Multi-approach gravity field models from Swarm GPS data

TN-01: Standards and Background Models

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Astronomical Institute of the University of Bern (AIUB)
Astronomical Institute Ondřejov (ASU)
Institute of Geodesy Graz (IfG)
Ohio State University (OSU)

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Version history

Version 1, 2017-10-29

- Initial release.

Version 1A, 2017-11-12

- Version numbering is now adhering to the DISC conventions;
- Added logos of Swarm and DISC to the cover page;
- Added section on the dissemination of data, specifically what concerns packaging, in Section 7.2;
- Added version history;
- Added document version to the header;
- Corrected naming convention of the deliverables, in Section 5.1;
- Added the naming convention of the version numbers, in Section 6.1.

Version 1B, 2017-11-16

- Modified the format of the Kinematic Orbits, in Section 6.2;
- Minor typographical corrections in the bibliography.

Version 1D, 2018-1-19

- Added the format description, naming convention and directory locations for the non-gravitational accelerations;
- Fixed typo at the bottom of the title page.

Version 1D, 2018-1-22

- Added the format description, naming convention and directory locations for the GPS data weights.

1 Introduction

The objective of this document is to address Task 1. According to the Statement of Work (SoW), this task includes the following activities (cf. Section 4.2.1.2 in that document):

1. Description of Swarm specific adaptations of the gravity field processors
2. Adapt gravity field processors to Swarm L1 products
3. Description of standards and background models
4. Implement GRACE and GRACE-FO standards in gravity field processor

This document pertains mostly to point 3, as presented in Section 4. Points 2, 3 and 4 have already been completed by all partners, as demonstrated by Jäggi et al. (2016) (for AIUB), Bezděk et al. (2016) (for ASU), Zehentner and Mayer-Gürr (2016) (for IfG) and Shang et al. (2017) (for OSU). Unlike what is specified in point 4, all partners adhere to European Gravity Service for Improved Emergency Management (EGSIEM) data standards, cf. Section 6.

Section 2 compares the processing of the Kinematic Orbits (KOs) for TU Delft, AIUB and IfG. Section 3 illustrates a few details of the Kinematic Baselines (KBs) for TU Delft and AIUB. Finally, Sections 5, 6 and 7 describes the file name conventions, data formats and directory structure of the data exchange server (respectively), used in the project activities.

2 Kinematic Orbits

2.1 Delft University of Technology

Software:	GPS High precision Orbit determination Software Tool (GHOST) (Helleputte 2004; Wermuth, Montenbruck and Helleputte 2010)
Differencing Scheme:	Undifferenced
Linear combination:	Ionosphere-free
GPS observations:	Code and carrier phase
Estimator:	Bayesian weighted Least-Squares (LS)
Arc length:	30 hours
Data weighting:	a-priori weights equal to 1m and 1mm for code and phase observations (resp.)
Transmitter PCV:	IGS08.atx model (Schmid et al., 2007)
Receiver PCV:	Empirical, derived from 70 days of data
Data screening:	minimum Signal-to-Noise Ratio (SNR) of 10, minimum of 6 GPS satellites, code and phase outlier editing threshold of 2 m and 3.5 cm, respectively, 1 meter or larger difference between estimated KO positions and with Reduced-Dynamic Precise Science Orbit (PSO)
Earth precession model:	International Astronomical Union (IAU) 1976 (Lieske et al., 1977)
Earth nutation model:	IAU 1980 (Seidelmann, 1982)
Earth orientation model:	Centre for Orbit Determination in Europe (CODE) final Earth Rotation Parameters (ERP)

2.2 Astronomical Institute of the University of Bern

Software:	Bernese v5.3 (Dach et al., 2015; Jäggi, Hugentobler and Beutler, 2006)
Differencing Scheme:	Undifferenced
Linear combination:	Ionosphere-free
GPS observations:	Carrier phase
Estimator:	Batch LS
Arc length:	24 hours
Data weighting:	N/A
Transmitter PCV:	Official IGS08 ANTEX up to day 17/028, official IGS14 ANTEX from day 17/029 on
Receiver PCV:	Stacking of residuals from reduced-dynamic Precise Orbit Determination (POD) of approx. 120 days, 9 iterations, 1° binning
Data screening:	2 cm/s or larger time-differences of the geometry-free linear combination of L1B GPS carrier phase observations
Earth precession model:	International Earth Rotation Service (IERS) 2010 Conventions (Petit and Luzum, 2010)
Earth nutation model:	IERS 2010 Conventions (Petit and Luzum, 2010)
Earth orientation model:	CODE final ERP

2.3 Institute of Geodesy Graz

Software:	Gravity Recovery Object Oriented Programming System (GROOPS)
Differencing Scheme:	None
Linear combination:	None (the ionospheric influence is co-estimated)

GPS observations:	Code and carrier phase
Estimator:	LS
Arc length:	24 hours
Data weighting:	Elevation and azimuth-dependent, epoch-wise Variance Component Estimation (VCE)
Transmitter PCV:	Empirical, estimated from 5.5 years of data, including data from several Low-Earth Orbit (LEO) missions (Gravity Recovery And Climate Experiment (GRACE), Jason 2 & 3, MetOp-A & -B, Sentinel 3A, Swarm, TanDEM-X, TerraSAR-X) (Zehentner, 2016)
Receiver PCV:	Empirical, spherical harmonics (maximum D/O 60), derived from 38 months of data
Data screening:	Implicit in VCE
Earth precession model:	IAU 2006/2000A precession-nutation model (Petit and Luzum, 2010)
Earth nutation model:	IAU 2006/2000A precession-nutation model (Petit and Luzum, 2010)
Earth orientation model:	IERS Earth Orientation Parameter (EOP) 08 C04 (Petit and Luzum, 2010)

2.4 Common

Carrier phase ambiguities:	Float
Receiver clock corrections:	Co-estimated
Sampling rate:	10 or 1 seconds (depending on L1B GPS data)
Elevation cut-off angle:	0°
GPS orbits and clocks:	Final orbits and 5 seconds clocks of Centre for Orbit Determination in Europe (CODE) (Dach et al. 2017)
Swarm attitude:	L1B attitude data

2.5 Summary

Institute	Software	Reference
AIUB	Bernese v5.3 (Dach et al., 2015; Jäggi, Hugentobler and Beutler, 2006)	Jäggi et al. (2016)
IfG	Gravity Recovery Object Oriented Programming System (GROOPS) (in-house development)	Zehentner and Mayer-Gürr (2016)
TUD	GPS High precision Orbit determination Software Tool (GHOST) (Helleputte 2004; Wermuth, Montenbruck and Helleputte 2010)	IJssel et al. (2015)

Table 1 – Overview of the Kinematic Orbits and the software packages used to estimate them

3 Kinematic Baselines

3.1 Delft University of Technology

Software:	Multiple satellites Orbit Determination using Kalman filtering (MODK) (Barneveld 2012)
Linear combination:	N/A (the ionospheric influence is modelled)
Estimator:	Iterative Extended Kalman Filter (EKF)
Carrier phase ambiguities:	Integer, using the Least-squares Ambiguity De-correlation Adjustment (LAMBDA) (Teunissen 1995) method
Receiver PCV:	Empirical Phase Center Variations (PCVs) and Code Residual Variations (CRVs) maps are estimated a priori for each GPS frequency

3.2 Astronomical Institute of the University of Bern

Software:	Bernese v5.3 (Dach et al., 2015; Jäggi et al., 2007)
Linear combination:	Ionosphere-free
Estimator:	LS
Carrier phase ambiguities:	wide-lane and narrow-lane integer bootstrapping with the Melbourne-Wübbena and the ionosphere-free linear combination, respectively
Receiver PCV:	Empirical

3.3 Common

Differencing Scheme:	Double-differenced
GPS observations:	Code and carrier phase
Carrier phase ambiguities:	Integer

3.4 Summary

Institute	Software	Reference
AIUB	Bernese v5.3 (Dach et al., 2015; Jäggi et al., 2007)	Allende-Alba et al. (2017)
TUD	Multiple satellites Orbit Determination using Kalman filtering (MODK) (Barneveld 2012)	Mao et al. (2017)

Table 2 – Overview of the Kinematic Baselines and the software packages used to estimate them

4 Gravity Field Models

4.1 Astronomical Institute of the University of Bern

Software:	Bernese v5.3 (Dach et al. 2015)
Approach:	Celestial Mechanics Approach (CMA) (Beutler et al. 2010)
Reference GFM:	AIUB GRACE-only static model, version 3 (AIUB-GRACE03S) (Jäggi et al. 2011)
Empirical Parameters:	Daily piecewise-constant, 15 minutes piecewise-constant (constrained)
Drag Model:	None
EARP Model:	None
EIRP Model:	None
Non-tidal Model:	Atmosphere and Ocean De-aliasing Level 1B (AOD1B) product (Flechtner, Schmidt and Meyer 2006; Flechtner 2007; Flechtner 2011)
Ocean Tidal Model:	2011 Empirical Ocean Tide model (EOT11a) (Savcenko and Bosch 2012)
Permanent Tide System:	tide-free

4.2 Astronomical Institute Ondřejov

Software:	(developed in-house)
Approach:	Decorrelated Acceleration Approach (DAA) (Bezděk et al. 2014; Bezděk et al. 2016)
Reference GFM:	ITG GRACE-only static model, 2010 (ITG-GRACE2010s) (Mayer-guerr et al. 2010)
Empirical Parameters:	Daily constant-piecewise
Drag Model:	(US)Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar tmospheric model (NRLMSISE) (Picone et al. 2002)
EARP Model:	Knocke, Ries and Tapley (1988)
EIRP Model:	Knocke, Ries and Tapley (1988)
Non-tidal Model:	Atmosphere and Ocean De-aliasing Level 1B (AOD1B) product (Flechtner, Schmidt and Meyer 2006; Flechtner 2007; Flechtner 2011)
Ocean Tidal Model:	2004 Finite Element Solution (FES2004) global tide model (Lyard et al. 2006)
Permanent Tide System:	tide-free

4.3 Institute of Geodesy Graz

Software:	GROOPS
Approach:	Short-Arcs Approach (SAA) (Mayer-Gürr 2006)
Reference GFM:	GOCO release 05 satellite-only gravity field model (GOCO05S) (Mayer-Gürr 2015)
Empirical Parameters:	Piecewise linear for each arc (ranging from 15 to 45 minutes)
Drag Model:	None
EARP Model:	None
EIRP Model:	None
Non-tidal Model:	Atmosphere and Ocean De-aliasing Level 1B (AOD1B) product (Flechtner, Schmidt and Meyer 2006; Flechtner 2007; Flechtner

	2011)
Ocean Tidal Model:	2014 Finite Element Solution (FES2014) global tide model (Carrere et al. 2015)
Permanent Tide System:	zero tide

4.4 Ohio State University

Software:	(developed in-house)
Approach:	Improved Energy Balance Approach (IEBA) (Shang et al. 2015)
Reference GFM:	GOCO release 05 satellite-only gravity field model (GOCO05S) (Mayer-Gürr 2015)
Empirical Parameters:	Drag and Radiation Pressure Coefficients, global and 1 Cycle Per Revolution (CPR) piecewise-constant
Drag Model:	(US)Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar tmospheric model (NRLMSISE) (Picone et al. 2002)
EARP Model:	Knocke, Ries and Tapley (1988)
EIRP Model:	Knocke, Ries and Tapley (1988)
Non-tidal Model:	Atmosphere and Ocean De-aliasing Level 1B (AOD1B) product (Flechtner, Schmidt and Meyer 2006; Flechtner 2007; Flechtner 2011)
Ocean Tidal Model:	2011 Empirical Ocean Tide model (EOT11a) (Savcenko and Bosch 2012)
Permanent Tide System:	zero tide

4.5 Common

Atmospheric Tidal Model:	Biancale and Bode (2006)
Solid Earth Tidal Model:	IERS2010
Pole Tidal Model:	IERS2010
Ocean Pole Tidal Model:	IERS2010
Third body perturbations:	Sun, Moon, Mercury, Venus, Mars, Jupiter and Saturn, following the JPL Planetary and Lunar Ephemerides (Folkner et al. 2014)

4.6 Summary

Inst.	Approach	Reference
AIUB	Celestial Mechanics Approach (CMA) (Beutler et al. 2010)	Jäggi et al. (2016)
ASU	Decorrelated Acceleration Approach (DAA) (Bezděk et al. 2014; Bezděk et al. 2016)	Bezděk et al. (2016)
IfG	Short-Arcs Approach (SAA) (Mayer-Gürr 2006)	Zehentner and Mayer-Gürr (2016)
OSU	Improved Energy Balance Approach (IEBA) (Shang et al. 2015)	Guo et al. (2015)

Table 3 – Overview of the gravity field estimation approaches

5 File name conventions

5.1 Documentation

The file names of the documents shall be compliant with ESA requirements for Configuration and Document Management[1]. As such, the following naming syntax applies:

SW_TN_<p>_GS_<n>_<dl>_<t>.pdf

The file name particles are identified as:

<p>: issuing institute (i.e. the affiliation of the corresponding Work Package (WP) manager)

- **DUT:** Delft University of Technology[2]
- **AIUB:** Astronomical Institute of the University of Bern
- **ASU:** Astronomical Institute Ondřejov
- **IFG:** Institute of Geodesy Graz
- **OSU:** Ohio State University

<n>: ever increasing four digit, zero padded number designating a unique number of this document type for this institute[3]

<dl>: deliverable name, i.e. either TN-01, TN-02, TN-03 or TN-04

<t>: document title

Note that there is no version number in the file names.
Examples:

- SW_TN_DUT_GS_0001_TN-01_Standards_and_Background_models.pdf, as a result of WP100;
- SW_TN_ASU_GS_0001_TN-02_Pre-processing_baselines_and_accelerometer_data.pdf, as a result of WP200;
- SW_TN_DUT_GS_0002_TN-03_Swarm_models_validation.pdf, as a result of WP300;
- SW_TN_IFG_GS_0001_TN-04_Swarm_models_description.pdf, as a result of WP400.

5.2 Data

The names of data files start with the string GSWARM and are composed of a series of *particles* (identified below between the < and > characters) connected by the underscore character (_):

GSWARM_<dt>_<s>_<p>_<v>_<dv>[_<sd>].<e>

The file name particles are identified as:

<dt>: data type

- **KO:** Kinematic Orbit
- **KB:** Kinematic Baseline
- **GF:** Gravity Field Model
- **NE:** Normal Equation

[1] https://smart-svn.spacecenter.dk/svn/smart/SwarmESL-All/Management/Plans/SW-PL-DTU-GS-007_ESL_CDMP.pdf

[2] This particle is not in agreement with the remaining naming conventions because this is the acronym attributed to TU Delft within DISC.

[3] The <n> particle is used to distinguish different documents of the same type and institute, since the <dl> and <t> particles are formally optional. As a result of the obvious impracticability of (the non-optional part of) this naming convention, the code<dl> and <t> particles are highly encouraged and widely used.

AC: Modelled non-gravitational accelerations
WO: GPS data weights

<s>: satellite(s)

SA, SB, SC: single satellite
SAB, SBC, SAC: two satellites (SBA, SCB and SCA are not contemplated)
SABC: all satellites (other orders of the A, B and C characters are not contemplated)

<p>: processor

TUD: Delft University of Technology
AIUB: Astronomical Institute of the University of Bern
ASU: Astronomical Institute Ondřejov
IFG: Institute of Geodesy Graz
OSU: Ohio State University
COMBINED: combined solutions from AIUB, ASU, IfG and OSU (relevant only for Gravity Field Models (GFMs) and Normal Equations (NEs))

<v>: data validity

KO, KB: yyyy-mm-dd_doy
GF, NE: yyyy-mm
yyyy: four digit year
mm: two digit calendar month (zero padded)
dd: two digit calendar day (zero padded)
doy: two digit Day of Year (DoY) (zero padded)

<dv>: data version

- two digits (zero padded)
- GFMs and NEs inherit the version number from the KOs used in their processing (if KBs are used, this is additionally specified in the header)
- GF_COMBINED need to specify the solutions and respective versions in the header; the version number is incremented only because of reprocessing or data combinations changes

<sd>: source data

KO, KB, COMBINED: empty
GF, NE: a valid <p>

<e>: file extension

KO, KB: sp3
GF: gfc
NE: snx
AC: nrtdm
OW: wgt

Examples:

- GSWARM_KO_SA_AIUB_2016-02-25_056_03.sp3
- GSWARM_KB_SAB_TUD_2016-03-25_084_01.sp3
- GSWARM_GF_SABC_OSU_2016-02_01_TUD.gfc
- GSWARM_NE_SABC_IFG_2016-02_01_IFG.snx
- GSWARM_GF_SABC_COMBINED_2016-02_01.gfc

6 Formats

6.1 Documentation

The deliverable documents are distributed in Portable Data Format (PDF) (with extension `pdf`) or MicroSoft Word format (with extension `docx`). Templates for LaTeX and Word are available in the dissemination server (see Section 7), under the directory `management/Templates/`.

A version tracking number shall be maintained authors, under the following syntax:

`<i>[<r>][ d<dr>]`

`<i>`: ever increasing integer number (not zero-padded);
`<r>`: capital letter, initially blank and progressing alphabetically;
`<dr>`: capital letter reserved for draft versions of the document, initially blank and progressing alphabetically (omitted for non-drafts).

Examples:

`1 dA`: issue 1, draft A;
`1 dB`: issue 1, draft B;
`1`: issue 1, final version;
`1A`: issue 1, revision A, final version;
`2O dD`: issue 2, revision O, draft D.

6.2 Data

Data compression

All data files shall be compressed **individually** using the *zip* or *gzip* compression formats (usually with file extensions `zip` and `gz`, respectively). It is the responsibility of every partner to compress/uncompress the data before/after uploading/downloading it to/from the dissemination server. The file name extension resulting data compression is omitted elsewhere in this document.

Kinematic Orbits

The KO are preferably distributed in the *SP3k* format, described below, which is a modification of the Extended Standard Product 3 Orbit Format (SP3c)[4] format. The variance-covariance information is identified by the EPx record name.

The main innovation in the *SP3k* is the increased precision to the sub-millimetre level, by adding one additional significant digit after the comma in the kinematic positions and variances (expressed in the form of STandard Deviation (STD)). The co-variances, represented by the correlation factors, remains unchanged. This means that:

1st header line: format identifier `#c` of the SP3c format is replaced by `#k`;
`P` **record:**

- **Columns 1 to 4:** unchanged;
- **Columns 5 to 46:** there are 7 digits after the comma (instead of 6), at the expense of a digit before the comma, as described by the format `F14.7` (instead of `F14.6`); these fields describe the kinematic positions;
- **Columns 47 to 60:** unchanged;
- **Columns 62 to 80:** unchanged and optional;

[4] `ftp://igs.org/pub/data/format/sp3c.txt`

Example:

```
         1    1    2    2    3    3    4    4    5    5    6
    5    0    5    0    5    0    5    0    5    0    5    0
PL49  -519.6320223 -1895.3792238 -6545.3236807     -0.000884
```

`EP` **record:**

Columns 1 to 2: unchanged;

Columns 3: contains the character `x` to distinguish from the `EP` record of the SP3c format;

Columns 5 to 24: these (mandatory) fields describe the STD of the positions according to the `F6.1` format;

Column 25: unused;

Columns 26 to 86: unchanged relative to columns 20 to 80 in the SP3c format; these (mandatory) fields contain the cross-correlations in the form of correlation coefficients;

Example:

```
         1    1    2    2    3    3    4    4    5    5    6    6    7    7    8    8
    5    0    5    0    5    0    5    0    5    0    5    0    5    0    5    0    5
EPx   55.1  55.1  55.1     222 1234567 -1234567 5999999     -30        21 -1230000
```

Although the *SP3k* format allows for multiple satellites in one data file, the team shall exchange KO data files relevant to individual Swarm satellites (as it has been traditionally done with other formats, see below).

Since numerous KO orbit files are already available at the dissemination server, the existing alternative formats shall also to be supported by all (relevant) partners, in addition to the *SP3k* format. The original file names have been replaced by the convention described in Section 5.2. The alternative formats of the KOs are specific to each institute:

TU Delft:

File name extension: `sigma`

File header: none

Data records:

- **Column 1-6:** GPS epoch: year, month, day, hour, minute, second (fractional)
- **Column 7-9:** position x, y and z-component [m]
- **Column 10:** clock correction (or 't'-component, already applied to columns 1 to 6) [μs]
- **Column 11-20:** xx, yy, zz, tt (clock-correction variance), xy, xz ,xt, yz, yt and zt-element of 4x4 epoch-wise covariance matrix [m^2][5]

AIUB:

File name extension: `KIN`

File header:

- **Line 1:** description of orbit including release number and orbit generation date and time
- **Line 2:** dummy line
- **Line 3:** information about geodetic datum and date & time of first epoch (GPS time)
- **Line 4:** a posteriori STD of L1/L2 GPS carrier phase obs. [m]
- **Line 5:** description of columns

[5] The (variance) covariance terms involving the clock correction (represented by 't') are also in units of m^2; the conversion to units of time can be done by dividing by the (square of the) speed of light.

Line 6: dummy line

Data records: After the header each line represents one epoch. The columns contain the following quantities:

Column 1: internal AIUB satellite name (Swarm-A: `SWMA`, Swarm-B: `SWMB`, Swarm-C: `SWMC`)
Column 2: modified SVN number (Swarm-A: `L47`, Swarm-B: `L48`, Swarm-C: `L49`)
Column 3: GPS week
Column 4: GPS second within the given GPS week [s]
Column 5-7: position x, y, and z-componentz [m]
Column 8: quality flag (possible values are `K`, `X`, `S` and `G`, see below)
Column 9-14: xx, yy, zz, xy, xz, yz-elements of 3x3 epoch-wise cofactor matrix

Meaning of quality flags:

`K`**:** KO position could be properly determined
`X`**:** KO position could not be determined (less than 4 satellites)
`S`**:** KO position could be determined, but less than 5 satellites were available
`G`**:** KO position has been flagged during internal AIUB orbit screening

IfG:

File name extension: `txt`

File header:

Line 1: short description of the orbit product
Line 2: geodetic datum

Data records: The epochs are in the GPS time system.

Column 1: Modified Julian Date (MJD) in the GPS time system
Column 2-4: position x, y, and z-componentz [m]
Column 5-10: xx, yy, zz, xy, xz, yz-elements of 3x3 epoch-wise covariance matrix

Kinematic Baselines

The KB data are distributed in the *SP3k* format, with the following modification:

`EB` **record:** a new record containing the variance-covariance information of the KBs, following the same format as the `EPx` record (which describes variance-covariance information for the positions);

`P` **records:** describe the orbits of the **two** satellites (with 7 significant digits, under the *SP3k* format) from which it is possible to reconstruct the estimated KBs.

Gravity Field Model

The GFMs data are distributed in the International Centre for Global Earth Models (ICGEM) format[6].

Normal Equation

The NEs data are distributed in the Solution-Independent Exchange (SINEX) format[7].

[6] `http://icgem.gfz-potsdam.de/ICGEM-Format-2011.pdf`
[7] `www.iers.org/IERS/EN/Organization/AnalysisCoordinator/SinexFormat/sinex.html`

Modelled non-gravitational accelerations

The modelled non-gravitational accelerations are distributed in the *nrtdm* format (since this format is readily available in TU Delft's Near Real-Time Density Model (NRTDM) software). It is a column-wise, plain text, self-explanatory format. The header is optional but useful, since it describes what each column contains. Maintaining the `yyyy-mm-dd` and `hh:mm:ss.sss` date and time formats is important, since otherwise it would make parsing the header mandatory. Additional columns may be appended, with their description appended after line 6 of the header.

File name extension: `nrtdm`
File header: (optional but highly encouraged)

- **Lines 1-6:** Description of the contents of columns 1 to 6 (see below)
- **Line 7:** Fortran format string
- **Line 8:** Column headers
- **Line 9:** Column-wise units of the data (columns 4 to 6)

Data records: After the header each line represents one epoch. The columns contain the following quantities:

- **Column 1:** calendar date in the `yyyy-mm-dd` format
- **Column 2:** time in the `hh:mm:ss.sss` format
- **Column 3:** time system, i.e. `GPS`, `UTC`, `UT1` or `TAI`
- **Column 4-6:** x, y and z coordinates of the non-gravitational acceleration in the Satellite Body Reference Frame

An example of this format is:

```
# Column  1:         Date (yyyy-mm-dd)
# Column  2:         Time (hh:mm:ss.sss)
# Column  3:         Time system
# Column  4:  E13.6  Linear acceleration in S/C X-direction (m/s/s)
# Column  5:  E13.6  Linear acceleration in S/C Y-direction (m/s/s)
# Column  6:  E13.6  Linear acceleration in S/C Z-direction (m/s/s)
# Format string: (a27,1x,E13.6,1X,E13.6,1X,E13.6)
# Date/time                    Column  4     Column  5     Column  6
#                              m/s/s         m/s/s         m/s/s
2005-01-01 00:00:00.000 GPS  0.424512E-07  0.479988E-08  0.103282E-07
2005-01-01 00:00:10.000 GPS  0.425367E-07  0.483965E-08  0.104057E-07
2005-01-01 00:00:20.000 GPS  0.428182E-07  0.513651E-08  0.104278E-07
2005-01-01 00:00:30.000 GPS  0.433768E-07  0.467810E-08  0.101609E-07
2005-01-01 00:00:40.000 GPS  0.440563E-07  0.492133E-08  0.993525E-08
2005-01-01 00:00:50.000 GPS  0.446449E-07  0.543075E-08  0.971838E-08
2005-01-01 00:01:00.000 GPS  0.451432E-07  0.539917E-08  0.929534E-08
```

GPS data weights

The GPS data weights aim to provide an optimum weighting scheme for the GPS code and phase measurements, by indicating the a-priori STD for specific GPS satellites at specific epochs. It is a column-wise, plain text format.

File name extension: `wgt`
File header:

- **Line 1:** Description of the data and date and time it was exported

Line 2: Header separator, consisting of several – characters
Line 3: Column description
Line 4: Place-holder for the digits in the columns, using the * character

Data records: After the header each line represents one epoch. The columns contain the following quantities:

Column 1: initial epoch, in MJD
Column 2: final epoch, optionally empty indicating one single epoch is affected
Column 3: GPS satellite number
Column 4: a priori STD to assign to the corresponding data

An example of this format is:

```
Observation-specific weights                                 18-Jan-2018 15:51
-------------------------------------------------------------------------------
Start MJD              End MJD                 SAT  SIGMA
*****.************     *****.************      **   ***.***
57023.001122700000                             04    21.000
57023.001134300001                             04    21.000
57023.001145800001                             04    21.000
57023.001157400002                             04    21.000
57023.001169000003                             04    21.000
57023.001180599997                             04    21.000
```

7 Dissemination Server

The server is located at `aristarchos.lr.tudelft.nl` and can only be accessed using secure shell client (and related utilities). The access to this server requires dedicated credentials, usually issued in the name of the institute team leaders (TU Delft team members have individual access). Additional user credentials can be issued if needed. All users (except TU Delft team members) share the same `$HOME` directory, `/home/gswarm`.

7.1 Directory structure

The directory structure of the distribution server is:

```
/home/gswarm/
├── management/
│   ├── Data formats/
│   ├── Templates/
│   ├── Website/
│   └── WP[1-5]00/
└── data/
    ├── <p>/
    │   ├── acceleration/
    │   ├── baseline/
    │   ├── gravity/
    │   ├── normaleq/
    │   ├── orbit/
    │   └── wgt/
    │       └── <yyyy>/
    └── dissemination/
```

The contents of the directories above is:

`Data formats`:	documentation on the data formats mentioned in Section 6
`Proposal`:	the files used in producing the answer of the team to the Swarm DISC ITT 1.1
`Templates`:	LaTeX and Microsoft Word templates for reports
`Website`:	github repository with the contents of `https://jgte.github.io/gswarm/`
`WP[1-5]00`:	reserved for the activities of the corresponding WP
`<p>`:	data distributed by each processor: `aiub`, `asu`, `ifg`, `osu` or `tudelft`
`acceleration`:	Modelled non-gravitational acceleration data
`baseline`:	KB data
`gravity`:	GFM coefficients
`normaleq`:	NE data
`orbit`:	KO data distributed in yearly directories, with names <yyyy> (four digit year)
`dissemination`:	data to be disseminated to ESA

7.2 Data dissemination

The `dissemination` directory contains the GFMs that are uploaded to the ESA dissemination servers. These data are packaged according to the Swarm Level 2 (L2) Product Format[8] and following all required naming conventions.

[8] `https://earth.esa.int/web/guest/missions/esa-eo-missions/swarm/data-handbook/level-2-product-format`

A Acronyms

AA Acceleration Approach, Rummel (1979)

AIUB Astronomical Institute of the University of Bern, Switzerland, `www.aiub.unibe.ch`

ASU Astronomical Institute (Astronomický ústav), AVCR, Ondřejov, `www.asu.cas.cz/en`

AVCR Czech Academy of Sciences (Akademie věd České Republiky), Czech Republic, `www.avcr.cz/en/`

CODE Centre for Orbit Determination in Europe, Dach et al. (2017)

CPR Cycle Per Revolution

CRV Code Residual Variation

D/O Degree and Order

DISC Data, Innovation and Science Cluster

DoY Day of Year

EARP Earth Albedo Radiation Pressure

EGSIEM European Gravity Service for Improved Emergency Management, EU Horizon 2020, `www.egsiem.eu`

EIRP Earth Infrared Radiation Pressure

EKF Extended Kalman Filter

EBA Energy Balance Approach, O'Keefe (1957) and Jekeli (1999)

EOT Empirical Ocean Tide model

EOP Earth Orientation Parameter

ERP Earth Rotation Parameters

ESA European Space Agency, `www.esa.int`

EU European Union

FES Finite Element Solution global tide model

GFM Gravity Field Model

GOCO Gravity Observation COmbination

GPS Global Positioning System

GRACE Gravity Recovery And Climate Experiment, Tapley, Reigber and Melbourne (1996) and Tapley et al. (2004)

GRACE-FO GRACE Follow On, Sheard et al. (2012), Larkin (2012) and Flechtner et al. (2014)

GROOPS Gravity Recovery Object Oriented Programming System

IAU International Astronomical Union

ICGEM International Centre for Global Earth Models, `icgem.gfz-potsdam.de`

IERS International Earth Rotation Service

IERS2010 IERS Conventions 2010, Petit and Luzum (2010)

IfG Institute of Geodesy, TUG, Graz, `www.ifg.tugraz.at`

ITG Institut für Geodäsie und Geoinformation, Germany, `www.igg.uni-bonn.de`

ITT Invitation To Tenders

JPL Jet Propulsion Laboratory, USA, `www.jpl.nasa.gov`

JPL-PLE JPL Planetary and Lunar Ephemerides, Folkner et al. (2014)

KB Kinematic Baseline

KO Kinematic Orbit

L1B Level 1B data

L2 Level 2 data

LEO Low-Earth Orbit

LS Least-Squares

MJD Modified Julian Date

N/A Not Applicable

NE Normal Equation

NRTDM Near Real-Time Density Model

OSU Ohio State University, `www.osu.edu`

PCV Phase Center Variation

PDF Portable Data Format, `en.wikipedia.org/wiki/Portable_Document_Format`

POD Precise Orbit Determination

PSO Precise or Post-processed Science Orbit

SINEX Solution-Independent Exchange Format, `www.iers.org/IERS/EN/Organization/AnalysisCoordinator/SinexFormat/sinex.html`

SoW Statement of Work, Doc. Ref. SW-SW-DTU-GS-111_ITT1-1

SP3c Extended Standard Product 3 Orbit Format, `ftp://igs.org/pub/data/format/sp3c.txt`

SNR Signal-to-Noise Ratio

STD STandard Deviation

TU Delft Delft University of Technology, Netherlands, `www.tudelft.nl`

TUG Graz University of Technology, Austria, `www.tugraz.at`

USA United States of America

VCE Variance Component Estimation

WP Work Package

References

Allende-Alba, Gerardo et al. (2017). **Reduced-dynamic and kinematic baseline determination for the Swarm mission**. In: *GPS Solut.* 21.3, pp. 1275–1284. DOI: 10.1007/s10291-017-0611-z (cit. on p. 7).

Barneveld, Pieter Willem Lucas van (2012). **Orbit determination of satellite formations**. PhD thesis. Delft University of Technology. DOI: 10.4233/uuid:c5ac8599-fca2-40eb-adc6-bbfeeec38fa (cit. on p. 7).

Beutler, Gerhard et al. (2010). **The celestial mechanics approach: theoretical foundations**. In: *J. Geod.* 84.10, pp. 605–624. DOI: 10.1007/s00190-010-0401-7 (cit. on pp. 8, 9).

Bezděk, Aleš et al. (2014). **Gravity field models from kinematic orbits of CHAMP, GRACE and GOCE satellites**. In: *Adv. Sp. Res.* 53.3, pp. 412–429. DOI: 10.1016/j.asr.2013.11.031 (cit. on pp. 8, 9).

Bezděk, Aleš et al. (2016). **Time-variable gravity fields derived from GPS tracking of Swarm**. In: *Geophys. J. Int.* 205.3, pp. 1665–1669. DOI: 10.1093/gji/ggw094 (cit. on pp. 4, 8, 9).

Biancale, R. and A. Bode (2006). **Mean annual and seasonal atmospheric tide models based on 3-hourly and 6-hourly ECMWF surface pressure data**. Tech. rep. Potsdam, Germany: Deutsches GeoForschungsZentrum GFZ. DOI: 10.2312/GFZ.b103-06011 (cit. on p. 9).

Carrere, L et al. (2015). **FES 2014, a new tidal model on the global ocean with enhanced accuracy in shallow seas and in the Arctic region**. In: *EGU Gen. Assem. Conf. Abstr.* Vol. 17. EGU General Assembly Conference Abstracts, p. 5481 (cit. on p. 9).

Dach, Rolf et al. (2015). **Bernese GNSS Software Version 5.2**. Bern: Bern Open Publishing. DOI: 10.7892/boris.72297 (cit. on pp. 5–8).

Dach, Rolf et al. (2017). **CODE final product series for the IGS**. Bern, Switzerland. DOI: 10.7892/boris.75876.2 (cit. on pp. 6, 19).

Flechtner, Frank (2007). **Gravity Recovery and Climate Experiment AOD1B Product Description Document for product releases 01 to 04**. Technical report GR-GFZ-AOD-0001. GeoForschungszentrum Potsdam, pp. 1–33. URL: ftp://podaac.jpl.nasa.gov/pub/grace/doc/AOD1B_20070413.pdf (cit. on pp. 8, 9).

— (2011). **GRACE AOD1B RL04 Quality Assurance**. Miscellaneous. URL: http://op.gfz-potsdam.de/grace/results/grav/g007_aod1b_rl04.html (visited on 23/07/2015) (cit. on pp. 8, 9).

Flechtner, Frank, Roland Schmidt and Ulrich Meyer (2006). **De-aliasing of Short-term Atmospheric and Oceanic Mass Variations for GRACE**. In: *Obs. Earth Syst. from Sp.* Ed. by J. Flury et al. Springer Berlin Heidelberg, pp. 83–97. DOI: 10.1007/3-540-29522-4_7 (cit. on pp. 8, 9).

Flechtner, Frank et al. (2014). **Status of the GRACE Follow-On Mission**. In: *Int. Assoc. Geod. Symp.* Vol. 141. Springer, Cham, pp. 117–121. DOI: 10.1007/978-3-319-10837-7_15 (cit. on p. 19).

Folkner, William M et al. (2014). **The Planetary and Lunar Ephemerides DE430 and DE431**. In: *Interplanet. Netw. Prog. Rep* 42.196. URL: https://ipnpr.jpl.nasa.gov/progress_report/42-196/196C.pdf (cit. on pp. 9, 20).

Guo, J. Y. et al. (2015). **On the energy integral formulation of gravitational potential differences from satellite-to-satellite tracking**. In: *Celest. Mech. Dyn. Astron.* DOI: 10.1007/s10569-015-9610-y (cit. on p. 9).

Helleputte, T. van (2004). **GPS High Precision Orbit De- termination Software Tools: User Manual**. Oberpfaffenhofen (cit. on pp. 5, 6).

IJssel, Jose van den et al. (2015). **Precise science orbits for the Swarm satellite constellation**. In: *Adv. Sp. Res.* 56.6, pp. 1042–1055. DOI: 10.1016/j.asr.2015.06.002 (cit. on p. 6).

Jäggi, A. et al. (2007). **Precise orbit determination for GRACE using undifferenced or doubly differenced GPS data**. In: *Adv. Sp. Res.* 39.10, pp. 1612–1619. DOI: 10.1016/j.asr.2007.03.012 (cit. on p. 7).

Jäggi, A. et al. (2011). **AIUB-GRACE03S**. Bern, Switzerland. URL: http://icgem.gfz-potsdam.de/ (cit. on p. 8).

Jäggi, A. et al. (2016). **Swarm kinematic orbits and gravity fields from 18 months of GPS data**. In: *Adv. Sp. Res.* 57.1, pp. 218–233. DOI: 10.1016/j.asr.2015.10.035 (cit. on pp. 4, 6, 9).

Jäggi, Adrian, U. Hugentobler and G. Beutler (2006). **Pseudo-Stochastic Orbit Modeling Techniques for Low-Earth Orbiters**. In: *J. Geod.* 80.1, pp. 47–60. DOI: 10.1007/s00190-006-0029-9 (cit. on pp. 5, 6).

Jekeli, Christopher (1999). **The determination of gravitational potential differences from satellite-to-satellite tracking**. In: *Celest. Mech. Dyn. Astron.* 75.2, pp. 85–101. DOI: 10.1023/A:1008313405488 (cit. on p. 19).

Knocke, P., J. Ries and B. Tapley (1988). **Earth radiation pressure effects on satellites**. In: *Astrodyn. Conf.* Reston, Virigina: American Institute of Aeronautics and Astronautics. DOI: 10.2514/6.1988-4292 (cit. on pp. 8, 9).

Larkin, Philip (2012). **ESTO :: News :: Laser System for GRACE Follow-On**. URL: http://esto.nasa.gov/news/news_gracefollowon.html (visited on 06/07/2013) (cit. on p. 19).

Lieske, J H et al. (1977). **Expression for the precession quantities based upon the IAU (1976) system of astronomical constants**. In: *Astron. Astrophys.* 58, pp. 1–16 (cit. on p. 5).

Lyard, Florent et al. (2006). **Modelling the global ocean tides: modern insights from FES2004**. In: *Ocean Dyn.* 56.5-6, pp. 394–415. DOI: 10.1007/s10236-006-0086-x (cit. on p. 8).

Mao, X. et al. (2017). **Impact of GPS antenna phase center and code residual variation maps on orbit and baseline determination of GRACE**. In: *Adv. Sp. Res.* 59.12, pp. 2987–3002. DOI: 10.1016/j.asr.2017.03.019 (cit. on p. 7).

Mayer-guerr, Torsten et al. (2010). **ITG-Grace2010: the new GRACE gravity field release computed in Bonn**. In: *EGU Gen. Assem. Abstr.* Vol. 12.EGU2010-2446, p. 2446. URL: http://www.igg.uni-bonn.de/apmg/index.php?id=itg-grace2010 (cit. on p. 8).

Mayer-Gürr, Torsten (2006). **Gravitationsfeldbestimmung aus der Analyse kurzer Bahnbögen am Beispiel der Satellitenmissionen CHAMP und GRACE**. PhD thesis. Rheinischen Friedrich-Wilhelms Universität Bonn. URL: http://hss.ulb.uni-bonn.de/2006/0904/0904.pdf (cit. on pp. 8, 9).

— (2015). **The Combined Satellite Gravity Field Model GOCO05s**. In: *Geophys. Res. Abstr.* 17.EGU2015-12364 (cit. on pp. 8, 9).

O'Keefe, John A. (1957). **An application of Jacobi's integral to the motion of an earth satellite**. In: *Astron. J.* 62, p. 265. DOI: 10.1086/107530 (cit. on p. 19).

Petit, Gérard Gerard and Brian Luzum (2010). **IERS Conventions (2010)**. Frankfurt am Main. URL: http://www.iers.org/TN36/ (cit. on pp. 5, 6, 19).

Picone, J. M. et al. (2002). **NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues**. In: *J. Geophys. Res. Sp. Phys.* 107.A12, SIA 15–1–SIA 15–16. DOI: 10.1029/2002JA009430 (cit. on pp. 8, 9).

Rummel, R. (1979). **Determination of short-wavelength components of the gravity field from satellite-to-satellite tracking or satellite gradiometry**. In: *Manuscripta Geod.* 4.2, pp. 107–148 (cit. on p. 19).

Savcenko, R and W Bosch (2012). **EOT11a - Empirical ocean tide model from multi-mission satellite altimetry**. Tech. rep. München, Germany: Deutsches Geodätisches Forschungsinstitut. URL: https://epic.awi.de/36001/1/DGFI_Report_89.pdf (cit. on pp. 8, 9).

Schmid, Ralf et al. (2007). **Generation of a consistent absolute phase-center correction model for GPS receiver and satellite antennas**. In: *J. Geod.* 81.12, pp. 781–798. DOI: 10.1007/s00190-007-0148-y (cit. on p. 5).

Seidelmann, P. K. (1982). **1980 IAU Theory of Nutation: The final report of the IAU Working Group on Nutation**. In: *Celest. Mech.* 27.1, pp. 79–106. DOI: 10.1007/BF01228952 (cit. on p. 5).

Shang, K. et al. (2017). **Low-Degree Temporal Gravity Field Solution from SWARM Constellation of Satellites Using the Energy Balance Approach**. In: *Fourth Swarm Sci. Meet. Geod. Mission. Work.* Banff, Canada (cit. on p. 4).

Shang, Kun et al. (2015). **GRACE time-variable gravity field recovery using an improved energy balance approach**. In: *Geophys. J. Int.* 203.3, pp. 1773–1786. DOI: 10.1093/gji/ggv392 (cit. on p. 9).

Sheard, B. S. et al. (2012). **Intersatellite laser ranging instrument for the GRACE follow-on mission**. In: *J. Geod.* 86.12, pp. 1083–1095. DOI: 10.1007/s00190-012-0566-3 (cit. on p. 19).

Tapley, B., C. Reigber and W Melbourne (1996). **Gravity Recovery And Climate Experiment (GRACE) mission**. Baltimore, USA (cit. on p. 19).

Tapley, Byron D. et al. (2004). **GRACE Measurements of Mass Variability in the Earth System**. In: *Science (80-.).* 305.5683, pp. 503–505. DOI: 10.1126/science.1099192 (cit. on p. 19).

Teunissen, P. J. G. (1995). **The least-squares ambiguity decorrelation adjustment: a method for fast GPS integer ambiguity estimation**. In: *J. Geod.* 70.1-2, pp. 65–82. DOI: 10.1007/BF00863419 (cit. on p. 7).

Wermuth, Martin, Oliver Montenbruck and Tom Van Helleputte (2010). **GPS high precision orbit determination software tools (GHOST)**. In: *4th Int. Conf. Astrodyn. Tools Tech.* Madrid: ESA WPP-308 (cit. on pp. 5, 6).

Zehentner, Norbert (2016). **Kinematic orbit positioning applying the raw observation approach to observe time variable gravity**. Doctoral Dissertation. Graz University of Technology, p. 175 (cit. on p. 6).

Zehentner, Norbert and Torsten Mayer-Gürr (2016). **Precise orbit determination based on raw GPS measurements**. In: *J. Geod.* 90.3, pp. 275–286. DOI: 10.1007/s00190-015-0872-7 (cit. on pp. 4, 6, 9).