COST-G

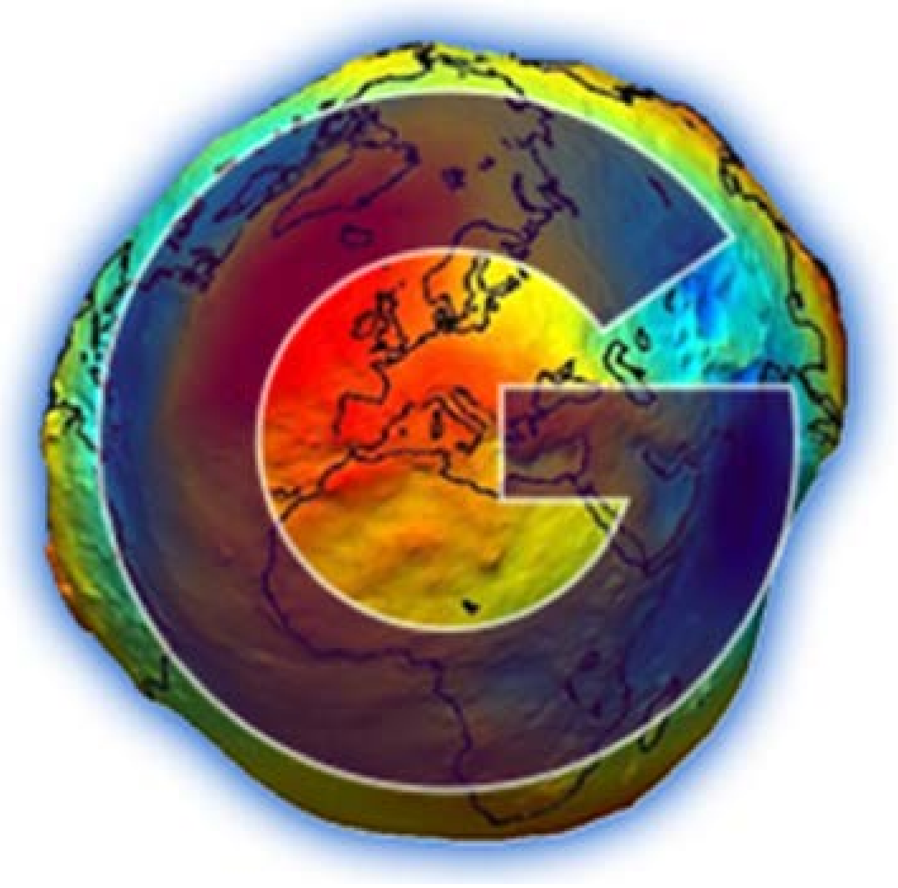
International Association of Geodesy
IAG
IGFS

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

---

COST-G
Processing Standards

Date: 14/02/2020



Prepared by: U. Meyer

<u>**Name**</u>	<u>**Author(s)**</u>	<u>**Date**</u>	<u>**ID**</u>
Processing Standards	UM	02.05.2018	
Individual AC content	UM	16.01.2019	
<u>**Full signal combination**</u>	<u>**UM**</u>	<u>**14.02.2020**</u>	

Table of Contents

1. Purpose

This technical note provides definitions and requirements for the GRACE(-FO) level 2 products that are combined by COST-G.

2. Definitions and Standards

In the frame of COST-G monthly Earth gravity fields that were computed by the COST-G Analysis Centers (ACs) and partner ACs are combined on the level of either spherical harmonic coefficients (SHC) of the gravity field (Jean, Meyer, & Jäggi, 2018) or normal equations (NEQs) thereof (Meyer, et al., 2019).

All ACs depend on the same types of input data:

- GPS constellations, Earth orientation parameters (EOPs) and GPS satellite clock-corrections,
- GRACE(-FO) L1B data: KBR, LRI, ACC, SCA, GPS (or kinematic orbits derived thereof).

The processing standards concerning reference frame and Earth orientation are defined by the GPS constellations, EOPs and clock-corrections used. Errors introduced by commonly used input data will not be reduced in the combination.

All ACs provide monthly gravity field solutions and/or NEQs and the monthly means of all background models that are needed to restore full signal content, i.e.:

- Solid Earth tide
- Ocean tides
- Atmosphere and ocean dealiasing
- Pole tide
- Ocean pole tide
- other, e.g. hydrology, glaciology, GIA, … if applied.

The monthly gravity fields are provided in the ICGEM format (.gfc), NEQs containing only gravity field parameters are provided in the SINEX format. The monthly means of background models may be provided in either ICGEM or AOD-format (GAC). GRACE-FO gravity fields for operational combination have to be provided within 3 months latency.

The monthly means of the background models serve to reconstruct full signal content of the individual gravity fields prior to combination. After combination, a well-defined set of monthly means is removed again to ensure consistency with the gravity field definition as adapted by the GRACE/GRACE-FO Science Data System (SDS):

- Solid Earth tide: IERS conventions 2010 (McCarthy & Petit, 2010)
- Ocean tides: FES2014b
- Atmosphere + ocean: AOD1B RL06 (Dobslaw, et al., 2017)
- Pole tide: IERS conventions 2010, linear pole (v1.2)
- Ocean pole tide: Desai 2004, IERS conventions 2010, linear pole (v1.2)

For each COST-G release of combined gravity fields the processing strategies and background models applied by the different ACs are listed in the corresponding release notes. These models are not free of errors, background model errors include:

- Errors in ocean variability (tidal or non-tidal)
- Errors in atmospheric variability (tidal or non-tidal)
- Errors in solid-Earth tidal variability
- Errors in pole-tide (solid Earth and oceans)

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.

Monthly solutions have to be free, i.e., non-regularized, because regularization may cause undesired bias of signal content. Regularized solutions are therefore not accepted for combination. This holds for explicit regularization as well as for implicit regularization.

It is not the goal of this document or the release notes to duplicate the existing literature on releases of monthly gravity fields or the IERS conventions 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.

3. Time System

Different time systems are used in the computation of gravity models from GRACE(-FO) observations. The GRACE(-FO)-L1B data are given in GPS time. The integration of the equations of motion of the GRACE(-FO) 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

4. GPS Orbits and Clocks

Every AC is free to use the GPS orbits, clock corrections and EOPs of its choice.

5. GPS Orbit Dynamics

The GPS orbit dynamics are of interest for all ACs that either directly use the GRACE(-FO) GPS observations, or determine their own GRACE(-FO) kinematic orbits from the GPS observations. In this case ACs have to fit or interpolate the GPS orbits to the GRACE(-FO) 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.

6. Reference Frame

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

7. 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

The **Mean Pole** model may be choosen individually by the individual ACs and has to be reported to COST-G. It is harmonized prior to combination by a posteriori corrections to C_{21} and S_{21}.

8. Geometrical Model

The geometry of the GRACE(-FO) satellites and the definition of the satellite reference frame (SRF) are treated in the GRACE Product Specification Document (Bettadpur, 2012) and in the GRACE-FO Level-1 Data Product User Handbook (Wen, et al., 2019). The antenna phase center offsets of the GPS antennas and the geometrical offsets of the K-Band antennas are stated in the GRACE(-FO) L1B VGN1B- and VKB1B-products. The geometric antenna offsets of the GPS antennas coincide with the given L1 phase center values. ACs are enrouraged to use these values.

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 the release notes.

The K-Band antenna offset mapped to the line-of-sight between both GRACE(-FO)-satellites is available as KBR antenna phase center range correction in the KBR1B-files.

9. Processing Strategy and Parametrization

Each AC applies its own, individual approach to process the GRACE(-FO) data. Approaches differ by the used observables, 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.

10. Input Data and Corrections

Each AC basically depends on the same set of input data. Differences arise in the application of geometric corrections that may either be estimated or used as given in the L1B data. The GRACE(-FO) 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). The use of dynamic orbits as pseudo-observations should be avoided due to the regularization effect of the a priori gravity field model the dynamic orbits are based upon. Errors introduced by common input data will not be reduced in the combination.

11. 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 or de-aliasing 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.

Monthly means of all background models that are available in spherical harmonics have to be provided by the individual ACs to be restored by the Analysis Center Coordinator (ACC) prior to combination. This is necessary not to bias the combination. Gravitational forces due to celestial bodies and corrections due to relativistic effects should be handled consistently by all ACs.

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

12. Bibliography

Bettadpur, S. (2012). *GRACE Product Specification Document, Rev. 4.6.* GRACE 327-720.

Dobslaw, H., Bergmann-Wolf, I., Dill, R., Poropat, L., Thomas, M., Dahle, C., . . . Flechtner, F. (2017). A new high-resolution model of non-tidal atmosphere and ocean mass variability for de-aliasing of satellite gravity observations: AOD1B RL06 . *Geophysical Journal International (211:1)*, 263-269.

Jean, Y., Meyer, U., & Jäggi, A. (2018). Combination of GRACE monthly gravity field solutions from different processing strategies. *Journal of Geodesy (92)*, 1313-1328.

McCarthy, D., & Petit, G. (2010). *IERS Conventions (2010), IERS Technical Note No. 36.* Frankfurt am Main: Verlag des Bundesamtes für Kartographie und Geodäsie.

Meyer, U., Jean, Y., Kvas, A., Dahle, C., Lemoine, J.-M., & Jäggi, A. (2019). Combination of GRACE monthly gravity fields on the normal equation level. *Journal of geodesy (93)*, 1645-1658.

Wen, h. Y., Kruizinga, G., Paik, M., Landerer, F., W., B., Sakumura, C., . . . Mccullough, C. (2019). *Gravity Recovery and Climate Experiment Follow-On (GRACE-FO) Level-1 Data Product User Handbook.* Pasadena: NASA Jet Propulsion Laboratory, California Institute of Technology.

13. Glossary

AC	Associated processing Center
ACC	GRACE ACCelerometer data
AOD	Atmosphere-/Ocean-Dealiasing
EOP	Earth Orientation Parameters
GIA	Global Isostatic Adjustment
GPS	Global Positioning System
GMST	Greenwich Mean Sidereal Time
GRACE(-FO)	Gravity Recovery and Climate Experiment (Follow On)
GST	Greenwich Sidereal Time
IAU	International Astronomical Union
ICGEM	International Center for Global Earth Models
IERS	International Earth rotation and Reference system Service
KBR	GRACE K_Band Range, range-rate and range-acceleration data
LRI	Laser Ranging Interferometer
L1B	Level 1B
NEQ	Normal Equation
PCO	Phase Center Offset
PCV	Phase Center Variations
SCA	GRACE Star CAmera data
SDS	Science Data System
SHC	Spherical Harmonic Coefficients
SINEX	Solution INdependent EXchange format
TAI	International Atomic Time
TDB	Barycentric Dynamical Time
TGPS	GPS Time
TT	Terrestrial Time
UT1	Universal Time
UTC	Universal Time Coordinated

14. End of document