Action Acronym: **COST-G**
Action full title: Combination Service for time-variable gravity fields

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COST-G-RL01
Release Notes

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1. Purpose

This technical note provides information on the combination approach and on the contributions of the individual COST-G Analysis Centers (ACs) and Partern Analysis Centers (PCs). The background models applied by the different ACs are listed in detail.

2. Combination approach

The monthly gravity fields are combined on the solution level. Relative weights are derived by Variance Component Estimation (VCE) on the solution level (Jean, Meyer, & Jäggi, 2018). Prior to combination, the diverse meanpole models of the individual solutions are harmonized to be consistent with the linear IERS2020 (McCarthy & Petit, 2010) v1.2 model. No background models are added back prior to combination.

The ACs provide monthly means of the atmosphere and ocean de-aliasing products used. These monthly means serve to derive combined GAC-products applying the weights used for the combination of the monthly gravity fields. The combined GAC-products serve to approximately restore full (non-tidal) signal content of the combined monthly gravity fields.

3. Individual contributions

COST-G RL01 is a combination of the following time-series:

- AIUB-RL02 (Beutler, Jäggi, Mervart, & Meyer, 2010a) (Beutler, Jäggi, Mervart, & Meyer, 2010b) (Meyer, Jäggi, & Beutler, 2012) (Meyer U. , Jäggi, Jean, & Beutler, 2016)
- CSR-RL06 (Bettadpur, 2018)
- GFZ-RL06 (Dahle, et al., 2019a) (Dahle, et al., 2019b)
- GRGS-RL04 (Bruinsma, Lemoine, Biancale, & Valès, 2010) (free inversion of the unconstrained normal equations)
- ITSG-Grace 2018 (Mayer-Gürr, Eicker, Kurtenbach, & Ilk, 2010) (Klinger & Mayer-Gürr, 2016) (Ellmer, 2018) (Mayer-Gürr, et al., 2018) (Kvas, et al., 2019) (Kvas & Mayer-Gürr, 2019)

3.1 GPS Orbits and Clocks

3.1.1 AIUB

GPS orbits	CODE
format	SP3
sampling	15 min
EOPs	CODE
format	IERS
GPS clock corrections	CODE
format	Clock RINEX
sampling	5 s

The CODE GNSS orbits and clocks have been generated from a rigorous combination of GPS and GLONASS to guarantee the best possible consistency. The processing details can be found in ftp://ftp.unibe.ch/aiub/CODE/0000_CODE.ACN

3.1.2 GFZ

GPS orbits	GFZ
format	SP3
sampling	30 s
EOPs	IERS-EOP14C04/Bulletin A/Bulletin B
GPS clock corrections	
sampling	30 s

3.1.3 GRGS

GPS orbits	JPL / CODE
format	SP3
sampling	30 s / 900 s
GPS clock corrections	
sampling	30 s / 5 s

3.1.4 ITSG

GPS orbits	CODE
format	SP3
sampling	15 min
EOPs	IERS-EOP14C04/Bulletin A/Bulletin B
GPS clock corrections	CODE

format	Clock RINEX
sampling	5 s

3.2 Reference frame

Time argument	TT, TGPS (all but GRGS)
Inertial frame	Geocentric; mean equator and equinox of 2000 Jan 1 at 12:00 (J2000.0)
Terrestrial frame	As defined by the GPS constellations used.

3.2.1 AIUB

GPS constellations	CODE
Terrestrial frame	IGb08

3.2.2 GFZ

GPS constellations	GFZ
Terrestrial frame	IGS14

3.2.3 ITSG

GPS constellations	Code
Terrestrial frame	IGS14

3.2.4 GRGS

Time argument	TAI
Inertial frame	Geocentric; mean equator and equinox of 2000 Jan 1 at 12:00 (J2000.0)
Terrestrial frame	As defined by the GPS constellations used.

GPS constellations	GRGS
Terrestrial frame	IGb08

3.3 Earth Orientation

3.3.1 AIUB

Mean Pole	IERS2010

In the case of CODE GPS constellations, 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[1]. They are fully consistent with the orbits and clock-corrections and have to be used together.

3.3.2 GFZ

Mean Pole	IERS2010 v1.2: linear model

3.3.3 GRGS

Mean Pole	IERS2010

3.3.4 ITSG

Mean Pole	IERS2010 v1.2: linear model

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

3.4 GPS orbit dynamics

3.4.1 CODE

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[2]
Satellite clock corrections	2nd order relativistic correction for non-zero orbit ellipticity (-2*R*V/c)
RHC phase rotation corr.	Phase polarization effects applied (Wu, Wu, Hajj, Bertiger, & Lichten, 1993)

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

3.4.2 GFZ

Geopotential	EIGEN-6C4 (Förste, et al., 2011), combined model
l_{max}	12
a_E	6378136.46 m
GM	3.986004415E+14 m^3/s^2
Oean tides	FES2014
l_{max}	12
Solid Earth tides	IERS2010
Earth pole tide	IERS2010
Ocean pole tide	IERS2010 (Desai)
3rd bodies	Point masses : Sun, moon, 8 planets ; indirect J2
Planetary ephemerides	DE 430
Relativistic effects	
Dynamical correction	IERS2010, incl. Lense-Thirring and de Sitter
Orbit parameters Empirical parameters (per arc and satellite)	6 initial elements per satellite Sin and Cos 1/rev terms in T and N, solar radiation model scaling factor, solar radiation model biases in y and z
Solar radiation model	ROCK 4
Attitude model and windup correction	applied
Satellite antenna phase center corrections	IGS14.ATX
Ground station parameters	station coordinates in x, y and z, 10 troposhpere scaling factors (per station and arc)
GPS phase ambiguities	integer fixed

3.5 Processing strategy and parametrization

3.5.1 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.
Empirical/instrument 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)

3.5.2 GFZ

Method	Dynamical approach, non-gravitational 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	KBR: manual GPS: automted
Empirical/instrument parameters	
K-Band	none
ACC In case of single ACC solutions	Bias 3 per arc in R, T; 9 per arc in N; minimum spacing 3 hours Scale 1 per arc in R, T, N Full 3x3 scale factor matrix
Empirical accelerations	sin and cos terms 1/rev estimated once per rev in T and N constraint: a priori sigma 1E-8 m/s^2
Relative weighting GPS/KRR	Screening: GPS code: 40 cm GPS phase: 0.3 cm KRR: 0.3 µm/s Gravity field estimation: Arc-specific, based on prefit residual RMS (GPS down-weighted by a factor of 7).

3.5.3 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 recomputd once per day in Y and Z; range correction replaced by own value
GPS	PCO 0.44 m -> 0.414 m New PCV consistent with new PCO
ACC	2 biases per revolution in X_{SRF}, Y_{SRF}, Z_{SRF} 1 scale per 24 h in X_{SRF}, Y_{SRF}, Z_{SRF}
Relative weighting GPS/KRR	GPS: 20 mm KRR: 0.1 µm/s with cos(lat) weighting

3.5.4 ITSG

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	Gross outlier detection (threshold based), observation weights (3 h patches) determined by variance component estimation
Empirical/instrument parameters	
K-Band	Monhtly antenna center variations in y and z (Horwath, Lemoine, Biancale, & Bourgogne, 2011)
ACC	Cubic splines with 6h node interval per 24 h in X_{SRF}, Y_{SRF}, Z_{SRF} One 3x3 full scale factor matrix (Klinger & Mayer-Gürr, 2016) per 24 h
Additional parameters	Daily gravity field variations from degree 2 to 40, constrained
Relative weighting GPS/KRR	determined by variance component estimation for 3 h batches (Kvas & Mayer-Gürr, 2019)

3.6 Input Data and Corrections

3.6.1 AIUB

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
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

3.6.2 GFZ

GRACE data	L1B-RL02 (GPS, ACC), L1B-RL03 (KBR, SCA)
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
GPS	30 s, undifferenced
GPS phase center variations	Estimated from residuals (code and phase)

3.6.3 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 from estimated positions
GPS	30 s, undifferenced, elevation cutoff 10°
GPS phase center variations	Estimated

3.6.4 ITSG

GRACE data	L1B-RL03
ACC	5 s
ATT	5 s
KBR	5 s, range-rates, empirical error covariance function estimated (correlation length 3 h)
Light-time-correction	Applied, from KBR1B-file
K-Band attitude correction	Estimated
Kinematic orbits	
GPS	300 s, undifferenced
GPS phase center variations	Estimated (Zehentner & Mayer-Gürr, 2016)

3.7 Background Models

3.7.1 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[3] (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 linearly (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
3rd bodies	Point masses: Sun, moon, 8 planets; indirect J2
Planetary ephemerides	DE 421
Relativistic effects	IERS2010, incl. Lense-Thirring and de Sitter

3.7.2 GFZ

A priori gravity model	EIGEN-6C4 (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	GFZ-RL05a, DDK1 filtered (only screening)
Ocean tides	FES2014
l_{max}	100
Atmosphere tides	According to (Biancale & Bode, 2006)
Non-tidal Atmosphere and Ocean variations	AOD1B-RL06 (Dobslaw, et al., 2017)

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

l_{max}	180
Solid Earth tides	IERS2010
Planetary ephemerides	DE 430
Earth pole tide	IERS2010
Ocean pole tide	Desai
l_{max}	30
3rd bodies	Point masses: Sun, moon, 8 planets; indirect J2
Planetary ephemerides	DE 430
Relativistic effects	IERS2010, incl. Lense-Thirring and de Sitter

3.7.3 GRGS

A priori gravity model	EIGEN-GRGS-RL04 (TVG up to 90), static part from GOCE
l_{max}	200
a_E	6378136.46 m
GM	3.986004415E+14
Ocean tides	FES2014
l_{max}	80
Atmosphere tides	none
Non-tidal Atmosphere and Ocean variations	3-hourly ERA-interim & TUGO
l_{max}	80
Solid Earth tides	IERS2010
Planetary ephemerides	DE 421
Earth pole tide	IERS2010
Ocean pole tide	Desai
l_{max}	100
3rd bodies	Point masses: Sun, moon, 8 planets; indirect J2
Planetary ephemerides	DE 421
Relativistic effects	IERS2010, incl. Lense-Thirring and de Sitter

3.7.4 ITSG

A priori gravity model	Current: internal GRACE/GOCE combination with secular annual variations
l_{max}	280
a_E	6378136.3 m
GM	3.986004415E+14 m^3/s^2
A priori time variations	
l_{max} trend	120
l_{max} annual	120
Ocean tides	FES2014b

l_{max}	180
Additional tides	Constrained GRACE estimates
Admittances	Applied, linear regression through each frequency band
Atmosphere tides	AOD1B-RL06
Non-tidal Atmosphere and Ocean variations	AOD1B-RL06, sub-monthly hydrology from LSDM
l_{max}	180
Solid Earth tides	IERS2010
Planetary ephemerides	DE 421
Earth pole tide	IERS2010
Ocean pole tide	Desai 2002/2004
l_{max}	120
3rd bodies	Point masses: Sun, moon, 8 planets; indirect J2
Planetary ephemerides	DE 421
Relativistic effects	IERS2010, incl. Lense-Thirring and de Sitter

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5. Glossary

AC	Associated processing Center
ACC	GRACE ACCelerometer data
CODE	Center for Orbit Determination in Europe
DE405	JPL Development Ephemerides
EOP	Earth Orientation Parameters
GNSS	Global Navigation Satellit System
GPS	Global Positioning System
GRACE	Gravity Recovery and Climate Experiment
IERS	International Earth rotation and Reference system Service
ITRF	International Terrestrial Reference Frame
KBR	GRACE K-Band Range, range-rate and range-acceleration data
KRR	K-Band Range-Rate data
LoD	Length of Day
L1B	Level 1B
PCO	Phase Center Offset
PCV	Phase Center Variations
POD	Precise Orbit Determination
RINEX	Receiver Independent Exchange format
SCA	GRACE Star CAmera data
SLR	Satellite Laser Ranging
SRF	Satellite Reference Frame
TGPS	GPS Time
TT	Terrestrial Time
UT1	Universal Time
VCE	Variance Component Estimation

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