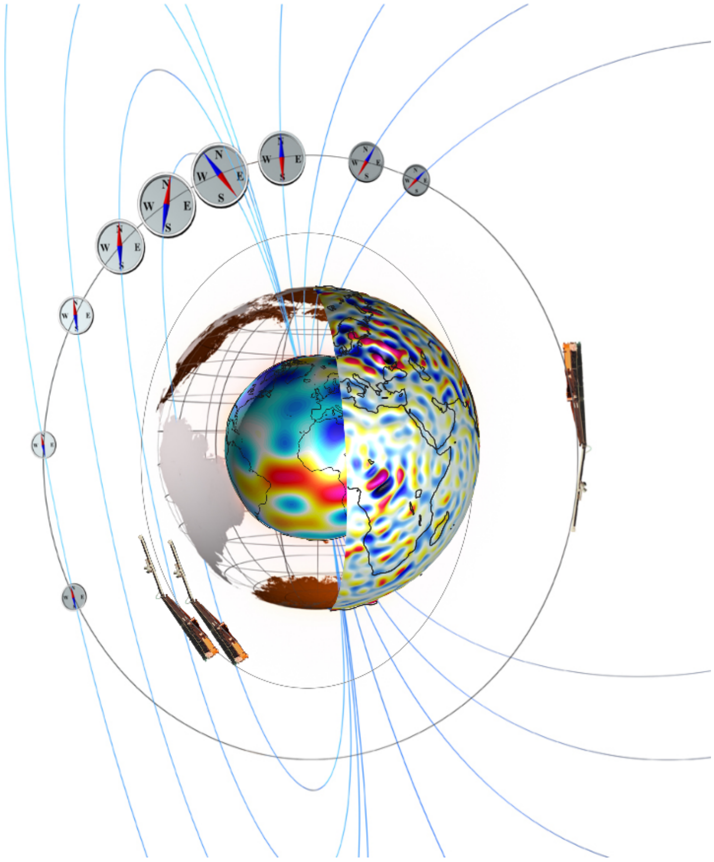
Data, Innovation, and Science Cluster

Swarm LP Ion Drift and Effective Mass Product Definition



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Record of Changes

Reason	Description	Rev	Date
Initial vers.	Draft	1dA	30 Aug 2021
Revision	Addition of CDF file variables, elaborated processing scheme, and CDF structure updates requested by DTU.	1dB	29 Nov 2021
Revision	Revisions based on DTU feedback: satellite velocity to be imported from MODx file; Satellite velocity to be stored as vector; names and labels revised; flag value typo fixed.	1dC	30 Nov 2021
Revision	Using PREL for product type. Updated list of inputs. Added a flag bit for magnetic field validity. Formatting of matlab example updated. Clarification of data product validation approach.	1dD	13 Dec 2021
Revision	Updated document name to GS-002 from GS-001 (already used for work plan). Revised Validation section. Added Releases section. Corrected Matlab flag example.	1dE	20 Jan 2022
Release	Added note about flags; fixed equation typos. Signed version 1.	1	11 Feb 2022
Revision	Revised table of flags to include applicability. Revised reference documents.	2dA	11 Aug 2022
Release	Added note about PREL 0102 dataset. Signed.	2	13 Sep 2022
Revision	Version PREL 0103 release notes.	3dA	9 Nov 2022
Release	Signed.	3	14 Nov 2022

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1 Introduction

This document describes the Swarm Langmuir Probe Ion Drift and Effective Mass (SLIDEM) product.

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

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] SW-TN-UoC-GS-003_3-1, SLIDEM Validation Report

[RD-3] Knudsen, D. J., J. K. Burchill, S. C. Buchert, A. I. Eriksson, R. Gill, J.-E. Wahlund, L. Åhlen, M. Smith, and B. Moffat (2017), Thermal ion imagers and Langmuir probes in the Swarm electric field instruments, J. Geophys. Res. Space Physics, 122, 2655–2673, doi:10.1002/2016JA022571.

[RD-4] Mott-Smith, H. M., and I. Langmuir, "The Theory of Collectors in Gaseous Discharges", Phys. Reviews, 28, 727, 1926.

[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. https://doi.org/10.1029/2020EA001344

[RD-8] Weimer, D. R. (2005). Improved ionospheric electrodynamic models and application to calculating Joule heating rates. Journal of Geophysical Research, 110, A05306.

[RD-9] 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, 411–432. https://doi.org/10.1029/2018EA000546

[RD-10] SW-RN-IRF-GS-005, Extended Set of Swarm Langmuir Probe Data

[RD-11] SW-RN-UoC-GS-004, EFI TII Cross-Track Flow Data Release Notes

[RD-12] 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. https://doi.org/10.1016/j.asr.2014.07.033

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***
IDM	Ion-drift, Density, and effective Mass
OML	Orbit motion limited
SLIDEM	Swarm Langmuir Probe Ion Drift and Effective Mass

3 Product Description

3.1 Outline

This document details calculation of ion drift velocity, effective ion mass, and electron density using measurements taken from the Swarm electric field instrument [RD-1] Langmuir Probes (LP) and faceplate, within the framework of modified orbital motion limited (OML) theory [RD-4]. The Swarm Level 1b ion density currently relies on the ionospheric drift being zero in a frame of reference co-rotating with the Earth and on the ionospheric composition being pure O^+. SLIDEM makes use of an additional measurement, the EFI faceplate current, to eliminate one of these assumptions, thereby improving the accuracy of the Swarm ion density and providing an estimate of either along-track ion drift or effective ion mass, depending on the location of the measurement. Section 3.2 elaborates the physics and methods of the SLIDEM product. Section 3.3 describes model inputs used in calculating the product. Remaining sections describe the SLIDEM file format (3.4), product data fields (3.5) and validation approach (3.6). Refer to Pakhotin et al (2022, submitted to Earth, Planets and Space, [RD-1]) for additional details.

3.2 Approach

Presently the Swarm Level 1b LP ion density product is estimated from the ion admittance (derivative of current with respect to applied voltage) in the ion saturation region of the characteristic using the so-called Harmonic Mode of the LP [RD-1]:

$$d_s = \frac{\partial I}{\partial V_b} = -\frac{2N_s q_s^2}{m_s v_s} \pi r_p^2 \tag{1}$$

where I is the probe current, N_s is the ion density, V_b is Langmuir probe bias (typically set to -2.5 V with a high-frequency small-amplitude ripple), r_p is the Langmuir probe radius, q_s is the ion charge, v_s is the along-track component of ion drift, and m_s is the ion mass. The LP ion density product assumes that the ionosphere is composed of pure O^+ that is stationary in a frame of reference co-rotating with the Earth, such that $v_s = 7.6$ km/s as seen by the satellite. It is expected that these assumptions are routinely violated along the Swarm orbits in cases of ion drift associated with ionospheric convection at high latitudes and additional ion species such as H^+ at low and mid latitudes.

When more than one ion species is present, their admittances sum. In this case the effective mass M_{eff} replaces m_s, and all S species are assumed to have the same charge state e and along-track ion drift speed v_i:

$$d_i = -\frac{2N_i e^2}{M_{eff} v_i} \pi r_p^2 \tag{2}$$

where

$$N_i = \sum_{s=1}^{Species} N_{is} \tag{3}$$

and

$$\frac{1}{M_{eff}} = \frac{1}{N_i} \sum_{s=1}^{S} N_{is} \frac{1}{m_{is}} \tag{4}$$

Note that, unlike average mass, effective mass is relatively sensitive to a small proportion of light ion such as H^+.

Under the same assumptions for multiple ion species above, the faceplate current I_{FP} collected by a negatively charged faceplate with area A_{FP} may be expressed as

$$I_{FP} = -N_i e v_i A_{FP}. \tag{5}$$

Combining equations (1) and (5) removes one of the unknowns. A refinement to the Level 1b ion density at high latitudes is given by

$$N_i = \sqrt{\frac{d_i I_{FP} M_{eff}}{2e^3 A_{FP} \pi r_p^2}} \tag{6}$$

where the effective mass is the IRI estimate based on the topside ion composition model of [RD-12] In this case the along-track ion drift in the satellite reference frame is estimated using

$$v_i = \sqrt{\frac{2e\pi r_p^2 I_{FP}}{d_i A_{FP} M_{eff}}}. \tag{7}$$

At low latitudes, the ion drift may be neglected in comparison with satellite speed, yielding respective estimates for ion density and effective ion mass:

$$N_i = -\frac{I_{FP}}{A_{FP} e\, v_{sat}} \tag{8}$$

$$M_{eff} = \frac{2e\pi r_p^2 I_{FP}}{d_i A_{FP} v_{sat}^2}. \tag{9}$$

It has been found that the effective faceplate area A_{FP} is not equal to its geometrical area due to the plasma sheath [RD-6], so a correction term is necessary to bring the current into agreement with independent IRI observations. The spherical probe effective radius r_p is different from the measured radius because of the sheath as well as the presence of the nearby negatively charged body of the Swarm satellite [RD-7].

For the faceplate area A_{FP} an empirical adjustment from [RD-6] is applied, where the effective area is related to the measured area by a correction term $\delta = \frac{A_{FP} - A_{geo}}{A_{geo}}$. Here, A_{geo} is the measured faceplate area equal to 0.229 * 0.351 = 0.0804 m^2. The correction term δ depends on effective mass, ram ion velocity, electron temperature and spacecraft floating potential:

$$\delta = \frac{\alpha P \lambda_D}{A_{geo}}\left(1 - \frac{eV}{\frac{1}{2}M_{eff}{v_i}^2} - \beta\frac{eV}{kT_e} - \frac{\gamma}{eV}\frac{e^2}{4\pi\varepsilon_0\lambda_D}\right) \tag{10}$$

where $\lambda_D = (\varepsilon_0 k T_e / e^2 n)^{1/2}$ is the Debye length, ε_0 is the electric constant, k is Boltzmann's constant, T_e is electron temperature, P is measured faceplate perimeter, V is satellite potential (equal to the floating potential plus the bias of the faceplate, usually -3.5 V). The fitting parameters α = 0.06929, β = 0.11552, γ = 66.0913 x 10e6, were obtained empirically by [RD-6]. In principle the fitting parameters can be adjusted to bring SLIDEM measurements into agreement against reference calibration measurements.

For the effective Langmuir probe radius, sheath effects as well as the effects of the nearby negatively charged body of the satellite distort the effective area of the probe such that the correction factor may be approximated using [RD-7] as follows:

$$\delta = \alpha \frac{\lambda_D}{r_p}\left(1 - \beta \frac{eV_f}{\frac{1}{2} m_{eff} v_i^2} - \gamma \frac{eV_f}{kT_e}\right) - \zeta V_f + \xi \tag{11}$$

In the above equation, α = 7.996 x 10e-3, β =5.431, γ = 0.2191, ζ =5.915e-3 /V, ξ = -1.743e-2 are empirically fitted parameters [RD-7].

Because the effective faceplate area and the effective Langmuir probe radius both depend on effective mass and velocity, and yet are also required to estimate effective mass and velocity, an iterative approach is required. For geometric area corrections, the satellite speed is assumed at low latitude, and the derived ion ram speed is assumed at high latitude. The electron temperature and satellite floating potential and initial electron density are those estimated by the LP as provided in the EXTD LP_FP and LP_HM datasets. Ion admittance is calculated from the EXTD LP_HM ion density. Iterations are carried until the solution converges.

Along-track ion drifts are post-processed to remove residual background flows at mid-latitude, using the methodology employed in the TII cross-track ion drift calibrations [RD-11]. The product files contain both raw and corrected ion drifts. The IRI-2016 topside ion composition model by Truhlik, Bilitza, and Triskova (2015), or 'TBT' model, estimates relative concentrations for four ion species (O^+, N^+, He^+ and H^+) and is used to calculate a model effective ion mass at all latitudes.

3.3 Inputs

Ion admittance, electron temperature, initial density estimates, and satellite floating potential are obtained from the ESA 2 Hz extended LP_HM data product [RD-10]. LP faceplate current measurements are obtained from the 16 Hz LP_FP data product. The availability of the faceplate current product, limited to intervals when the faceplate voltage is set to -3.5 V, determines the availability of the SLIDEM products. The LP_HM dataset Flagbits variable is used to establish a baseline for flagging the SLIDEM products.

At high latitudes effective ion mass is calculated using the topside TBT 2015 empirical model whereas at low latitudes the TBT model is used to initialize the iterative effective mass estimate. The daily and 81-day mean solar activity indicators based on F10.7 solar radio flux is needed for the TBT effective mass calculation. This is obtained from the apf107.dat file courtesy of the ECHAIM project at https://chain-new.chain-project.net/echaim_downloads/apf107.dat. Magnetic dip latitude, also required for the TBT empirical effective mass calculation, is derived from the MAGx_LR_1B product.

The satellite position and measurement timing are obtained from the EXTD LP_HM product. Satellite velocity in north, east, centre coordinates are obtained from the MODx_SC_1B SP3C product.

The validity of each product is flagged depending in part on quasi-dipolar latitude, which is obtained from the LP dataset [RD-10].

3.4 File format

Daily data of Ion temperature estimates are provided in Common Data Format files (CDF) at 2Hz resolution with the following naming convention:

SW_PREL_EFIxIDM_2__yyyymmddThhmmss_YYYYMMDDTHHMMSS

where

• X is the satellite letter, one of A, B or C;

• YYYYMMDDTHHMMSS marks the beginning of the interval;

• yyyymmddThhmmss marks the end of the interval.

The CDF files are zipped together with a Swarm Header file (HDR). The CDF files are compressed internally at the variable level, with blocking factor 43200.

Table 1. Swarm ion drift, density and effective mass (IDM) product definition

Product Identifier	SW_PREL_EFIxIDM
Definition	Estimated along-track ion drift, ion effective mass, and revised ion density along the Swarm satellite orbits
Input Data	SW_EXTD_EFIx_LP_FP (faceplate current) SW_EXTD_EFIx_LP_HM (ion admittance, satellite position, magnetic coordinates, electron temperature, satellite potential) apf10.7.dat (F10.7 from ECHAIM) SW_OPER_MODx_SC_1B (satellite velocity) SW_OPER_MAGx_LR_1B (for dip latitude calculation) .slidem_modified_oml_configrc (Resendiz Lira et al. correction parameters)
Input Time Span	1 day
Spatial representation	Estimates along the Swarm satellite's orbit
Time representation	Time series every 0.5 seconds
Units	m/s, AMU, cm^{-3}
Resolution	1 m/sec , 0.01 AMU, 100 cm^{-3}

Uncertainty	(TBD)
Quality Indicator	Bitwise-OR'd flags (one each for ion drift, effective mass, and density)
Data Volume	up to 18 Mbyte (daily file with GZIP compression per variable)
Data Format	CDF
Output Data	CDF file with time series (refer to Table 2)
Output Time Span	1 day
Update Rate	two months
Latency	TBD
Notes	

The CDF variables are as described in Table 2. V_sat_nec is 3-vector, all other variables are scalars.

Table 2. Swarm effective mass and ion along-track drift CDF fields

Variable	CDF Type	Unit	Note
Timestamp	CDF_EPOCH	ms	UTC
Latitude	CDF_REAL8	deg	Geodetic latitude
Longitude	CDF_REAL8	deg	Geodetic longitude
Radius	CDF_REAL8	m	Geocentric radius
Height	CDF_REAL8	m	Height above WGS84 reference ellipsoid
QDLatitude	CDF_REAL8	deg	Quasi-dipole magnetic latitude
MLT	CDF_REAL8	hour	Magnetic local time
V_sat_nec	CDF_REAL8	m/s	Satellite velocity in north, east, centre (NEC) reference frame
M_i_eff	CDF_REAL8	AMU	Ion effective mass
M_i_err_err	CDF_REAL8	AMU	Ion effective mass uncertainty
M_i_eff_Flags	CDF_UINT4		Ion effective mass validity flag

Variable	CDF Type	Unit	Note
M_i_eff_tbt_model	CDF_REAL8	AMU	Ion effective mass model based on Truhlik et al. (2015) empirical topside ion composition model.
V_i	CDF_REAL8	m/s	Along-track component of ion drift velocity, detrended
V_i_err	CDF_REAL8	m/s	Ion drift velocity resolution estimate
V_i_Flags	CDF_UINT4		Ion drift velocity validity flag
V_i_raw	CDF_REAL8	m/s	Uncorrected ion drift velocity
N_i	CDF_REAL8	cm^{-3}	Revised estimate of ion density
N_i_err	CDF_REAL8	cm^{-3}	Ion density uncertainty
N_i_Flags	CDF_UINT4		Ion density validity flag
A_fp	CDF_REAL8	m^2	Modified-OML faceplate area
R_p	CDF_REAL8	m	Modified-OML Langmuir probe radius
T_e	CDF_REAL8	K	Electron temperature used in modified OML calculations
Phi_sc	CDF_REAL8	V	Satellite potential used in modified OML calculations

3.5 Data field description

The flags included in the CDF files denote the various validity domains of the products. At low quasi-dipolar latitudes equatorward of 50°, along-track ion drift is assumed to be zero and this region is valid for estimating the effective mass and ion density. For quasi-dipolar latitudes poleward of 50°, the along-track drift can be significant and is therefore not assumed to be zero. An effective mass must be assumed, and the SLIDEM products derive this from TBT-2015 topside ion composition model. High latitude regions are valid for deriving ion drift and ion density. Consequently, the products are flagged according to their region of validity.

As an aid to the study of the product validity, effective mass is calculated at all latitudes but only flagged as potentially valid at low-to-mid latitudes. The effective mass based on the TBT model is provided for reference. This version of the processing does not provide an estimate for ion effective mass uncertainty.

The along-track component of the ionospheric ion drift vector is approximately parallel to the satellite velocity, which is provided in the CDF files in the north-east-centre (NEC) reference frame. A positive value of the along-track drift signifies ion drift in the direction of travel of the satellite. The uncertainty estimate is based on the variability of measurements in the quasi-dipole latitude range 50-51 degrees poleward, where flows are expected to be close to zero. This assumption may be untrue for strong geophysical or auroral activity. This in effect represents the velocity resolution of the SLIDEM technique. This version of the processing does not estimate systematic uncertainty in the ion drift.

Density estimates represent revised values with respect to the EXTD LP_HM ion density product. This version of the processing does not estimate density uncertainty.

The modified OML correction to the faceplate area and Langmuir probe radius is an experimental feature based on sophisticated simulations of the Swarm satellite interaction with ionospheric plasma ([RD-6], [RD-7]). While the corrections are found to improve the along-track drift and ion effective mass estimates, they should nonetheless be considered a preliminary step in calibrating the SLIDEM technique. To aid assessment of the data quality, the electron temperature and satellite potential estimates (from the LP_HM dataset) as well as the adjusted faceplate area and Langmuir probe radius are provided.

Each of the ion drift, effective ion mass, and ion density products has an accompanying validity flag. Each flag consists of the bit-wise logical OR of the numbers in Table 3. As square roots and tiny divisors appear in the calculation of the products, the results can sometimes be complex or not finite. Such values are flagged and replaced with dummy real values. Similarly, dummy values are used in cases of missing or invalid inputs. Use the flags to identify such values. Flag values of zero are generally considered to signify the highest quality data. The flagging system is at an early stage of development, and data flagged zero can still be suspect. It is recommended to assess measurements within the context of neighbouring values, trends and error estimates.

Table 3. Description of flags: M_i_Flags, V_i_Flags, and N_i_Flags

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
512	IDM product estimate is large. Interpret with caution	M_i_eff, n_i, v_i

Flag value	Description	Applicable data product
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

As an example in matlab, to select ion effective mass data for which the faceplate current data were available within valid QDLatitude regions and the solution converged, one could pass the predicate **bitand(M_i_Flags, bitor(bitor(1,64),2))==0** to the **find()** function.

3.6 Validation

Validation of the SLIDEM historical dataset PREL 0101 is reported in [RD-1] and [RD-2]. The ion density, effective mass and drift have been validated using empirical models (IRI, TBT, Weimer 2005, and PIC), satellite-satellite conjunctions, and satellite and ground-based incoherent radar conjunctions for a variety of orbital configurations and mission times. Further validation is anticipated from assessment of the dataset by the scientific community as presented at the Swarm Data Quality Workshops and in peer-reviewed publications.

4 Releases

4.1 PREL 0101

This is the first draft of the SLIDEM historical dataset. Due to its reliance on the extended LP datasets (LP_HM and LP_FP), from the Advanced/ folder of the Swarm-DISS data portal, this version also resides in the Advanced folder and is considered a preliminary dataset. This version includes estimates of random error for ion velocity only. No systematic uncertainties are currently provided, and the M_i_err and N_i_err variables are set to an arbitrary value. Flags are indicators of the input data quality or the processing status. This version of the processing does not consider an assessment of the geophysical validity of the measurements. Estimates for which the effective mass is less than about 5 AMU are based in part on empirical expressions for ion admittance and faceplate current that are extrapolated from rigorous simulations. Interpret the products with caution.

4.2 PREL 0102

Radius is now calculated from height obtained from the LP_HM dataset as a workaround for occasional zero radius in that dataset. The TBT model calculation of invariant latitude has been corrected. CDF global attributes have been revised. Longitudes are now within the range ±180°.

Known issues: This version calculates ion effective mass prior to baseline subtraction of along-track ion drift, resulting in a small step in ion effective mass at ±50°QD latitude.

4.3 PREL 0103

Corrected reading of medium orbit determination (MOD) ephemeres. Versions PREL 0101 and PREL 0102 had read MOD times, which are GPS epochs, as UT. This introduced an error of about 16 s to 18 s in the latitude, longitude, radius, and satellite velocity (corresponding to an error in latitude of about 1° at low and middle latitude).

Known issues: Same as version PREL 0102.