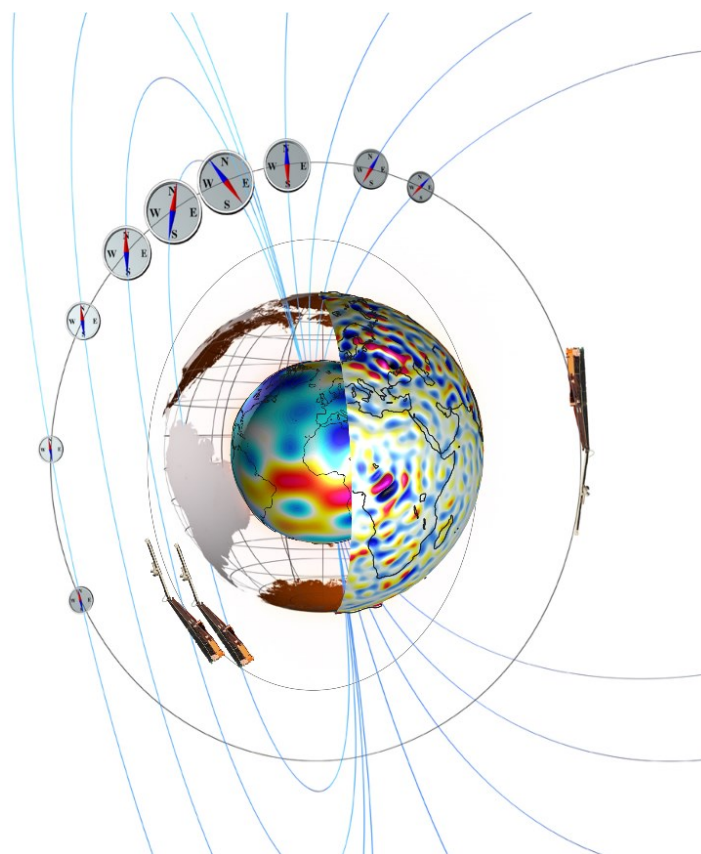


Data, Innovation, and Science Cluster

Accelerometer Level 2

Processor Algorithm



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Prepared:

Sergiy Svitlov

Scientist

Approved:

Sergiy Svitlov

Team Leader

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1 Introduction

1.1 Preamble

Each Swarm satellite carries the electrostatic accelerometer to measure non-gravitational accelerations experienced by the spacecraft. Because of variety of disturbances and anomalies in the Swarm ACC L1b data, the Swarm ACC L2 processor is developed to mitigate disturbances and to produce the Swarm ACC L2 products. Currently, only linear accelerations along the X-axis, which is approximately pointing in the along-track direction, are processed and provided for public.

1.2 Scope and applicability

This document is provided beyond the required deliverables to offer an overview of the Swarm ACC L2 Processor Algorithm.

This document is available on <https://swarmhandbook.earth.esa.int/article/documentation>.

2 Applicable and Reference Documentation

2.1 Applicable Documents

The following documents are applicable to the definitions within this document.

- [AD-1] SW-DS-DTU-GS-0001, Swarm Level 2 Processing System. Product specification for L2 Products and Auxiliary Products, Rev: 3.0.
- [AD-2] SW-RS-DSC-SY-0007, Level 1b Product Definition, issue 5.3.
- [AD-3] Swarm Product Data Handbook https://swarmhandbook.earth.esa.int/catalogue/SW_ACCxCAL_2

2.2 Reference Documents

The following documents contain supporting and background information to be taken into account during the activities specified within this document.

- [RD-1] SW-RP-VZLU-GS-002, Swarm Accelerometer Anomaly Report, Rev: 1dA [smart - Revision 19369: /SwarmESL-AII/R-W-AII/ACC/ARB_Report/](#)
- [RD-2] Siemes et al. Swarm accelerometer data processing from raw accelerations to thermospheric densities, Earth, Planets and Space (2016) 68:92. DOI 10.1186/s40623-016-0474-5.

2.3 Abbreviations

A list of acronyms and abbreviations used by Swarm partners can be found [here](#). Any acronyms or abbreviations not found on the online list but used in this document can be found below.

Acronym or abbreviation	Description
DQI	Daily Quality Index
EDAC	Error Detection and Correction (failure event)
FM	Force Model
PDF	Portable Document Format
UTC	Coordinated Universal Time

3 Processing overview

Processing is performed under the MATLAB^{®1} environment. Individual modules of the processor are tuned manually, in response to the highly variable satellite- and epoch-dependent L1b ACC data quality (see [RD-1]). Upon converting the pre-processed L1b accelerations (raw data from ACCx_PR_1B products) into the corrected and calibrated accelerations, the approved daily L2 ACC products ACCxCAL_2_ (CDF files), ACCxDISi2_ (CDF files), and ACCxVAL_2_ (PDF files) are generated and provided at:

- HTTPS (Product files): https://swarm-diss.eo.esa.int/#swarm/Level2daily/Latest_baselines/ACC/
- FTP (Product files): ftp://swarm-diss.eo.esa.int/Level2daily/Latest_baselines/ACC/

3.1 ACC L2 Products

ACCxCAL_2_ products contain time series of the corrected and calibrated accelerations, including all corrections, flags, and calibration parameters. Individual variables of this product are shown in Table 3-1.

Table 3-1 Variables in the ACCxCAL_2_ product

Field name	Dimension	Unit	Contents
time	1	CDF epoch	Epoch of observation (UTC)
a_cal	3	m/s ²	Calibrated linear acceleration (X,Y,Z)
a_stp	3	m/s ²	Step correction for linear accelerations
a_tmp	3	m/s ²	Temperature correction for linear accelerations
a_gg	3	m/s ²	Gravity gradient correction for linear accelerations
a_aa	3	m/s ²	Angular acceleration correction for linear accelerations
a_ca	3	m/s ²	Centrifugal acceleration correction for linear accelerations
s	3	(m/s ²)/(m/s ²)	Scale factor (time series) for linear accelerations
b	3	m/s ²	Bias for linear accelerations
a_spk	3	m/s ²	Spike correction for linear accelerations
a_jit	3	m/s ²	Voltage jitter correction for linear accelerations

¹ Commercial programming environment for technical computing.

Field name	Dimension	Unit	Contents
a_rh	3	m/s ²	Resonant harmonics correction for linear accelerations
flag_cor	1	N/A	Flag indicating which corrections are applied (combination of corrections is coded in the binary system)
flag_val	1	N/A	Flag indicating if data is valid (flag_val = 0)
flag_thr	1	N/A	Flag indicating if thruster is activated (flag_thr = 1)

ACCxDISi2_ products each contain a list of disturbances in the relevant ACCxCAL_2_ product classified as ‘steps’ (type = 2) or as ‘bad data quality’ (type = 1) with information on magnitude (for steps) and duration (for bad data quality). Currently, disturbances are provided only for linear accelerations.

ACCxVAL_2_ products present the validation report for both raw L1b accelerations and corrected and calibrated L2 accelerations, showing detailed information on data quality, validity, and availability, as well as plots of all applied corrections.

3.2 Method

The Swarm ACC L2 processor performs a linear transformation of the raw L1b accelerations $a_{raw}(t)$ into the measured $a_{meas}(t)$, corrected $a_{cor}(t)$ and calibrated $a_{cal}(t)$ accelerations by consequent application of several corrections (for details, see [RD-2]), as shown below:

$$a_{meas}(t) = s(t) \left(a_{raw}(t) + a_{stp}(t) + a_{spk}(t) + a_{jit}(t) + a_{rh}(t) \right) \quad (3-1)$$

$$a_{cor}(t) = a_{meas}(t) + a_{tmp}(t) + b(t) \quad (3-2)$$

$$a_{cal}(t) = \mathcal{F}^{-1} \{ \mathcal{F} \{ a_{POD}(t) \} * H_{POD} + \mathcal{F} \{ a_{cor}(t) \} * H_{cor} \} \} \quad (3-3)$$

Components contributing to equations (3-1) and (3-2) correspond to the variables of the same names that are explained in Table 3-1, while components and notations of equation (3-3) are as follows:

- $a_{cor}(t)$ is the corrected acceleration, derived from equation (3-2);
- $a_{POD}(t)$ is the POD-derived model of non-gravitational acceleration, constructed as

$$a_{POD}(t) = a_{ae}(t) + a_{alb}(t) + a_{ir}(t) + 1.054 \cdot a_{srp}(t) \quad (3-4)$$

with $a_{ae}(t)$ being the aerodynamic accelerations taken from the ACCx_POD2_ products, and other terms are respectively the radiation pressure from the Earth’s albedo, the Earth’s infrared radiation and the solar radiation pressure, taken from the ACCx_FMi2_ products;

- H_{POD} and H_{cor} are the frequency-domain weighting functions for the POD-derived model and corrected accelerations (low-pass and high-pass filters, respectively) with equal weights of 0.5 at the merging frequency of about 0.354 mHz;
- ‘ $\mathcal{F}$ ’ and ‘ $\mathcal{F}^{-1}$ ’ denote the Fourier transform and the inverse Fourier transform, respectively.

3.3 Algorithm

The main modules of the computation algorithm are shown in Figure 3-1.

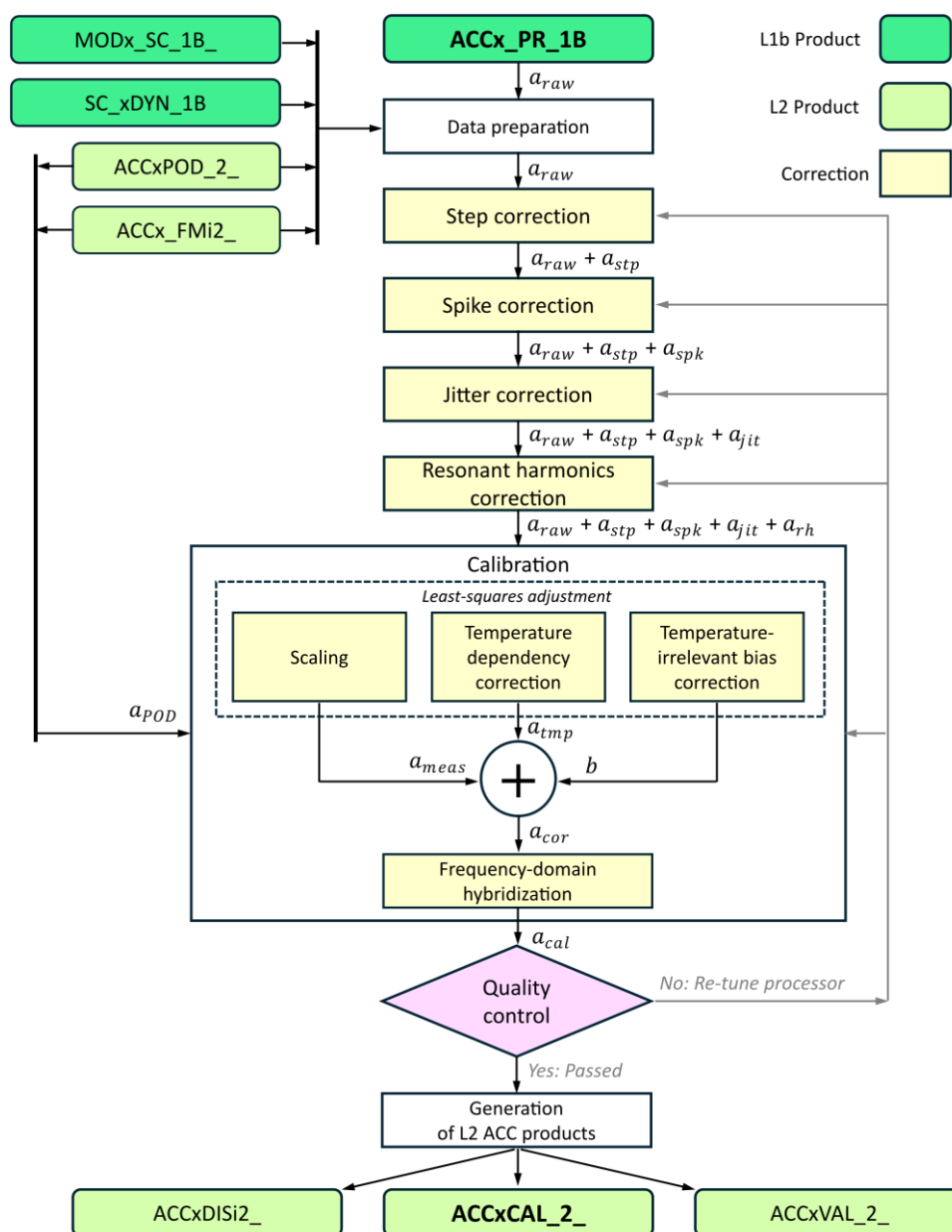


Figure 3-1 Swarm ACC L2 processor algorithm.

3.3.1 Data preparation

The following data products are needed for Swarm L2 ACC data processing:

- ACCx_PR_1B – pre-processed non-gravitational acceleration;
- MODx_SC_1B – satellite position and velocity from the Medium Accuracy Orbit Determination;
- SC_xDYN_1B – auxiliary data needed for POD and non-gravitational force modelling;
- ACCxPOD_2_ – non-gravitational acceleration from Precise Orbit Determination;
- ACCx_FMI2_ – non-gravitational acceleration from Force Models (internal product).

3.3.2 Correction of disturbances in ACC L1b data

This section provides an overview of the methods that are used to mitigate disturbances identified in the L1b ACC data.

3.3.2.1 Step correction

Steps are defined as an abrupt bias change in the raw acceleration above a noise level. To correct steps, two dedicated software tools are consequently used. The first tool automatically recognizes and corrects steps, while the second one is used to manually correct lost steps (false negatives) or to remove false steps (false positives), if appeared, and to mark invalid data. The accumulated steps create the step correction (time series), provided as the variable 'a_stp' (Table 3-1). As steps are usually accomplished with some fast transients, an interval of about $\pm (15-20)$ s around every corrected step is automatically flagged as 'invalid' with contribution to the validity flag 'flag_val' (Table 3-1).

3.3.2.2 Spike correction

Spikes are defined as fast short-duration transients returning to the same signal level, usually, with an exponential decay. Spikes are detected selecting statistically significant and serially correlated outliers in a difference of the original and low-pass filtered step-corrected raw accelerations. Detected spikes are provided as the variable 'a_spk' (Table 3-1), replaced with the linearly interpolated data for the variable 'a_cal' and flagged as 'invalid' with contribution to the validity flag 'flag_val' (Table 3-1).

3.3.2.3 Jitter correction

Voltage jitter (impulse noise) is observed as dual artificial lines in the raw accelerations. It is corrected by replacing the outliers above a threshold with a low-pass filtered replica of the step- and spike-corrected raw accelerations without invalidation, and is provided as the variable 'a_jit' (Table 3-1).

3.3.2.4 Resonant harmonics correction

Resonant harmonics are identified as artificial components in the ACC signal with clear spectral signatures of the modulation products and multiples of frequencies of 0.317 Hz, 1/2080 Hz, 1/3600 Hz and 1/5643 Hz. The bank of harmonics contains 538 frequencies for Swarm A, 670 frequencies for Swarm B and 54 frequencies for Swarm C. The resonant harmonic correction is obtained by tuning the harmonic resonators (sinusoids with the given frequency represented in terms of complex exponential) around the predefined frequency peaks from the bank of harmonics. Currently, the resonant harmonic correction 'a_rh' (Table 3-1) is computed and applied for Swarm A and Swarm B ACC data only (without invalidation of the corrected epochs), and it is set to zero in Swarm C.

3.3.2.5 Formless noise correction and data invalidation

Upon application of the corrections described above, raw accelerations are inspected visually to recognize any possible remaining data anomalies, for example associated with orbital manoeuvres, data gaps, EDAC failure events, invalid POD or FM data and invalid eclipse transitions. Such epochs are manually invalidated with a relevant contribution to the validity flag 'flag_val' (Table 3-1). Accelerations that are measured during thruster activations are marked as flag_thr = 1 and also flagged as invalid (flag_val = 1), but not removed from the corrected accelerations, because they are the result of the physical sensor's response on the external force.

3.3.3 Calibration

The Swarm accelerometers scale factors were estimated via dedicated calibration manoeuvres, using attitude thrusters to generate short reference accelerations. The temperature-induced bias variations are modelled and removed from the accelerometer data. The accelerometer biases, including residual variations, are corrected by replacing the low-frequency content of the accelerometer measurements with the POD-derived accelerations (see below for details).

3.3.3.1 *Scaling*

The nominal scale factor $s(t)$ in equation (3-1) is equal or close to unity. However, dedicated calibration manoeuvre campaigns revealed significant distinctions from unity for all three linear axes and also different scale factors for all three satellites. After analysing all campaigns and keeping consistency between ACC of the Swarm A and Swarm C satellites, which are in close proximity throughout the entire mission, constant scale factors² are assigned for equation (3-1) as shown in Table 3-2.

Table 3-2 Adopted ACC scale factors $s(t) = \text{const}$ for the along-track axes.

Swarm A	Swarm B	Swarm C
2.40	3.63	1.28

3.3.3.2 *Temperature sensitivity and bias*

After application of the corrections derived above and scaling, the measured acceleration $a_{meas}(t)$ (equation (3-1)) is reconstructed. It is still contaminated with slow bias variations, attributed to the observable difference $a_{POD}(t) - a_{meas}(t)$ through the linear least-squares adjustment³ of the parameters β_k in a model

$$a_{POD}(t) - a_{meas}(t) = (a_{tmp}(t) + b(t)) + \varepsilon(t), \quad (3-5)$$

where

$$a_{tmp}(t) = \beta_1 T_1(t) + \beta_2 T_2(t) \quad (3-6)$$

is the temperature correction with $T_1(t)$ being the temperature measured by the first ACC temperature sensor (from six available), and $T_2(t)$ being the temperature derived in advance after propagation of temperature $T_1(t)$ through the dedicated radiation heat transfer model to another location,

$$b(t) = \sum_{k=3}^{K+1} \beta_k \cdot q_k(t) \quad (3-7)$$

is the temperature-irrelevant correction (slow bias change due to the low-frequency drifts of the electrostatic accelerometers and errors in step correction) estimated using the spline approximation (q_k are the quadratic B-splines on K nodes with typical node distance of 6 or 12 hours), and $\varepsilon(t)$ are the random measurement errors.

The derived corrections 'a_tmp' and 'b' are provided as separate variables in the ACCxCAL_2_ product (Table 3-1).

3.3.3.3 *Frequency-domain hybridization*

Considering accelerations $a_{cor}(t)$ (equation (3-2)) and $a_{POD}(t)$ (equation (3-4)), accelerations from the ACC measurements are more accurate at higher frequencies, while the non-gravitational accelerations from POD are more accurate at lower frequencies. To exploit the synergy between both accelerations, the hybridized accelerations $a_{cal}(t)$ are computed as a sum of two accelerations $a_{cor}(t)$ and $a_{POD}(t)$, weighted in the frequency domain (equation (3-3)), and are provided as the final result of the ACC L2 data processing – variable 'a_cal' (Table 3-1) in the ACCxCAL_2_ product.

² Scaling is included in the module 'Calibration' on Figure 3-1 in order to keep a possibility to adjust the scale factors, if needed.

³ Invalid data are excluded from the least-square adjustment by setting zero weights at respective epochs; the rest of data are weighted with the unit weights.

4 Data quality indicators

The L2 ACC products contain auxiliary information on the ACC data quality.

4.1 Validity flag

The validity flag 'flag_val' (Table 3-1) indicates on data validity for the respective epoch ('0' – nominal data; '1' – anomalous data). It is set to '1' for any of the following reasons:

- epochs around the corrected steps;
- epochs during the corrected spikes;
- low data quality, decided either automatically or manually after visual data inspection;
- epochs when thrusters are activated;
- invalid or missing data in the ACCxPOD_2_ or ACCx_FMi2_ products;
- epochs around the eclipse transitions, if recognized as anomalous;
- invalid data after an EDAC failure event.

Information on data quality and validity and on composition of the validity flag is provided as part of the validation reports ACCxVAL_2_ and also available in the metadata of the ACCxCAL_2_ products.

4.2 Thruster flag

The thruster flag 'flag_thr' (Table 3-1) indicates on the thrusters' activity: '0' = inactivated; '1' = activated (2 seconds before and after thruster activations are in addition also marked as 'activated'). It is constructed using information from the SC_xDYN_1B products. Invalid calibrated accelerations 'a_cal' under the thruster activations can be marked separately using the thruster flag, as shown in the validation reports ACCxVAL_2_.

4.3 Correction flag

Variable 'flag_cor' (Table 3-1) provides information on the combination of all applied non-zero corrections and is coded in the binary system: '0' – correction not applied; '1' – correction applied. Several combinations, that appeared in different versions of the ACCxCAL_2_ products, are shown in Table 4-1.

Table 4-1 Value of the variable 'flag_cor' depending on set of applied corrections from Table 3-1.

a_stp	a_tmp	a_gg	a_ca	a_aa	a_spk	a_jit	a_rh	flag_cor
1	1	0	0	0	0	0	0	3
1	1	0	0	0	1	0	0	35
1	1	0	0	0	1	1	0	99
1	1	0	0	0	1	1	1	227
2 ⁰	2 ¹	2 ²	2 ³	2 ⁴	2 ⁵	2 ⁶	2 ⁷	

The sequence of corrections in Table 4-1 is fixed starting from the first release of the ACC L2 products. To define, which corrections are applied in the given baseline, it is necessary to decode the correction flag from the decimal to the binary system, and compare the binary representation with Table 4-1. An example of

decoding is shown in the validation report ACCxVAL_2_ (Figure 4-1), which also provides a list of specific corrections for the given day.

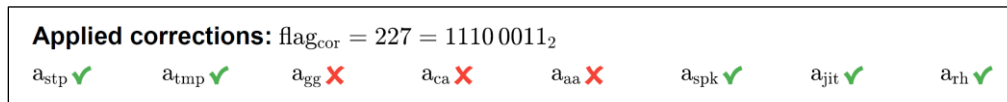


Figure 4-1 Exemplary decoding of the correction flag, as reported in the validation report for Swarm A and Swarm B (recent baselines)

4.4 Daily quality index

The DQI is an empirical quality measure of the corrected and calibrated acceleration ‘a_cal’, reported in the ACCxCAL_2_ (in the CDF global attributes) and ACCxVAL_2_ products (Figure 4-2). It combines three empirical ratings for the noise power variability, data validity and data continuity, tuned in such a way that the aggregated numerical value for the DQI ranges from ‘1’ (very good data quality) to ‘5’ (very bad data quality). More details on components of the DQI, including a colour representation, are available in the validation reports ACCxVAL_2_.

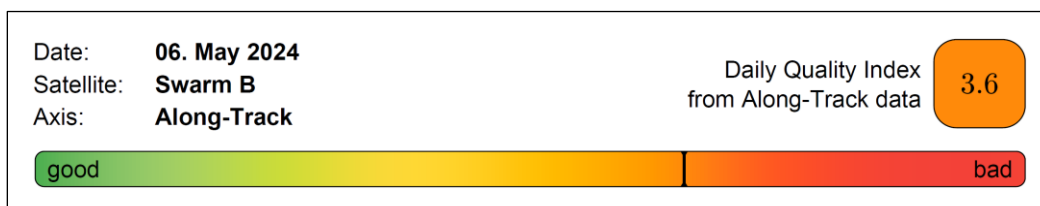


Figure 4-2 An example of the DQI, as reported in the validation report.