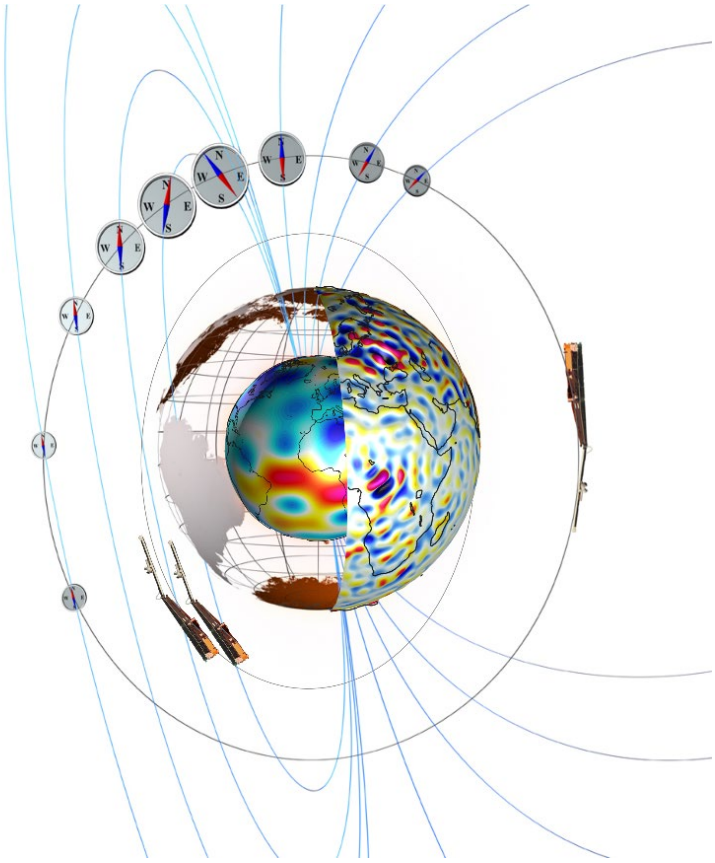
Data, Innovation, and Science Cluster

Swarm SLIDEM Description of Product Algorithms



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Record of Changes

Reason	Description	Rev	Date
Initial vers.	Draft	1dA	2 May 2022
Revision	Revised flag information; include reference to SLIDEM PDD; refer to GitHub site for source code; remove zip command (archive is made by the processor now).	1dB	6 Jun 2022
Revision	Revised table of flags to include applicability. Revised reference documents.	1dC	11 Aug 2022
Release	Signed version 1.	1	13 Sep 2022
Revision	Updated high-latitude effective ion mass and ion density estimation, taking into account along-track ion drift.	2dA	30 Mar 2023
Revision	Credit Ivan Pakhotin contributing to previous revisions. Signed release.	2	22 Jun 2023

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1 Introduction

The document provides information about the progressing algorithms that are used to generate Swarm ion density, along-track velocity, and effective mass of the SLIDEM product. Ivan Pakhotin contributed to previous revisions of this document.

1.1 Scope and applicability

This document is a deliverable of the Swarm LP Ion Drift and Effective Mass (SLIDEM) project [AD-1].

2 Applicable and Reference Documentation

2.1 Applicable Documents

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

[AD-1] SW-OF-UOC-GS-124, Rev: 1 SLIDEM subcontract

[AD-2] SW-TN-UOC-GS_002, Rev: 1, Swarm LP Ion Drift and Effective Mass Product Definition

2.2 Reference Documents

The following documents contain supporting and background information relevant to the SLIDEM product.

[RD-1] Pakhotin, I. P., J. K. Burchill, M. Förster, and L. Lomidze (2022) The Swarm Langmuir Probe Ion Drift, Density and Effective Mass (SLIDEM) Product. Earth, Planets and Space 74.1, 1-18, doi.org/10.1186/s40623-022-01668-5.

[RD-2] Bilitza, D., D. Altadill, V. Truhlik, V. Shubin, I. Galkin, B. Reinisch, and X. Huang (2017), International Reference Ionosphere 2016: From ionospheric climate to real-time weather predictions, Space Weather, 15, 418–429, doi:10.1002/2016SW001593.SW-RN-UoC-GS-004

[RD-3] Truhlik, V., D. Bilitza, and L. Triskova. "Towards better description of solar activity variation in the International Reference Ionosphere topside ion composition model." Advances in Space Research 55.8 (2015): 2099-2105

[RD-4] Resendiz Lira, P. A., Marchand, R., Burchill, J., & Förster, M. (2019). Determination of swarm front plate's effective cross section from kinetic simulations. IEEE Transactions on Plasma Science, 47(8), 3667–3672.

[RD-5] Resendiz Lira, P. A., & Marchand, R. (2021). Simulation inference of plasma parameters from Langmuir probe measurements. Earth and Space Science, 8, e2020EA001344. https://doi.org/10.1029/2020EA001344

[RD-6] Weimer, D. R. (2005). Improved ionospheric electrodynamic models and application to calculating Joule heating rates. Journal of Geophysical Research, 110, A05306. https://doi.org/10.1029/2004JA010884

[RD-7] Knudsen, D.J., Burchill, J.K., Buchert, S.C., Eriksson, A.I., Gill, R., Wahlund, J.E., Ahlen, L., Smith, M. and Moffat, B., 2017. Thermal ion imagers and Langmuir probes in the Swarm electric field instruments. Journal of Geophysical Research: Space Physics, 122(2), pp.2655-2673.

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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***
AMU	Atomic Mass Unit
IDM	Ion-drift, Density, and effective Mass
IRI	International Reference Ionosphere
OML	Orbit motion limited
PIC	Particle-In-Cell
QD	Quasi-Dipole
SLIDEM	Swarm Langmuir Probe Ion Drift and Effective Mass

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3 Processing Algorithms

3.1 Outline

Processing software responsible for Swarm density, ion drift and effective mass estimation combines the Swarm faceplate and Langmuir probe measurements (in particular, ion admittance) with IRI-2016 [RD-2] effective mass estimations, in particular the ion composition model developed by [RD-3]. It is implemented in C, run on a UCalgary server, and produces ion density, along-track ion drift and effective mass data at 2 Hz. The product is detailed in the Product Definition Document [AD-2].

3.1 Observational data

3.1.1 Geophysical data

The IRI2016 model [RD-2] is utilised to obtain effective mass estimates. In particular, not the entire model but only the ion composition subset of it, using [RD-3], is utilised. The formulae are coded directly from the mathematics of the publication, driven by geophysical parameters ($F_{10.7}$). The $F_{10.7}$ input parameter is obtained in the form of a text file from ECHAIM. Swarm location is also provided.

3.1.2 Swarm data

For each day, a Swarm Langmuir probe (LP) 2 Hz CDF data file is selected, available at ftp://swarm-diss.eo.esa.int/Advanced/Plasma_Data/2_Hz_Langmuir_Probe_Extended_Dataset. At the same time, a faceplate data CDF file for the same day is selected from ftp://swarm-diss.eo.esa.int/Advanced/Plasma_Data/16_Hz_Faceplate_plasma_density. The 16 Hz faceplate data is interpolated to 2 Hz. If both Langmuir probe ion admittance and faceplate current data measurements are simultaneously available, density, along-track ion drift and effective mass are calculated for these times. The parameters retained from the Langmuir probe CDF file are satellite geolocation, epoch, and ion admittance. The parameters retained from the faceplate plasma density CDF are satellite geolocation, epoch, and faceplate density which is converted into current. Flags are used to filter out unusable data.

Both ion drift and effective mass are calculated for all magnetic latitudes (QD Lat), however flagging is applied for high latitudes (>50° QD Lat) to indicate the presence of strong along-track ion drifts, which are expected to compromise the validity of effective mass estimates. Figure 1 shows this effect in action, where it can be seen that effective mass values deviate significantly from TBT-2015 model estimates at latitudes >50° MLAT, rising to unrealistically high values (>16 AMU). Version PREL 0201 and later versions provide revised estimates of ion effective mass and ion density taking into account the along-track drift.

In order to account for plasma sheath effects, effective faceplate and Langmuir probe cross-sectional areas are calculated, in terms of correction factors to the physical areas, following the methodology of [RD-4] for the faceplate and [RD-5] for the Langmuir probe. Since both these formulae contain density, ion velocity and effective mass, and as also utilised in the calculations of density, ion velocity and effective mass, an iterative approach is applied where the equations are iterated until convergence. The convergence threshold for density is 0.01 (fraction of the total density); the convergence threshold for effective mass is 0.01 (fraction of total effective mass); the convergence threshold for ion velocity is 1.0 m/s. A maximum of 100 iterations are carried out; if the iterations do not converge to within these thresholds after 100 iterations, this datum is flagged.

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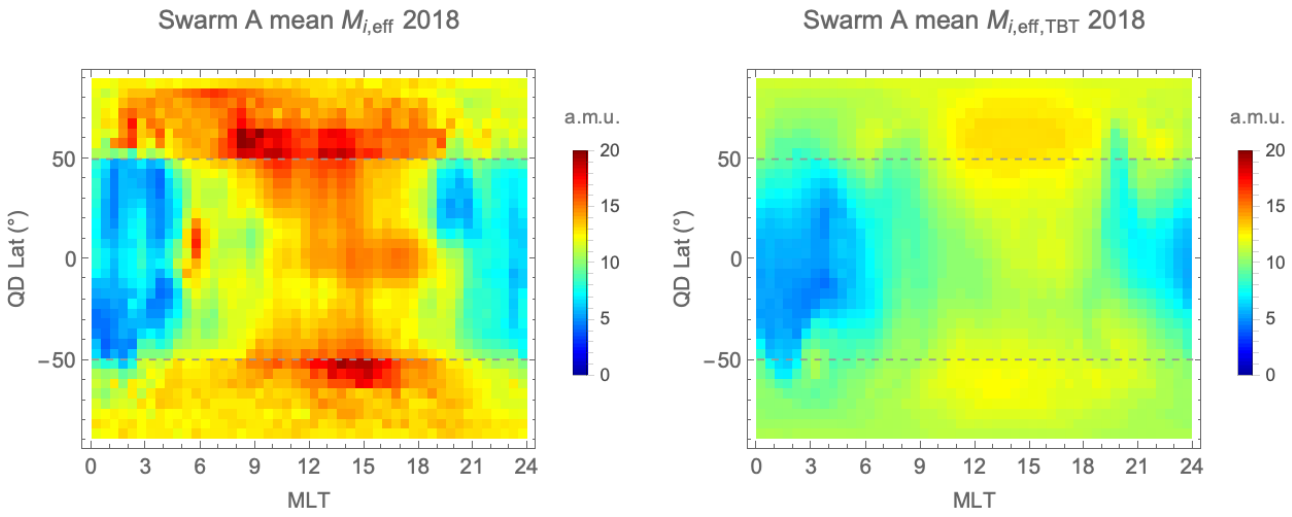

Figure 1: Swarm A ion effective mass calculations using flagged SLIDEM measurements (version PREL 0201, left) and TBT-2015 model (right) for the year 2018. Measured effective mass shows higher peaks and lower troughs compared to the model.

3.2 Data Quality Flags

A table of data quality flags is presented below. This table is identical to Table 3 found in [AD-2].

Table 1: data quality flags used in the SLIDEM dataset.

Flag value	Description	Applicable data product
0	Data product nominal	M_i_eff, n_i, v_i
1	Faceplate current unavailable	M_i_eff, n_i, v_i
2	IDM product calculation did not converge	M_i_eff, n_i, v_i
4	IDM product estimate is not finite and real	M_i_eff, n_i, v_i
8	IDM uncertainty estimate is not finite and real	M_i_eff, n_i, v_i
16	Modified OML faceplate area is not finite and real	M_i_eff, n_i, v_i
32	Modified OML LP probe radius is not finite and real	M_i_eff, n_i, v_i
64	QDLatitude is not within region of validity	M_i_eff, v_i
128	Modified OML faceplate area estimate is not valid	M_i_eff, n_i, v_i
256	Modified OML LP probe radius estimate is not valid	M_i_eff, n_i, v_i

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Flag value	Description	Applicable data product
512	IDM product estimate is large. Interpret with caution	M_i_eff, n_i, v_i
1024	IDM product estimate is small. Interpret with caution	M_i_eff, n_i, v_i
2048	Extended LP dataset inputs are invalid	M_i_eff, n_i, v_i
4096	LP Probe potentials differ by more than 0.3 V	M_i_eff, n_i, v_i
8192	Spacecraft potential is too negative	M_i_eff, n_i, v_i
16384	Spacecraft potential is too positive	M_i_eff, n_i, v_i
32768	Spacecraft velocity unavailable	M_i_eff, n_i, v_i
65536	Post processing error / post-processing not done.	v_i
131072	Magnetic field input invalid	M_i_eff, n_i, v_i

A more detailed description of each flag follows below.

0 ESTIMATE_OK

Estimate is nominal.

1 SLIDEM_FLAG_NO_FACEPLATE_CURRENT

The value for faceplate current is either infinite or NaN (not-a-number).

2 ESTIMATE_DID_NOT_CONVERGE

The effective faceplate and Langmuir probe areas are calculated recursively after initialising Equation (6) from [RD-4] and Equation (15) from [RD-5] respectively with initial estimates for effective mass and along-track ion velocity. If the recursive iteration fails to converge to within specified thresholds (see Section 3.1.2) after 100 iterations, this flag is set.

4 PRODUCT_ESTIMATE_NOT_FINITE

The data point is either infinite or NaN (not-a-number).

8 UNCERTAINTY_ESTIMTATE_NOT_FINITE

The estimate of the uncertainty of the measurement is either infinite or NaN (not-a-number).

16 FACEPLATE_AREA_ESTIMATE_NOT_FINITE

The estimate of the faceplate effective area is either infinite or NaN (not-a-number).

32 PROBE_RADIUS_ESTIMATE_NOT_FINITE

The estimate of the Langmuir probe effective radius is either infinite or NaN (not-a-number).

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64 BEYOND_VALID_QDLATITUDE

The quasi-dipole (QD) latitude is > 50 degrees and thus likely contaminated with auroral-zone ion drift (see Figure 1). Only applied to the effective mass product.

128 OML_FACEPLATE_AREA_CORRECTION_INVALID

The effective faceplate area is geophysically unlikely to be either >0.15 m^2 or <0.08 m^2. If the effective area estimate is outside of these bounds, this flag is raised.

256 OML_PROBE_RADIUS_CORRECTION_INVALID

The effective probe radius is geophysically unlikely to be either >0.005 m or <0.001 m. If the effective probe radius estimate is outside of these bounds, this flag is raised.

512 ESTIMATE_TOO_LARGE

For effective mass: m_i_eff > 40 AMU.

For along-track ion drift speed: v_i > 6000 m.

For plasma density: n_i > 2.0e13 m^-3.

1024 ESTIMATE_TOO_SMALL

For effective mass: m_i_eff < 1.0 AMU (corresponding to 100% H+ plasma)

For plasma density: n_i < 1.0e8 m^-3.

2048 LP_INPUTS_INVALID

One of the input parameters for the estimation of the effective faceplate area and effective Langmuir probe radius is outside of the validity range of the methodology [RD-1][RD-4][RD-5]. In particular, the floating potential is either too negative (see Flag 8192) or too positive (see Flag 16384), and/or the density is too large (see Flag 512) or too small (see Flag 1024), and/or estimated ion temperature is either < 0 K (unphysical), too large (20000 K), or unavailable. As a result, the effective faceplate area and the effective Langmuir probe radius cannot be reliably estimated.

4096 LP_PROBE_DIFFERENCE_TOO_LARGE

The difference in the potential measured by the two Langmuir probes > 0.3 V. Uncertain floating potential may make other measurements unreliable.

8192 SPACECRAFT_POTENTIAL_TOO_NEGATIVE

The spacecraft floating potential is <-5 V. Highly negative satellite floating potential measurements may introduce unusual effects as the plasma environment is outside the expected parameter range of SLIDEM methodology.

16384 SPACECRAFT_POTENTIAL_TOO_POSITIVE

The spacecraft floating potential > 5 V. A strongly positive satellite floating potential is expected to introduce unusual effects and to compromise the SLIDEM methodology which relies on a negatively charged frontal faceplate and Langmuir probe for normal ion admittance and faceplate current measurements.

32768 NO_SATELLITE_VELOCITY

Satellite velocity data is unavailable.

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65536 POST_PROCESSING_ERROR

A detrend is applied to the along-track ion drift estimates to remove baseline offsets [AD-2][RD-1], as seen in Figure 2, so that the ion drift values at either side of the high-altitude zones tend to zero. If this process fails, this flag is raised. Only applied to the along-track ion drift product.

131072 MAG_INPUT_INVALID

A problem with the input magnetic field data means dipolar latitude cannot be calculated.

3.3 Supporting Models

3.3.1 IRI-2016/TBT-2015

The TBT-2015 component of IRI-2016 uses empirical data and F10.7 as an input to estimate ion compositions [RD-3]. This is used as an input to SLIDEM at high latitudes (>50 MLAT) to calculate the along-track ion velocity. Calculations following TBT-2015 are performed in the C programming language as part of the SLIDEM processing chain, with code adapted from the IRI-2015 Fortran implementation.

3.4 Swarm Along-track Ion Velocity

For along-track ion velocity, effective mass is estimated from TBT-2015 based on F10.7 values obtained from ECHAIM, as well as satellite geolocation. Plasma sheath effects are accounted for as discussed in Section 3.2.2. The resulting ion velocity estimates are typically over-estimations, with the lower-latitude values trending towards ~8-9 km/s, rather than 7.6 km/s as expected. This is likely due either to additional effects unaccounted for in the current SLIDEM product iteration, or due to the uncertainty of some of the input parameters, e.g. floating satellite potential.

At the same time, comparison with the empirical Weimer (2005) electric field model [RD-6] show that the large-scale dynamics of the auroral zone are correctly captured both on a case-by-case basis and on a statistical basis. As such, the error is treated as a baseline issue and a simple detrend is applied to bring ion drift into alignment with Weimer (2005) estimates and physical expectations. This is similar to the approach taken in [RD-7] to address baseline issues in the cross-track ion velocity estimate by the Thermal Ion Imager experiment.

At quasi-dipole latitudes poleward of $\pm 50°$, once the along-track ion drift has been calculated and post-processed the effective ion mass and ion density are recalculated, taking into account the along-track ion drift.

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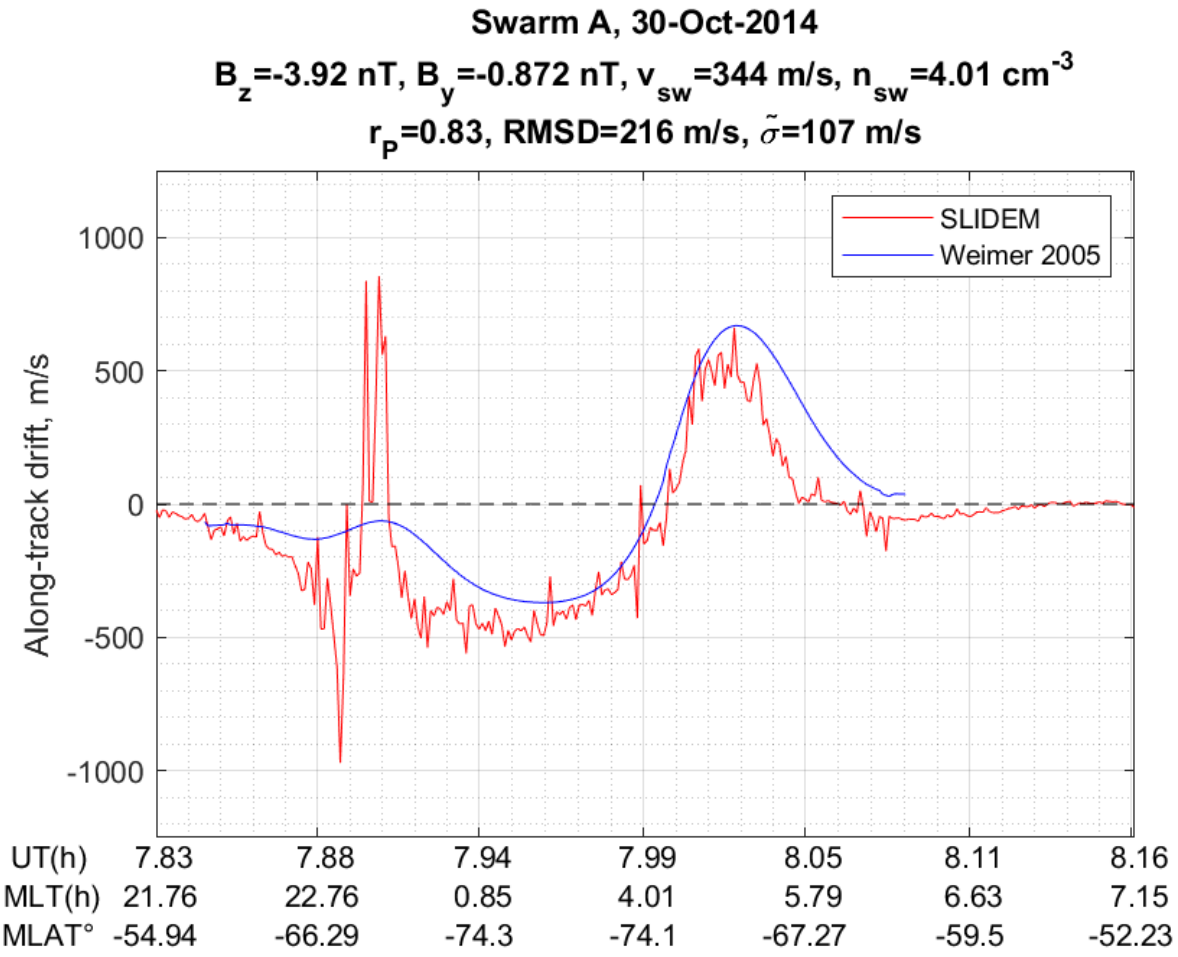

Figure 2: SLIDEM estimate and Weimer (2005) model of along-track ion velocity during an auroral zone crossing, after detrend has been applied to the SLIDEM measurements. Figure courtesy Levan Lomidze.

3.5 Operational implementation

The operational processor is written in C. The source code is available at https://github.com/Swarm-DISC/SLIDEM, and it is released under the terms of the GNU General Public License Version 3.0 (GPL3).

The processor is assumed to run on a Unix operating system. The processor depends on the following external tools and libraries:

- CMake Version 3.0 or greater
- GNU Scientific Library (latest version)
- NASA CDF library version 3.8
- BASH (Bourne-again shell)

The IRI2016 upper-atmosphere ion composition model has been ported to C and is included in the iri2016 subdirectory.

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Build and installation instructions for a unix-based operating system are including in the source distribution. The processor is run using the following syntax.

```
slidem satelliteLetter yyyymmdd lpDirectory modDirectory magDirectory exportDirectory
```

Here, lpDirectory specifies the location of LP input files (2 Hz HM and 16 Hz FP CDF files), modDirectory is the location of the Swarm L1B 1 Hz MOD position files, magDirectory is the location of the Swarm L1B 1 Hz MAGx_1B product, and exportDirectory specifies where to write the output CDF and metainfo files.

On computer systems with multiple processors, the program “slidemParallel” can be used to process long time intervals of SLIDEM data (including full mission reprocessing). It has the following syntax.

```
slidemParallel satellite lpDirectory modDirectory magDirectory exportDirectory
startyyyymmdd endyyyymmdd nthreads
```

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