





Data, Innovation, and Science Cluster Swarm Swarm Langmuir Probe Ion **Density and Effective Mass: Validation** Report

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Swarm Data, Innovation, and Science Cluster

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Record of Changes

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Initial vers.	Draft	1dA	20 Jan 2021
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1 Introduction

This document reports on the validation results of the Swarm Langmuir Probe Ion Density and Effective Mass (SLIDEM) data products: ion density, effective mass, and along-track ion drift. These parameters are estimated using a combination of ion admittance (in ion saturation) and faceplate current measurements from the Swarm Langmuir Probes (LP) under the assumption of the orbit-motion-limited (OML) description of the Langmuir Probe I-V characteristic curve, modified to incorporate empirical corrections revealed by Particle-In-Cell simulations (Lira Resendiz et al., 2019, 2021). Details of the analysis method are provided in [RD-1] and [RD-2].

Peer-reviewed studies of the SLIDEM products and published scientific results that are based on these products comprise the de-facto validation of the products. [RD-2] (Pakhotin et al., 2022) is intended to be a first step of validation. This validation report supplements [RD-2] with additional validation results that were deemed beyond the scope of the peer-reviewed article.

The validation is performed on representative long-duration time periods and is compared against estimates from the International Reference Ionosphere (IRI) 2016 empirical model for ion density and effective mass, and against the Weimer 05 model for along-track ion drift. Further assessment of ion effective mass is made using estimates of ion composition from the Swarm Echo (ePOP) IRM during conjunctions with Swarm A, B or C. Conjunctions of Swarm B with Swarm C or Swarm A when the two orbits are approximately 90 degrees apart in right ascension of their ascending nodes allows comparison of SLIDEM alongtrack drift from one satellite with TII cross-track ion drift from the other satellite.

The results show that SLIDEM (hereafter also referred to as the "Ion Drift, density, and effective Mass product", or in short the IDM product) qualitatively reproduces the expected effective mass variations in line with IRI estimates in the low-latitude regions where ion drifts may be neglected. In the high-latitude regions, effective mass is still calculated assuming zero ion drift, but flagged to indicate that this assumption may be violated.

For ion density, the incorporation of a variable effective mass as per the SLIDEM methodology results in improved statistical agreement with IRI estimates compared with the L1b ion density data product, in particular on the nightside (where effective mass deviates significantly from 16 AMU).

For along-track ion drift, periods of periods of noise exist in the SLIDEM product. Nevertheless, geophysically relevant features are visible in statistical comparison with Weimer 05 maps, and very good agreement is observed with Weimer 2005 for selected individual auroral zone crossings.

Additionally, simulations have been carried out using the PTetra particle-in-cell code, to verify that the assumptions inherent in the SLIDEM methodology hold and no additional significant effects are neglected. Seven overflights by Swarm of ground station radars have been selected – three at low latitudes with Jicamarca, two at mid-latitudes with Millstone Hill, and two at high latitudes for EISCAT-Tromso. The conjunctions, for each radar, were selected both during dayside and nightside periods. The inputs of ambient plasma parameters taken from the ground radar measurements, from Swarm, and from International Reference lonosphere 2016. The outputs were simulated Langmuir probe admittance and faceplate current measurements. The results of the simulations were found to be sufficiently inconsistent with the expected empirical values that further investigation is recommended to understand the causes of the discrepancies. The Swarm A measurements broadly follow the expected trend, albeit with significant scatter across the conjunction dataset that may be explained by uncertainty in both the ion density and ion composition.







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The results presented below demonstrate that the SLIDEM methodology provides estimates of ion effective mass, ion along-track drift, and ion density showing geophysical variability. Data quality flagging is based on a cautious approach involving the status of the processing algorithm steps and the flagging of input data. Error estimates remain to be characterized quantitatively; accuracy can be estimated from a sensitivity analysis. The SLIDEM data are of sufficient quality to warrant distribution to the Swarm Cal/Val community for review and use and continued generation and improvement of the products.

Several individuals assisted with various aspects of this validation study. Particle-in-cell simulations were performed by Akinola Olowookere under the supervision of Prof. Richard Marchand; this contribution was made by University of Alberta under contract to University of Calgary as part of this work and the results are presented in [RD-19]. Dr. Matthias Förster provided scientific consultation to the project, including IRI density calculations, independently checking the UCalgary processing approach, and providing analysis of satellite potential data quality. Levan Lomidze generated plots of the statistics and time series of ion drift in comparison with the Weimer 2005 model. Alexei Kouznetsov generated lists of conjunctions of the ePOP and Swarm satellites for both the ePOP IRM and Swarm-Swarm conjunction studies. Victoria Foss processed ePOP data to estimate the relative concentration of H+ and O+ from IRM time of flight data. Matthias Förster reviewed a draft of this report, and Ivan Pakhotin contributed to previous revisions.

1.1 Scope and applicability

This document is a deliverable of the Swarm Langmuir Probe Ion Density and Effective Mass 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-CO-DTU-GS-123, Rev: 1A 2019-10-08, Subcontract SLIDEM 3.1.

2.2 Abbreviations

A list of acronyms and abbreviations used by Swarm partners can be found <u>here</u>. 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
EUV	Extreme Ultraviolet
IDM	Ion drift, density, and effective mass product
OML	Orbital Motion Limited
PIC	Particle-In-Cell
SLIDEM	Swarm Langmuir Probe Ion Drift, Density, and Effective Mass product
ТВТ	Truhlik-Bilitza-Triskova high-altitude ion composition model







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2.3 Reference Documents

The following documents contain supporting and background information.

- [RD-1] SW-TN-UoC-GS-002, Swarm LP Ion Drift and Effective Mass Product Definition
- [RD-2] 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-3] SW-RN-IRF-GS-004, Extended EFI LP Data FP Release Notes
- [RD-4] SW-RN-IRF-GS-005, Extended Set of Swarm Langmuir Probe Data
- [RD-5] 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.
- [RD-6] Lira, P. A. R., 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-7] Resendiz Lira, P. A., & Marchand, R. (2021). Simulation inference of plasma parameters from Langmuir probe measurements. Earth and Space Science, 8, e2020EA001344. <u>https://doi.org/10.1029/2020EA001344</u>
- [RD-8] Truhlik, V., D. Bilitza, and L. Triskova (2015), Towards better description of solar activity variation in the International Reference Ionosphere topside ion composition model. Advances in Space Research, Volume 55, Issue 8, 15 April 2015, Pages 2099-2105. <u>https://doi.org/10.1016/j.asr.2014.07.033</u>
- [RD-9] SW-RN-UoC-GS-004, EFI TII Cross-Track Flow Data Release Notes
- [RD-10] Lomidze, L., Burchill, J. K., Knudsen, D. J., Kouznetsov, A., & Weimer, D. R. (2019). Validity study of the Swarm horizontal cross-track ion drift velocities in the high-latitude ionosphere. Earth and Space Science, 6.
- [RD-11] Lomidze, L., Knudsen, D. J., Burchill, J., Kouznetsov, A., & Buchert, S. C. (2018). Calibration and validation of Swarm plasma densities and electron temperatures using ground-based radars and satellite radio occultation measurements. Radio Science, 53.
- [RD-12] SW-RN-UoC-GS-004, EFI TII Cross-Track Flow Data Release Notes
- [RD-13] Weimer, D. R. (2005). Improved ionospheric electrodynamic models and application to calculating Joule heating rates. Journal of Geophysical Research, 110, A05306.
- [RD-14] SW-TN-UoC-GS-004_2-3_SITE, Swarm Ion Temperature Estimation: Processing algorithm description
- [RD-15] Hussain, S. and Marchand, R., 2014. Sheath-induced distortions in particle distributions near enhanced polar outflow probe particle sensors. Physics of Plasmas, 21(7), p.072902.







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- [RD-16] Marchand, R. and Hussain, S., 2015. Aberrations in Particle Distribution Functions Near
 e-POP Particle Sensors. IEEE Transactions on Plasma Science, 43(9), pp.2776-2781.
- [RD-17] Yau, A.W., Howarth, A., White, A., Enno, G. and Amerl, P., 2015. Imaging and rapid-scanning ion mass spectrometer (IRM) for the CASSIOPE e-POP mission. Space Science Reviews, 189(1), pp.41-63.
- [RD-18] Yau, A.W. and Howarth, A., 2016. Imaging thermal plasma mass and velocity analyzer. Journal of Geophysical Research: Space Physics, 121(7), pp.7326-7333.
- [RD-19] SW-TN-UoC-GS-004_3-1_SLIDEM_PIC_Report (Olowookere and Marchand, 2021). Report of simulation results made for the SLIDEM project made under contract from the University of Calgary.
- [RD-20] Burchill, J. K., and M. Förster (2019): Final report of the Langmuir Probe Pre Study on deriving along-track ion bulk drift and effective ion mass from the LP and faceplate currents.
- [RD-21] Förster, M., I. Pakhotin, J. K. Burchill, and R. Marchand (2021): The Effective Ion Mass estimated from Swarm Langmuir Probe and Faceplate data (SLIDEM project), poster, Swarm Data Quality Workshop 2021, 11-15 Oct 2021, Athens, Greece.



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This section presents an assessment and description of the inputs to the SLIDEM processing and highlights the findings of [RD-2] in terms of revised ion density, ion effective mass, and ion drift. The Swarm Echo IRM and Swarm-Swarm cross-track and along-track drift comparison studies are presented. The preliminary release of the SLIDEM dataset (PREL IDM_2 0101) was used in this study.

3.1 Validity of input parameters

Inputs used in processing the SLIDEM products are listed in Table 1 of [RD-1]. In all cases the validity of the processing software for reading the input files has been verified by plotting time series of the input parameters for several different input files. As this is not an operational processor, no further functional testing or validation of the software has been performed (e.g., Unit Testing). Aside from checking that the import algorithms work, the inputs themselves are not validated. This study rather examines the validity of the final products.

There are known issues of data quality in electron temperature ([RD-11]) and satellite potential ([RD-20]) and these naturally flow into to the SLIDEM products. Where available, input parameter flags, such as those provided for the electron temperature and satellite potential, are incorporated into the SLIDEM product flags. Photoelectrons (of either ionospheric or satellite origin) will alter the current and admittance to some extent. This is not accounted for in the initial release of the SLIDEM product.

The faceplate current is obtained from the EXTD LP_FP data product available in the advanced folder of the Swarm DISS data portal ([RD-2] and [RD-4]). The faceplate current product has no flag associated with individual measurements. Measurements are available only when the faceplate voltage has been biased to -3.5 V, due to the unreliability of estimating ion density for faceplate voltages of -1 V, which is the case when the TII is operating in science mode or daily scrubbing mode. No independent validation of the raw face-plate currents is available.

Being a level 0 data product, ion admittance is not a readily available Swarm measurement parameter. Its value for the SLIDEM processing is derived from the ion density parameter of the EXTD LP_HM data product ([RD-4]) using the pure O+ and stationary ionosphere approximations used for that density product. The LP_HM product flags are thus assumed to capture adequately the quality of the ion admittance measurement. The real part of the ion admittance (the specific quantity used for SLIDEM) is supposed to be a positive number, although in practice it is often observed to be negative. The LP_HM processing adds a small ad hoc positive offset (of order 10^{-10} A/V) to the raw measurement to reduce the occurrence of negative admittance values. This places an effective lower limit on the sensitivity of the ion admittance which will propagate into the SLIDEM products. In such cases this results in an imaginary quantity for some products, and this is flagged.

The empirical "modified OML" corrections to the faceplate current and Langmuir probe ion current ([RD-6] and [RD-7]) are modelled with three parameters for the faceplate corrections and five parameters for the LP probe current (and ion admittance). It is anticipated that these parameters have a range of validity in terms of environmental parameters (electron density, temperature, ion drift, magnetic field, ion composition, and satellite floating potential) that is less than actual environment conditions. Moreover, the simulations on which the parameters are based modelled a short satellite; this may result in biases of the correction parameters. The modified OML model parameters may be viewed as calibration coefficients which could be adjusted to handle real-world conditions of satellite-environment interactions. For the initial SLIDEM release, the correction model parameters are incorporated as published, but further research into







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characterizing the physics of the satellite-plasma interactions and optimizing the correction terms may improve the quality of the SLIDEM products.

3.2 Revised Density Product

By including the faceplate current in the LP analysis, which removes one of the assumptions of stationary plasma or pure oxygen ions, a new ion density estimate is obtained. It is useful to examine this revised ion density product with respect to the International Reference Ionosphere-2016 (IRI-2016) ion density [RD-5] as an overall validation of the SLIDEM methodology. Both SLIDEM and the nominal Swarm Level1b density product were compared with IRI-2016, and residuals were obtained. An example time interval for Swarm A is shown in Figure 3-1 using a linear scale on the ordinate. While in general both L1b and SLIDEM track the IRI-2016 estimates both at low and high latitudes, and across both dayside and nightside MLT sectors, the density estimate for SLIDEM is generally lower and closer to IRI than the L1b density, and this difference is most pronounced on the nightside. This is expected due to previously outlined considerations, where effective mass is not 16 AMU and, particularly on the nightside, it is expected to be significantly less than 16 AMU. In this case SLIDEM density is in better agreement with IRI-2016 density estimations.



Figure 3-1: Ion density time series for Swarm A

To examine a greater time range of the data, quasi-dipole (QD) latitude was transformed into 'argument of orbit' which is identical to QD latitude on the ascending pass, and equal to QD latitude + 180 degrees on the descending pass. An example 30-day interval plotted in this way is displayed in Figure 3-2 for Swarm A for January 2018. For all three density estimations density is highest at low QD latitudes, in line with expectations, and it is highest on the dayside (since this is at the descending track in January 2018, its argument







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of orbit is 180 at the equator). This is also as expected because the dayside equator is sunlit leading to higher plasma densities due to ionization by solar EUV. The orbit becomes more dawn-dusk due to local time drift, and thus the dayside and nightside densities become more comparable in magnitude of the ion density. SLIDEM captures the dynamics observed both by L1b and IRI-2016 and captures the correct magnitudes of density. However, due to frequent gaps in coverage (SLIDEM is currently only calculated when the faceplate voltage bias is -3.5 V) multiple data gaps exist. An evaluation as to whether the SLIDEM approach still applies when the faceplate bias is not -3.5 V is a candidate for future investigation.



Figure 3-2: Ion density statistics for Swarm A, January 2018.

Residuals of the SLIDEM density and the L1b product directly with respect to the IRI-2016 density are shown in Figure 3-3 for the same 30-day interval.











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Figure 3-4: Ion density estimates using SLIDEM (a), ESA Level1b product (b) and IRI-2016 (c), as well as SLIDEM-IRI2016 residuals (d) and L1b-IRI2016 residuals (e) for Swarm B, for 1-31 January 2018.



Figure 3-5: Ion density estimates using SLIDEM (a), ESA Level1b product (b) and IRI-2016 (c), as well as SLIDEM-IRI2016 residuals (d) and L1b-IRI2016 residuals (e) for Swarm C, for 1-31 December 2018.

During days 200-250 when arguments of orbit are between +-50 deg, the SLIDEM product delivers lower residual when compared with IRI relative to the existing methodology. Overall, the residual is lower for the entire interval. This is due to the SLIDEM methodology capturing changes in effective mass, thus the assumption of M_i_eff = 16 AMU is relaxed. This is particularly relevant on the nightside where concentrations of H+ ions can reach 5-10% on Swarm A, meaning M_i_eff can drop to below half of the 'nominal' 16







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AMU value. If average residuals between IRI-2016 and L1b and IRI-2016 and SLIDEM are calculated elementwise for the entire 30-day period, excluding in both cases those elements where SLIDEM returns no data, then the average SLIDEM-IRI2016 residual is 43.9% while the average residual between L1b and IRI-2016 is a higher 55.2%, demonstrating that the superior agreement on the nightside significantly impacts overall agreement.

For Swarm B (Figure 3-4: lon density estimates using SLIDEM (a), ESA Level1b product (b) and IRI-2016 (c), as well as SLIDEM-IRI2016 residuals (d) and L1b-IRI2016 residuals (e) for Swarm B, for 1-31 January 2018.), which is at higher orbit, and thus has even higher fractions of light ions, the differences are more pronounced. For the same time period as previously (1-30 Jan 2018), the mean absolute of the residual between IRI2016 and the ESA L1b product is 101.5%, while that between SLIDEM and IRI2016 is only 41.8%. As with Swarm A, residuals appear to be largest in shadow, presenting further evidence that inaccurate assumption regarding nightside effective mass inherent in the L1b product is primarily responsible for large differences in density estimations. SLIDEM removes the effective mass assumption and as such improves agreement, both statistically and on a case-to-case basis.

For Swarm C the availability of SLIDEM data is higher, particularly between mid-2018 and mid-2019 when the faceplate voltage at -3.5 V even during TII science operations. It is thus possible to calculate statistics without frequent data gaps. Figure 3-5: Ion density estimates using SLIDEM (a), ESA Level1b product (b) and IRI-2016 (c), as well as SLIDEM-IRI2016 residuals (d) and L1b-IRI2016 residuals (e) for Swarm C, for 1-31 December 2018. shows the result of Swarm C density estimations for the time period 1-31 December 2018, with SLIDEM-IRI2016 mean absolute residual yielding 47.2% vs 57.5% for Level1b. This is approximately in line with the results obtained from 1-31 Jan 2018 for Swarm A.

3.3 Ion Effective Mass Product

3.3.1 TBT (IRI) high-altitude ion composition model

SLIDEM ion effective mass estimates are compared here against an empirical model available in the SLIDEM product files as the "M_i_eff_TBT_model" variable. This quantity is calculated from the IRI high-altitude ion composition model as described by [RD-8] and named here the "TBT" to distinguish it from IRI proper due to it being adapted to the C programming language (i.e., IRI proper is not run to calculate this quantity). The TBT model provides composition estimates for four ions (O+, N+, He+, and H+) above 350 km (above 500 km under certain conditions) in terms of invariant dip latitude, time, and the F10.7 solar radio flux proxy.

At high latitudes (|QDLat| > 50 degrees), the M_i_eff product is still calculated assuming zero ion drift, but these entries are flagged to indicate this assumption may be violated. Figure 3-6 shows the ion effective mass as compared with IRI-2016 during a representative time on 1 May 2018. Note that values are plotted without regard to measurement flags to give a clear indication of the range of values in the products. Measurement flags should be used for scientific study; these signify issues such as M_i_eff less than 1.







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Figure 3-6: Ion effective mass time series for Swarm A on 1 May 2018.

It may be seen that the variations in effective mass due to dayside-nightside asymmetry are similar for both SLIDEM and the TBT model. A dashed red line denotes the 100% O+ effective mass, and it is unusual to expect M_i_eff values above that as that would imply heavy elements/molecules which are typically present in trace amounts in the topside ionosphere. SLIDEM does return values above 16 AMU, which are hence likely in error; some of this, however, is associated with strong ion drift in the auroral region and is flagged in the dataset. The SLIDEM data also show significant small-scale structure which is missing in the IRI-2016 output. There is currently no way to validate the extent to which such small-scale variations are of geophysical origin, possibly such as plasma bubbles, ion fountains, or discrete arcs.

Another interesting feature not captured by IRI-2016 is the abrupt drop in M_i_eff at the nightside on crossing the equator, e.g. around 0130 UT and just after 03 UT in Figure 4(b). It is currently unclear whether this is a geophysical effect or the result of e.g. the relative change of orientation of magnetic field causing the magnetic field lines carrying electrons to the Langmuir probe to become shielded by the body of the satellite on one hemisphere but not the other. The OML corrections based on [RD-6] and [RD-7] are possibly invalid at such low effective mass values, as the simulations did not include scenarios where ion effective mass is less than about 4 AMU. We note that the beta correction term [RD-7] involves a ratio with ion effective mass in the denominator. When this term is large it represents positive feedback in the Langmuir probe radius correction which results in smaller ion effective mass. This may be the cause of poor estimates when the ion effective mass is small. This is a case for further investigation and possible refinement of the algorithm, such as limiting the correction term magnitude or expanding the simulation parameter space.

Effective mass statistics for one year (2018) are displayed in Figure 5, where SLIDEM is validated against IRI-2016. SLIDEM effectively captures the effective mass changes due to orbital drift of the satellite over time, in terms of both the magnitudes and the temporal evolution of the values. There is overall an excellent agreement between the SLIDEM effective mass and the TBT (IRI) model.





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Figure 3-7: Ion effective mass (in AMU) statistics for Swarm A during 2018.









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Figure 3-8: Ion effective mass statistics for Swarm B during 2018. Effective mass is in atomic mass units.

3.3.2 Swarm Echo (ePOP) IRM

A list of conjunctions between Swarm Echo and each of the Swarm A, B and C satellites spanning the full Swarm operation history (up to 24 Oct 2021) was compiled by Alexei Kouznetsov (University of Calgary). This provides an opportunity to compare the SLIDEM effective mass product with ion composition measurements of the ePOP IRM. The conjunction criteria select events at low and mid latitude (equatorward of 50 degrees QD magnetic latitude) such that the satellites are within 300 km of one another in the horizontal plane and within 20 km of each other vertically. The tight constraint on vertical separation was chosen as a trade-off between the number of events and the accuracy of the comparison, given the locally exponential falloff in plasma concentration (and hence variation in relative ion compositions) with altitude. A total of 43 conjunctions were identified involving Swarm A, 33 involving Swarm B, and 41 involving Swarm C. Of these, one Swarm A conjunction had both the IRM operating and had the Swarm EFI faceplate voltage set to -3.5 V (i.e., the faceplate current measurement was available). No such conjunctions were found for







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Swarm B. Due to the significantly more frequent operation of Swarm C's faceplate voltage at -3.5 V, 13 conjunctions were found with measurements from both ePOP and Swarm.

IRM summary plots and data are available from ESA's Swarm-DISS data portal. Figure 3-9 shows an example of IRM data for a Swarm C conjunction at 16 June 2020 at 04:36:48 UT. The vertical separation of the satellites was 9.7 km, and their lateral separation was 232 km. The ion time of flight (TOF) spectrum in the lower-left panel of Figure 3-9 shows prominent signals near bin 75 and at bins less than 50. This indicates at least two, possibly more, ion species. IRM ion composition measurements are not available from ESA's data portal; ion composition was estimated from the raw IRM data using a model developed and run by Victoria Foss at University of Calgary. Details of the data reduction are beyond the scope of this report. Ion composition estimates for the Swarm A event and 11 of the 12 Swarm C events, courtesy Ms. Foss, is shown in Table 1, along with the corresponding ion effective mass assuming only O+ and H+ ion species. The processing derives the ratio of H+ to O+ concentrations and gives an estimate for satellite floating potential. These values are preliminary and have not been validated with independent measurements.



Figure 3-9 ePOP IRM summary plot for Swarm C conjunction 16 June 2020, 04:36:48 UT.







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Table 1 ePOP-Swarm conjunction results.

Swarm satel- lite	Date	Univer- sal Time	QD Lat (deg)	MLT (hour)	IRM H+/O+	IRM H+ (%)	ePOP SC Potential (V)	IRM 2-ion 8s average ion effective mass (AMU)	SLIDEM ion ef- fective mass (AMU)	TBT model ion effec- tive mass (AMU)
Swarm A	23-Jan-2019	00:10:15	25.4	1.0	0.0072	0.72	1.3	14	1.2	4.7
Swarm C	10-Aug-2017	21:26:44	42.3	0.8	0.048	4.6	1.5	9.4	-	6.6
Swarm C	12-Aug-2017	13:56:01	40.0	23.9	0.013	1.3	0.50	13	7.3	6.5
Swarm C	13-Aug-2017	10:10:46	46.5	23.9	0.0088	0.87	0.60	14	6.3	11
Swarm C	05-Jan-2019	02:52:20	-11.9	3.2	0.15	13	1.4	5.4	-	5.0
Swarm C	05-Jan-2019	23:05:03	-3.1	2.7	0.020	2.0	1.0	12	-	4.4
Swarm C	22-Sep-2019	11:08:58	-44.1	15.0	0.33	25	-3.0	3.4	16	12
Swarm C	02-Jun-2020	11:09:55	-47.9	5.1	0.43	30	0.48	2.9	7.4	5.4
Swarm C	16-Jun-2020	04:36:48	-17.7	2.9	1.4	58	-	1.7	2.9	3.3
Swarm C	17-Jun-2020	02:25:03	-23.8	3.3	1.5	60	-	1.6	2.8	3.5
Swarm C	01-Jul-2020	15:17:21	-37.4	13.1	1.2	54	-2.1	1.8	17	11
Swarm C	05-Jul-2020	03:15:56	-37.6	13.0	0.53	35	-3.1	2.6	17	11

Figure 3-10 shows SLIDEM results for the Swarm C – ePOP conjunction on 16 June 2020. Shown from top to bottom are revised ion density, ion effective mass, modified OML faceplate area, modified OML Langmuir probe radius, electron temperature (unadjusted EXTD product) and satellite potential (EXTD product). This is the best of the 13 cases examined, with all three estimates of ion effective mass within a couple of AMU of each other.

As shown in Table 1, most of these conjunctions had poorer agreement between the IRM composition and SLIDEM and the TBT model. An example of poor agreement is shown in Figure 3-11. Spacecraft charging is known to significantly affect the ion trajectories in the vicinity of the ePOP IRM ([RD-16], [RD-15]), but in contrast to the Swarm empirical modified OML corrections, there is no empirical correction model for the ePOP satellite-plasma interaction. The uncertainties of the IRM ion composition estimates are presumably large. Significantly, however, the results in Table 1 and Figure 3-10 reveal a consistent finding: there is need to incorporate additional information in the processing of LP data: the assumption of pure O+ is routinely violated – dramatically so at low and middle latitudes.







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Figure 3-10 Swarm C SLIDEM product parameters for ePOP conjunction 16 June 2020.









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3.4 Swarm Along-Track Ion Drift Product

Estimation of the component of ion drift parallel to the satellite velocity vector, the so-called along-track ion drift, is challenging. For example, the Swarm TII sensors are directly sensitive to variations in kinetic energy of the rammed plasma ions. A change in ram speed from the nominal ~7.6 km/s (4.8 eV for O+, neglecting the effects of satellite potential) by 100 m/s corresponds to a change in ram kinetic energy of only 0.13 eV.

The aim in developing the SLIDEM along-track ion drift estimate has been to avoid reliance on estimates of satellite potential. This motivated the choice of faceplate current rather than LP ion saturation current in the method, as the probe current depends directly on the satellite potential. It has been found, however, that the empirical corrections to the ion admittance and faceplate current, which are functions of the satellite potential, do improve the ion effective mass estimates (noticeably for masses at the upper end of the measurement range); they are therefore used also for the along-track ion drift estimates.







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Figure 3-12 Example SLIDEM along-track drift for Swarm A on 28 October 2014.

Quantitative validation of the correction models and the satellite potential inputs has not been performed in this work and warrants further investigation. Here the focus is on validating the ion drift itself using several methods described in the next sections.

The along-track drift estimates have other limitations, such as the need to assume a value for the ion effective mass, because, assuming it is required to estimate the ion density, both along-track drift and ion effective mass cannot be estimated simultaneous. The IRI high altitude empirical composition model (TBT) at high latitudes is considered here a rational choice over assuming pure O+. Even so, the TBT model by design does not capture much of the observed variability in ion composition, and this limits a priori the accuracy of the along-track ion drift. Additional errors will arise from satellite-plasma interactions, which are only partly captured by the correction models of [RD-6] and [RD-7] as discussed above.

One manifestation of the various inaccuracies is a large offset in the along-track drifts, clearly seen in the example of Figure 3-12 labelled "V_i_raw". This event consists of a satellite pass over the southern polar region with the closest approach to the pole being near 04:25 UT. The quantity V_i_raw is the direct output of the SLIDEM high-latitude processing algorithm, and an offset of approximately 800 m/s is evident at the beginning and end of the event, corresponding to QD latitude near -50 degrees. An ad hoc linear detrend is applied to get the quantity V_i, the SLIDEM along-track drift. This is the same technique used in the TII cross-track ion drift processing to remove instrumental offsets [RD-9]. The V_i data should be used generally for geophysical studies, whereas the V_i_raw data are expected to be useful in studies of satellite-plasma interactions and error sources, for example.

3.4.1 Comparison with empirical ion drift model (Weimer 2005)

Levan Lomidze (University of Calgary) has generated summary plots of SLIDEM along-track ion drift (V_i) and Weimer 2005 empirical model drifts using the method developed for [RD-10]; the results are shown in Figure 7 for IMF By < 0 and Bz < 0 and for the southern hemisphere. Weimer 2005 model drift statistics are shown in the top pair of polar plots and the SLIDEM results are shown at bottom. Plotted are medians of each bin. Magnetic local time and QD latitude are called out in a circular grid. The along-track drift has been projected into magnetic eastward (left panels) and magnetic northward (right panels) components. Some







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large-scale high-latitude convection features are evident, such as the extended band of northward (antisunward) drift on the nightside near -65 degrees QD latitude, and reversals seen in eastward drift along the 03 and 15 local time meridians.

Other morphological features have not been captured, and this is taken to be an indication of the general level of accuracy of the ion drift attained, being of order several hundred m/s. That the SLIDEM drifts are often of very small magnitude equatorward of -60 degrees is an indication of the effectiveness of the post-processing linear detrend. Plots showing drifts in both hemispheres for all four cases of IMF By and Bz are provided in Section 5.



Figure 3-13: SLIDEM ion drift statistics for Swarm A (bottom) and the Weimer 2005 model (top).

The Weimer 2005 model is empirical and is not meant to reproduce instantaneous measurements (of ion convection in this application). It is nonetheless interesting and instructive to compare the general flow patterns seen in individual satellite passes over the polar regions for both SLIDEM and Weimer 2005. In Figure 3-14 are plotted nine examples of such passes (plots were generated by Levan Lomidze), chosen for having







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high correlations between the detrended SLIDEM drifts (red) and Weimer 2005 empirical drifts (blue). SLIDEM drifts have been averaged to 1 s intervals. Excellent agreement can be found over a larger velocity range than is available in the polar plot representations which are based on median statistics for the entire Swarm mission. These examples are for Swarm A; similar results can be seen for Swarm B and C.



Figure 3-14 Examples of highly correlated SLIDEM ion drifts (red) and Weimer 2005 drifts (blue).

The Weimer 2005 empirical drifts provide a useful reference for assessing the SLIDEM ion drift data quality. The SLIDEM along-track ion drifts can complement the TII cross-track ion drift measurements by providing a heretofore missing third component of the drift vector statistically and in cases that multiple Swarm satellites sample a region simultaneously. The SLIDEM drifts may further lead to improved methods for estimating and assessing the TII along-track ion drifts.

3.4.2 Swarm-Swarm conjunctions

In this section ion drifts measured from two satellites, Swarm B and one of Swarm A or Swarm C, during conjunctions for which are satellites' orbital planes intersect at nearly 90 degrees (local time different near six hours) are compared. This allows assessment of the along-track ion drift estimate from one satellite with respect to the cross-track ion drift estimate, (from the TCT02 dataset; [RD-9], [RD-10]) from the other satellite. Alexei Kouznetsov (University of Calgary) compiled a list of conjunctions for which the satellites' horizontal separation at the time of closest approach was less than 300 km and the satellite tracks were no more than 10 degrees from perpendicular. The entire mission history was considered, and the conditions







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for such conjunction criteria were met from about mid 2017 to mid 2018, consistent with the difference in orbital planes for Swarm B and the lower pair during this period.

A total of 174 such conjunctions were identified for Swarm B and Swarm A, of which 60 events were found for which both SLIDEM and TCT data were available. Quality flags were not considered in either dataset, but events were examined for which both datasets had sufficient drift data with magnitudes less than 5 km/s. Only eight events survived the data select process; the best case is shown in Figure 3-15. All cases are shown in Appendix A. For each event shown, the geometry of the satellite track crossing is shown on the left and the "spatial series" of drift versus QD latitude is shown on the right. It is assumed for this analysis that the ionosphere is sufficiently stationary on timescales of the revisit times (of order 1 minute) at the latitude of closest approach. The reference latitude (dashed line) is usually taken to be that of the satellite measuring the cross-track ion drift. Violation of the assumption of stationarity on timescales of less than one minute (not uncommon at high latitudes) will affect the quality of the validations.

For the Swarm B and Swarm C conjunction analysis, 172 crossings met the orbital selection criteria and 42 of these had the respective instruments operating in the required modes. The same analysis was performed as for the Swarm B and Swarm A conjunctions. Because Swarm C operates in TII science (ion drift measurement) mode far less often than Swarm B (whereas Swarm A and B have comparable TII science duty cycles), there are more conjunctions with Swarm C producing SLIDEM measurements than Swarm A. A total of 15 events with suitable data overlap were identified, which are shown in Appendix A. The best case is shown in Figure 3-16.







Figure 3-16 Swarm B and Swarm C conjunction analysis.



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3.5 Particle-In-Cell Simulation Results

To investigate the extent to which relevant physical processes have been captured by the SLIDEM methodology, measurements from seven overflights by Swarm A of ground radar sites (Jicamarca, Millstone Hill, and EISCAT-Tromso) have been used as inputs to a series of particle-in-cell (PIC) simulations performed at University of Alberta as described in [RD-19]. This was done to cover low latitudes (Jicamarca), mid-latitudes (Millstone Hill) and high latitudes (EISCAT-Tromso). For each radar, one dayside and one nightside conjunction was identified. In addition, a second nightside conjunction was identified between Swarm A and Jicamarca, where the floating potential of Swarm A recorded an unusually low value (-8.42 V), to test whether this would invalidate the SLIDEM methodology.

For each of the seven conjunctions, values for electron density, electron temperature, and ion temperature have been obtained from the ground radar (Case A), from the Swarm satellite itself (Case B), and from IRI-2016 (Case C). For Case B, the ion and electron temperatures were obtained using the methodology of [RD-11]. In addition, ion percentage ratios were also obtained for each case from IRI-2016, and the magnetic field direction was recorded from the Swarm VFM. This information, along with Swarm A floating potential, was used as an input to the PIC simulation.

The simulations provided: simulated faceplate current, simulated faceplate admittance, and the currents for both Langmuir probes. These outputs were then compared with actual observed outputs recorded from Swarm A during those times, as well as the theoretical currents and admittances which would be expected (see theoretical treatment in [RD-1] and [RD-2]). Faceplate bias was -3.49 V in all cases; ion ram speed was 7620 m/s.

An example of the PIC results for a dawn Jicamarca event on 28 May 2015 at 06:38 UT is shown in Figure 3-17. The key simulation parameters were:

- Ion density (from ISR): 2.1x10¹¹ m⁻³
- Ti: 1641 K
- Te: 1641 K
- Ion composition (%): H+: 3.8%, He+: 0.2%, O+: 94.8%, N+: 1.6%
- Satellite potential: -1.55 V
- Magnetic field: North: 20320 nT, East: 762 nT, Centre: -3071 nT

Electric potential is shown in Figure 3-17 (a) and electric current density is shown in Figure 3-17 (b). An enhancement in faceplate current density is visible at the perimeter of the faceplate, whereas a depletion in current density is seen on the satellite structure in the vicinity of the faceplate. This is a manifestation of light ions, especially, being pulled towards the faceplate, resulting in a larger ion collection cross section. Further details on the simulations are available in University of Alberta report commissioned by UCalgary under this contract [RD-19].







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Figure 3-17 Example PIC simulation results showing (a) electric potential and (b) current density.

The simulated current densities were analyzed, and the results are displayed in Figure 3-18 (a). Theoretical current is estimated according to the modified OML model using electron density and temperature from radar (R), Swarm SITE (S), and IRI (I) estimates of electron density and temperature. Colours indicated the radar overflown by Swarm A (JRO – Jicamarca; MH – Millstone Hill; ET – EISCAT Tromso) and the part of the orbit (day, night, dawn, or dusk, and whether the satellite was ascending or descending in latitude). The dashed line represents agreement between theory and measurement. Swarm A measurements of faceplate current for the same theoretical values are shown in Figure 3-18 (b). Similar plots are shown for ion admittance for PTetra (Figure 3-18 c) and Swarm A (Figure 3-18 d).

Both faceplate current and ion admittance follow the expected linear trend. The PTetra results for faceplate current show high precision The PTetra ion admittance exhibits a large variability. It is noted that the PTetra model has been refined somewhat over the one used in [RD-6] and [RD-7], mainly in terms of using a finer mesh to better resolve the electron Debye scale and adjusting the voltage of the spherical probe shields. The origin of the discrepancies is not known and will require further PIC simulations and analysis, possibly resulting in a revised set of OML corrections for ion admittance. This activity requires a significant amount of time and is therefore beyond the capability of the present project. It is noted that in the event revised empirical correction models are devised based on the newer PIC simulations, the historical SLIDEM dataset will benefit from reprocessing with the new models.

The Swarm A results have a large scatter in both faceplate current and ion admittance. Scatter in the theoretical faceplate currents arises predominantly from large differences in estimated electron density between the radar, Swarm, and IRI model. The Swarm faceplate measurements are generally explained best by the in situ density from SITE.

A significant amount of scatter may be expected for the ion admittance due to its inverse dependence on ion effective mass, which can vary greatly for small variations in the concentration of light ions. To illustrate, Figure 3-19 shows the theoretical modified-OML ion admittance as a function of ion effective mass for the dayside ascending Jicamarca overflight using the radar density and temperature estimates. The point at upper right is the theoretical admittance for the Swarm A dayside ascending overflight of the Jicamarca incoherent scatter radar facility, using the radar estimates for electron density and temperature and







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IRI estimates for ion composition. An increase in hydrogen ion concentration to 3.5% with concomitant reduction in oxygen ion concentration (lower left point) decreases the expected ion admittance by almost 2 nA/V. This illustrates the difficulty in validating all inputs to the simulations of measurements that depend so sensitively on ion composition.











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Figure 3-19 Effect of ion composition on theoretical ion admittance.

3.6 Validity of Empirical Corrections (Modified OML)

The main SLIDEM products are estimated iteratively because the OML corrections include terms depending on the products (ion density, ion ram speed, and ion effective mass). The number of iterations typically required to converge is about 10 or less. An issue arises when the estimated effective mass is less than about 5 AMU at higher electron temperature and lower ion density, as illustrated in Figure 3-20. Shown are six cases (three ion densities, two electron temperatures) of the reduction in spherical LP effective cross section as a function ion effective mass, or in terms of the delta correction in [RD-7], $-\delta(M_{i,eff}) * 100\%$. According to the empirical formula, the spherical probe has zero area for effective mass of 3 AMU at 2x10¹⁰ m⁻ ³ and 3000 K. This can lead to divide-by-zero in some SLIDEM product estimates. Such cases are flagged in the dataset. The empirical models, however, have been devised based on PIC simulations carried out with effective masses > 4 AMU [RD-7]. In cases of low effective mass, the empirical corrections are rather extrapolations and cannot be relied upon. Future work on improving the SLIDEM products should include efforts to extend the range of validity of the empirical correction models.







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4 Measurement Uncertainty

4.1 SLIDEM parameters

Results of a sensitivity analysis of the SLIDEM ion density, ion along-track drift, and ion effective mass to variations in input parameters provides an indication of the uncertainty of the measurements. Table 2 summarizes the findings. Sensitivities are estimated at three densities; the dependence of ion effective mass and ion drift on uncertainty in ion density (through the OML corrections involving Debye length) can be interpolated from the values in the Table. Nominal conditions are as follows:

- Electron temperature: 1500 K
- Satellite potential: -2.5 V
- Ion effective mass: 9 AMU (corresponding to approximately 5% H+, 95% O+)
- Ion along-track drift: 0 m/s (with satellite speed of 7620 m/s)

A second set of calculations were performed at an electron temperature of 3000 K, allowing estimation of sensitivities at an average temperature of 2250 K where noted in the table.

	land an and a	Sensitivity at given ion density				
SLIDENI Product	input parameter	$N_i = 2x10^4 { m cm}^{-3}$	$2x10^5$ cm $^{-3}$	$2x10^6$ cm $^{-3}$		
Ion density (high latitude)	Effective mass @ 9 AMU	3.0 %/AMU	3.9 %/AMU	4.1 %/AMU		
	Satellite potential @ -2.5 V	-9.4 %/V	-2.2 %/V	-0.85 %/V		
	Electron temperature @ 2250 K	-2.4x10 ⁻³ %/K	-5.4x10⁻⁴ %/K	1.5x10 ⁻⁴ %/K		
Ion density (low latitude)	Effective mass @ 9 AMU	0.38 %/AMU	0.14 %/AMU	0.044 %/AMU		
	Satellite potential @ -2.5 V	1.8 %/V	0.46 %/V	0.020 %/V		
	Electron temperature @ 2250 K	-2.4x10 ⁻⁴ %/K	-8.8x10⁻⁵ %/K	-2.9x10⁻⁵ %/K		
	Along-track drift @ 0 m/s	0.011 %/m/s	0.012 %/m/s	0.013 %/m/s		
Ion effective mass	Satellite potential @ -2.5 V	3.8 AMU/V	0.72 AMU/V	0.26 AMU/V		
	Electron temperature @ 2250 K	-1.0x10 ⁻³ AMU/K	-4.3x10 ⁻⁵ AMU/K	-5.3x10 ⁻⁶ AMU/K		
	Along-track drift @ 0 m/s	2.1x10 ⁻³ AMU/m/s	3.5x10 ⁻³ AMU/m/s	3.9x10 ⁻³ AMU/m/s		
Ion along-track drift	Effective mass @ 9 AMU	4.0x10 ² m/s/AMU	5.2x10 ² m/s/AMU	5.5x10 ² m/s/AMU		
	Satellite potential @ -2.5 V	-1.7x10 ³ m/s/V	-2.5x10 ² m/s/V	-8.5x10 ¹ m/s/V		
	Electron temperature @ 2250 K	6.9x10 ⁻¹ m/s/K	1.5x10 ⁻² m/s/K	1.7x10 ⁻³ m/s/K		

Table 2 Sensitivity of SLIDEM products to uncertainty in input parameters.

4.2 Effects of Spacecraft-Plasma Interactions

The influence of satellite-plasma interactions on the product accuracy is more significant at higher electron temperature and lower electron density, corresponding to increased electron Debye length of the plasma.







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Other effects may be important, such as the variation in collected electron current (including photoelectrons) associated with the orientation of the geomagnetic field, and the presence of anomalous charging in the vicinity of the faceplate and probes, but they are beyond the scope of this study. For the most part, uncertainty in electron temperature of up to 500 K, as may be the case for the unadjusted LP_HM values used in SLIDEM, does not significantly affect the accuracy of the SLIDEM ion density and ion effective mass. At low densities, an error of 500 K in electron temperature corresponds to an error in along-track drift estimates of order 200 m/s.

There is currently no robust method for validating the satellite floating potential estimates provided by the EXTD LP_HM dataset [RD-4]. Two floating potentials are available, one from each of the spherical probes. Shown in Figure 4-1(a) are differences in estimated floating potential from the LP Sweep data for the ascending (nightside, top panel) and descending (dayside, bottom panel) orbits of Swarm C on 30 December 2017 (reproduced from [RD-20]; see [RD-21] for an updated overview of satellite potential statistics). The red curves represent the theoretical difference in potential associated with electromotive force (e.m.f.) arising from motion of the satellite through Earth's core magnetic field. The e.m.f. magnitude is of order no more than 0.1 V in the polar regions. Several features are prominent. The potential difference is greater than 1.5 V routinely at low and middle latitudes for nighttime orbits and greater than the e.m.f. in almost all cases. There is a clear hemispherical asymmetry in the potential difference on the daytime orbits, but of the opposite sign and much larger magnitude than expected for e.m.f. There is a variability of at least 0.1 V and often larger from measurement to measurement. This leads to errors in along-track drift exceeding 100 m/s at low densities in the polar regions. Further investigation of the causes of the large differences in satellite potential estimates is warranted. SLIDEM quality flags are raised when the potential difference exceeds 0.3 V.



Figure 4-1 Swarm satellite potential analysis (from [RD-20]).







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5 Supplementary Figures

5.1 Ion drift: Swarm-Swarm Conjunctions



Figure 5-1 Swarm B and Swarm A conjunction results.







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Figure 5-2 Results from Swarm B and Swarm C conjunction analysis.







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Figure 5-3 Additional results from the Swarm B and Swarm C conjunction analysis.