitions and by the commonly used input data will not be reduced in the combination.

The processing strategies and the background models applied by the different ACs are listed in Sects. 4.1 and 4.3. The processing errors and background model errors are expected to be reduced by the combination (they average out) and a wide variety of approaches and background models therefore is encouraged.

The gravitational corrections due to the different background models are added back to the normal equations prior to combination. They therefore do not afflict the user of the combined products.

The standards of the center for orbit determination in Europe (CODE) orbits and clock-corrections (Arnold, et al., 2015) and descriptions of the approaches and gravity field solutions of several of the ACs are available in detail in dedicated documents and articles (Beutler, Jäggi, Mervart, & Meyer, 2010a) (Beutler, Jäggi, Mervart, & Meyer, 2010b) (Bruinsma, Lemoine, Biancale, & Valès, 2010) (Mayer-Gürr, Eicker, Kurtenbach, & Ilk, 2010) (Meyer, Jäggi, & Beutler, 2012). It is not the goal of this document to duplicate these or the IERS conventions (McCarthy, 1996) (McCarthy & Petit, 2004) (McCarthy & Petit, 2010) in full detail, but to give a concise overview of all relevant information and to fix common requirements where necessary. For further information we refer to the specific documents.

2. GPS Orbits and Clocks

To guarantee the best possible consistency between ACs, all gravity field computations are based on the same GPS orbits, Earth rotation parameters (ERPs) and clock-corrections. Depending on the different latencies of near real time solutions or monthly solutions, different input products have to be used.

Near real time solutions use: CODE rapid products

GPS orbits	
format	SP3
sampling	15 min
latency	17 h
EOPs	
format	IERS
latency	17 h
GPS clock corrections	
format	Clock RINEX
sampling	30 s
latency	17 h

Monthly solutions use:

GPS orbits	t.b.d.
format	SP3
sampling	15 min
latency	t.b.d.
EOPs	t.b.d.
format	IERS
latency	t.b.d.
GPS clock corrections	t.b.d.
format	Clock RINEX
sampling	5 s
latency	t.b.d.

All CODE products will be published at the EGSIEM project website: http://egsiem.eu/

The CODE GNSS orbits and clocks have been generated from a rigorous combination of GPS and GLONASS to guarantee the best possible consistency. They have been computed in an uninterrupted precise orbit determination (POD) for all transmitting global navigation satellite systems (GNSS) and are regularly validated using satellite laser ranging (SLR) data. The processing details can be found in ftp://ftp.unibe.ch/aiub/CODE/0000_CODE.ACN

2.1 Time System

Different time systems are used in the computation of gravity models from GRACE observations. The GRACE-L1B data are given in GPS time. The integration of the equations of motion of the GRACE satellites takes place in TAI, TT or TGPS and for the computation of Earth orientation UT1 is used.

Fundamental time system	TAI
Orbit integration	TT = TAI + 32.184s
Intermediate products	UTC = TAI - n1 (leap seconds, IERS2010)
Earth orientation	UT1 = UTC + corrections
Tabular corrections	IERS EOP 08 C04
Diurnal tidal variations	IERS2010, Tab. 8.2a,b and 8.3a,b
Libration corrections	IAU2000[1], Tab. 5.1b
GRACE observations	TGPS = TAI – 19s

TDB: Barycentric Dynamical Time.

TT: Terrestrial Time which would be observed by an atomic clock on the geoid. It differs from TDB only by periodic terms (from relativity theory).

TAI: International Atomic Time realized by weighted mean of atomic clocks. TAI has a constant offset to TT of -32.184 s (TAI = TT – 32.184 s).

TGPS: Time realized by the GPS system. GPS time has a constant offset to TAI of -19 s (TGPS = TAI – 19 s).

UTC: The Universal Time Coordinated is on one hand kept synchronous with TAI and on the other hand it is kept to follow the actual angular rate of the Earth by introducing leap seconds within small bounds.

UT1: Universal Time corresponding to mean solar time corrected for polar motion of the observing station (including tidal variations). It represents the actual phase angle of the rotating Earth. The difference between UT1 and UTC is provided by the IERS.

GMST: Greenwich Mean Sidereal Time represents the mean angle of a terrestrial meridian with respect to the vernal equinox.

GST: Greenwich apparent Sidereal Time corresponds to GMST but corrected for nutation.

[1] http://hpiers.obspm.fr/eop-pc/index.html

2.2 Reference frame

The reference frame of the GRACE gravity field solutions is defined via the GPS orbits and clock-corrections used for the determination of the kinematic GRACE orbits.

Time argument	TT, TGPS
Inertial frame	Geocentric; mean equator and equinox of 2000 Jan 1 at 12:00 (J2000.0)
Terrestrial frame	ITRF2008 (Altamimi, Collilieux, & Métivier, 2011), realized through IGb08

2.3 Earth Orientation

The connection between inertial and terrestrial reference frame is via a rotation depending on the actual phase angle of the rotating Earth (UT1), polar motion, precession and nutation.

Precession	IAU2000
Nutation	IAU2000R06
High-frequency nutation	IERS2010, Tab. 5.1a
Mean pole	IERS2010

The X- and Y-pole coordinates and drifts are estimated during the GNSS POD together with length of day (LOD), UT1 is fixed to IERS EOP 08 C04[2]. They are fully consistent with the orbits and clock-corrections. For consistency these EOPs have to be used.

[2] http://www.iers.org/IERS/EN/DataProducts/EarthOrientationData/eop.html

2.4 GPS orbit dynamics

The GPS orbit dynamics are of interest for all ACs that either directly use the GRACE GPS observations, or determine their own GRACE kinematic orbits from the GPS observations. They have to fit or interpolate the CODE GPS orbits (given at 15 minute intervals) to the GRACE observation epochs. The needed consistency is at a level of a few milimeters. Important is the consistency in the orbit positions, not the orbit dynamics.

The GRACE orbit dynamics are in the responsibility of the individual ACs and the applied corrections will be added to the a priori values of the static geopotential field in the normal equations to enable combinability of the NEQs of different ACs. Consistency with the GPS orbit dynamics is ensured for 3rd bodies and relativistic effects.

Geopotential	EGM2008 (Pavlis, Holmes, Kenyon, & Factor, 2008)
l_{max}	12
a_E	6378136.3 m
GM	3.986004415E+14 m^3/s^2
Oean tides	FES2004 (Lyard, Lefevre, Letellier, & Francis, 2006)
l_{max}	8
Solid Earth tides	IERS2010
Earth pole tide	IERS2010
Ocean pole tide	IERS2010 (Desai): C21, S21
3rd bodies	Point masses : Sun, moon, 8 planets ; indirect J2
Planetary ephemerides	DE 421
Relativistic effects	
Dynamical correction	IERS2010 eq. 10.12, Lense-Thirring, de Sitter
Gravitational time delay	IERS2010 eq. 11.17
Orbit parameters	6 initial elements 9 emp. solar radiation pressure par. every 24h: D0, D2, D4, Y0, B0, B1 (Arnold, et al., 2015) stochastic pulses at noon for all satellites
Solar radiation model	
Earth shadow model	Cylindrical shadow
Earth albedo	According to (Rodriguez-Solano, Hugentobler, & Steigenberger, 2012)
Moon shadow model	Umbra and penumbra
Satellite attitude	Nominal
Antenna Thrust	http://acc.igs.org/orbits/thrust-power.txt
Satellite antenna phase center corrections	IGS08.ATX[3]
Satellite clock corrections	2nd order relativistic correction for non-zero orbit ellipticity (-2*R*V/c)

[3] http://igscb.jpl.nasa.gov/igscb/station/general/igs08.atx

RHC phase rotation corr.	Phase polarization effects applied (Wu, Wu, Hajj, Bertiger, & Lichten, 1993)

3. Geometrical Models

The geometry of the GRACE satellites and the definition of the satellite reference frame (SRF) are treated in the GRACE Product Specification Document (Bettadpur, 2012). The antenna phase center offsets of the GPS antennas and the geometrical offsets of the K-Band antennas are stated in the GRACE L1B VGN1B- and VKB1B-products (RL02). The geometric antenna offsets of the GPS antennas coincide with the given L1 phase center values.

	GRACE A	GRACE B
GPS antenna offset		
L1 L2	-0.40/-0.40/-451.42 mm -0.40/-0.40/-475.65 mm	0.60/0.75/-451.73 mm 0.60/0.75/-475.96 mm
K-Band antenna offset	1445.12/-0.42/2.28 mm	1444.39/0.58/3.30 mm

Additionally to the geometric GPS navigation antenna offset and phase center offsets (PCO), phase center variations (PCV) may be estimated. These are treated AC specific and are listed in Sect. 4.2.

The K-Band antenna offset mapped to the line-of-sight between both GRACE-satellites is available as KBR antenna phase center range correction in the KBR1B-files. The value given above is only needed, if the mapped values are recomputed by the ACs (as is the case when attitude data different from the official L1B SCA data is used).

4. AC specific Standards

In this section the processing strategies and the background models applied by the different ACs are detailed. The processing errors and background model errors are expected to be reduced by the combination (they average out) and a wide variety of approaches and background models therefore is encouraged.

The gravitational corrections due to the different background models are added back to the normal equations prior to combination. They therefore do not afflict the user of the combined products.

4.1 Processing strategy and Parametrization

Each AC applies its own, individual approach to process the GRACE data. Approaches differ by the used observable, the parametrization, the noise model applied and the relative weighting of the different observables. But all approaches should provide free solutions, i.e., solutions that do not depend on an a priori gravity model. This is important to avoid biases in the solutions. If all solutions are unbiased, then the strengths and weaknesses of the different solutions are expected to average out in the combination and the combined solution is statistically better and more robust.

	AIUB
Method	Dynamic approach: Celestial Mechanics Approach. All parameters are determined in one common adjustment.
Arc length kinematic orbits	24 h
Arc length K-Band	24 h
Data screening	Manual exclusion on the basis of pre-fit-residuals.
Instrument/empirical parameters	
K-Band	none
ACC	Bias per arc in local orbital frame (r/a/c) Scale per arc in r/a/c 1/rev per arc in r/a/c Polynomial of degree 3 per arc in along-track
Empirical	Piecewise constant every 15 min in r/a/c, constrained to 0 by 3e-9 m/(s*s)
Relative weighting GPS/KRR	1E-10 (constant for whole mission)

	GFZ
Method	Dynamical approach, a-priori calibration parameters adjusted iteratively. Final estimates in common adjustment with gravity field.
Arc length GPS	24 h or less (minimum 3h)
Arc length K-Band	24 h or less (minimum 3h)
Data screening	Automated, threshold based outlier detection (8 σ) for K-Band.
Empirical/instrument parameters	
K-Band	Rang-rate bias every 90 min, Range-rate drift every 90 min, sin- and cos of range bias (180 min)
ACC	Bias every 3 h in X_{SRF}, Y_{SRF}, Z_{SRF} Scale every 3 h in X_{SRF}, Y_{SRF}, Z_{SRF}
Empirical	Only in first screening run (K-Band

	downweighted): sin and cos terms 1/rev every 288 min
Relative weighting GPS/KRR	GPS code: 70 cm GPS phase: 0.7 cm KRR: 0.1 µm/s

	GRGS
Method	Dynamic approach, gravity field partials are computed after orbit convergence (one normal equation per arc)
Arc length GPS	24 h or less (minimum 6h)
Arc length K-Band	24 h or less (minimum 6 h)
Data screening	Dynamic 7 σ editing
Empirical/instrument parameters	
K-Band	Antenna phase offset correction
ACC	2 bias per 24 h in X_{SRF}, Y_{SRF}, Z_{SRF} 1 scale per 24 h in X_{SRF}, Y_{SRF}, Z_{SRF}
Empirical	1/rev and 2/rev per revolution in along-track and cross-track
Relative weighting GPS/KRR	GPS: 8 mm KRR: 0.1 µm/s with cos(lat) weighting

	TUG
Method	Short-arc approach, all parameters determined in one common adjustment.
Arc length kinematic orbits	24 h
Arc length K-Band	24 h
Data screening	None, observation weights (1 h patches) determined by variance component estimation
Empirical/instrument parameters	
K-Band	Monhtly antenna center variations
ACC	Polynomial of degree 3 per 24 h in X_{SRF}, Y_{SRF}, Z_{SRF} One set of scalefactors per 24 h in X_{SRF}, Y_{SRF}, Z_{SRF}
Empirical	
Additional parameters	Daily gravity field variations from degree 2 to 40, constrained
Relative weighting GPS/KRR	determined by variance component estimation for 1 h batches

	ULux
Method	Acceleration approach: Ulux variant, all parameters determined in one common adjustment.

Arc length kinematic orbits	Data dependent
Arc length K-Band	90 min
Data screening	3-sigma limits on pre-fit residuals
Empirical/instrument parameters	
K-Band	Constant, drift, 1/rev.
ACC	Bias per 24 h in X_{SRF}, Y_{SRF}, Z_{SRF}
Empirical	Piecewise constant every 15 min. in r/a/c
	Constrained to 0 by 1e-8 m/(s*s)
Relative weighting GPS/KRR	1E-10 (constant for whole mission)

4.2 Input Data and Corrections

Each AC basically depends on the same set of input data. Depending on the approach range-rate or range-acceleration data is used. Differences arise in the application of geometric corrections that may either be estimated or used as given in the L1B data. The GRACE GPS observations are not processed at each of the ACs individually. Kinematic orbits may be used instead without loss of accuracy (both approaches are equivalent, if complete covariance information is taken into account). Errors introduced by the input data will not be reduced in the combination

	AIUB
GRACE data	L1B-RL02
ACC	1 s
ATT	5 s
KBR	5 s, range-rates, no correlations considered
Light-time-correction	Applied, from KBR1B-file
K-Band attitude correction	Applied, from KBR1B-file
Kinematic orbits	
GPS	30 s, undifferenced
GPS phase center offset	L1: 1.49/0.60/-7.01 mm L2: 0.96/0.86/22.29 mm
GPS phase center variations	Estimated from reduced dynamic orbits

	GFZ
GRACE data	L1B-RL02
ACC	5 s
ATT	5 s
KBR	5 s, range-rates, no correlations considered
Light-time-correction	Applied, from KBR1B-file
K-Band attitude correction	Applied, from KBR1B-file
Kinematic orbits	
GPS	30 s, undifferenced, elevation cutoff 10°
GPS phase center variations	Estimated based on GPS residuals

	GRGS
GRACE data	L1B-RL02
ACC	1 s
ATT	5 s
KBR	5 s, range-rates, no correlations considered
Light-time-correction	Applied, from KBR1B-file
K-Band attitude correction	Applied, recomputed
Kinematic orbits	

GPS	30 s, undifferenced, elevation cutoff 10°
GPS phase center variations	Applied

	TUG
GRACE data	L1B-RL02
ACC	5 s
ATT	5 s, combination of star cameras and ACC angular accelerations
KBR	5 s, range-rates, empirical error covariance function estimated (correlation length 1 h)
Light-time-correction	Applied, from KBR1B-file
K-Band attitude correction	Estimated
Kinematic orbits	
GPS	300 s, undifferenced
GPS phase center variations	Estimated

	ULux
GRACE data	L1B-RL02
ACC	5 s
ATT	5 s
KBR	5 s, range-accelerations, no correlations considered
Light-time-correction	Applied, from KBR1B-file
K-Band attitude correction	Applied, from KBR1B-file
Kinematic orbits	TUG kinematic orbits (see there)

4.3 Background Models

This section refers to a priori models of gravitational forces that are either needed for the sake of linearization (a priori static or time-variable Earth gravity model), are well known (tides) or are of a very local or short-periodic nature and therefore not well modelled by the monthly gravity field solutions (e.g., non-tidal atmosphere and ocean variations). The background models are not free of errors. It is expected that these errors will at least partly average out in the combination and a wide variety of background models therefore is welcome. To facilitate the combination of the different solutions the effect of the background models on the spherical harmonic coefficients of the gravity field is added back to the normal equations prior to combination.

	AIUB
A priori gravity model	AIUB-GRACE03S, GRACE only
l_{max}	160
a_E	6378137.0 m
GM	3.986004415E+14 m^3/s^2
A priori time variations	Not applied
Ocean tides	EOT11a[4] (transformed to SHC by TMG)
l_{max}	100
Additional tides	M_{tm}, M_{sqm}: FES2004 (Lyard, Lefevre, Letellier, & Francis, 2006) $\Omega_{1,2}$, Sa, Ssa: HW95 (Hartmann & Wenzel, 1995)
Admittances	Applied, interpolated linearily (interpolation coefficients provided by TUG)
Atmosphere tides	none
Non-tidal Atmosphere and Ocean variations	AOD1B-RL05 (Flechtner, 2014)
l_{max}	100
Solid Earth tides	IERS2010
Planetary ephemerides	DE 421
Earth pole tide	IERS2010
Ocean pole tide	Desai
l_{max}	100

	GFZ
A priori gravity model	EIGEN-6C (Förste, et al., 2011), combined model
l_{max}	200
a_E	6378136.46 m
GM	3.986004415E+14 m^3/s^2
A priori time variations	Included in EIGEN-6C

[4] ftp://ftp.dgfi.badw.de/pub/EOT11a/

l_{max} trend	50
l_{max} annual	50
l_{max} semiannual	50
Ocean tides	EOT11a (transformed to SHC by TMG)
l_{max}	80
Additional tides	M_{tm}, M_{sqm}: FES2004 $\Omega_{1,2}$, Sa, Ssa: HW95
Admittances	Applied, interpolated linearily
Atmosphere tides	According to (Biancale & Bode, 2006)
Non-tidal Atmosphere and Ocean variations	AOD1B-RL05 S_2 removed
l_{max}	100
Solid Earth tides	IERS2010
Planetary ephemerides	DE 421
Earth pole tide	IERS2010
Ocean pole tide	Desai
l_{max}	30

	GRGS
A priori gravity model	EIGEN_from_RL02
l_{max}	180
a_E	6378136.46 m
GM	3.986004415E+14
A priori time variations	
l_{max} trend	From regression on CNES/GRGS RL02
l_{max} annual	From regression on CNES/GRGS RL02
l_{max} semiannual	From regression on CNES/GRGS RL02
Ocean tides	FES2012[5]
l_{max}	100
Additional tides	$\Omega_{1,2}$, Sa, Ssa: equilibrium
Admittances	Applied, interpolated
Atmosphere tides	none
Non-tidal Atmosphere and Ocean variations	3-hourly ERA-interim & TUGO
l_{max}	100
Solid Earth tides	IERS2010
Planetary ephemerides	DE 421
Earth pole tide	IERS2010
Ocean pole tide	Desai
l_{max}	100

	TUG

[5] http://www.aviso.altimetry.fr/en/data/products/auxiliary-products/global-tide-fes/description-fes2012.html

A priori gravity model	ITSG-GRACE2014k (Mayer-Gürr, Zehentner, Klinger, & Kvas, 2014)
l_{max}	200
a_E	6378137.0 m
GM	3.986004415E+14 m^3/s^2
A priori time variations	
l_{max} trend	120
l_{max} annual	120
Ocean tides	EOT11a
l_{max}	100
Additional tides	M_{tm}, M_{sqm}: FES2004 $\Omega_{1,2}$, Sa, Ssa: HW95
Admittances	Applied, interpolated linearily
Atmosphere tides	According to (Biancale & Bode, 2006)
Non-tidal Atmosphere and Ocean variations	AOD1B-RL05
l_{max}	100
Solid Earth tides	IERS2010
Planetary ephemerides	DE 421
Earth pole tide	IERS2010
Ocean pole tide	Desai
l_{max}	120

	ULux
A priori gravity model	Ulux-CHAMP2013s
l_{max}	90
a_E	6378136.3 m
GM	3.986004415E+14 m^3/s^2
A priori time variations	Not applied
Ocean tides	EOT11a
l_{max}	120
Additional tides	M_{tm}, M_{sqm}: FES2004 $\Omega_{1,2}$, Sa, Ssa: HW95
Admittances	Applied, interpolated linearily
Atmosphere tides	N1 model (GFZ)
Non-tidal Atmosphere and Ocean variations	AOD1B-RL05
l_{max}	100
Solid Earth tides	IERS2010
Planetary ephemerides	DE 421
Earth pole tide	IERS2010
Ocean pole tide	Desai
l_{max}	120

4.4 Orbit Dynamics

Listed here are gravitational forces due to celestial bodies and corrections due to relativistic effects that are not added back to the normal equations (because they are not given in the form of spherical harmonic coefficients). These corrections are harmonized between all ACs.

3rd bodies	Point masses: Sun, moon, 8 planets; indirect J2
Planetary ephemerides	DE 421
Relativistic effects	IERS2010, incl. Lense-Thirring and de Sitter

Note that all surface forces on the GRACE satellites are recorded by the onboard accelerometers and no models for air drag, solar radiation pressure, or albedo have to be applied.

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6. Glossary

AC	Associated processing Center
ACC	GRACE ACCelerometer data
CMC	Center of Mass Correction
CODE	Center for Orbit Determination in Europe
CoM	Center of Mass
DE405	JPL Development Ephemerides
EGSIEM	European Gravity Service for Improved Emergency Management
EOP	Earth Orientation Parameters
ERP	Earth Rotation Parameters
GNSS	Global Navigation Satellit System
GPS	Global Positioning System
GMST	Greenwich Mean Sidereal Time
GRACE	Gravity Recovery and Climate Experiment
GST	Greenwich Sidereal Time
IAU	International Astronomical Union
ICRF	International Celestial Reference Frame
IERS	International Earth rotation and Reference system Service
ITRF	International Terrestrial Reference Frame
KBR	GRACE K_Band Range, range-rate and range-acceleration data
LoD	Length of Day
NEQ	Normal Equation
PCO	Phase Center Offset
PCV	Phase Center Variations
POD	Precise Orbit Determination
SCA	GRACE Star CAmera data
SLR	Satellite Laser Ranging
SRF	Satellite Reference Frame
TAI	International Atomic Time
TDB	Barycentric Dynamical Time
TGPS	GPS Time
TT	Terrestrial Time
UT1	Universal Time
UTC	Universal Time Coordinated

7. End of document