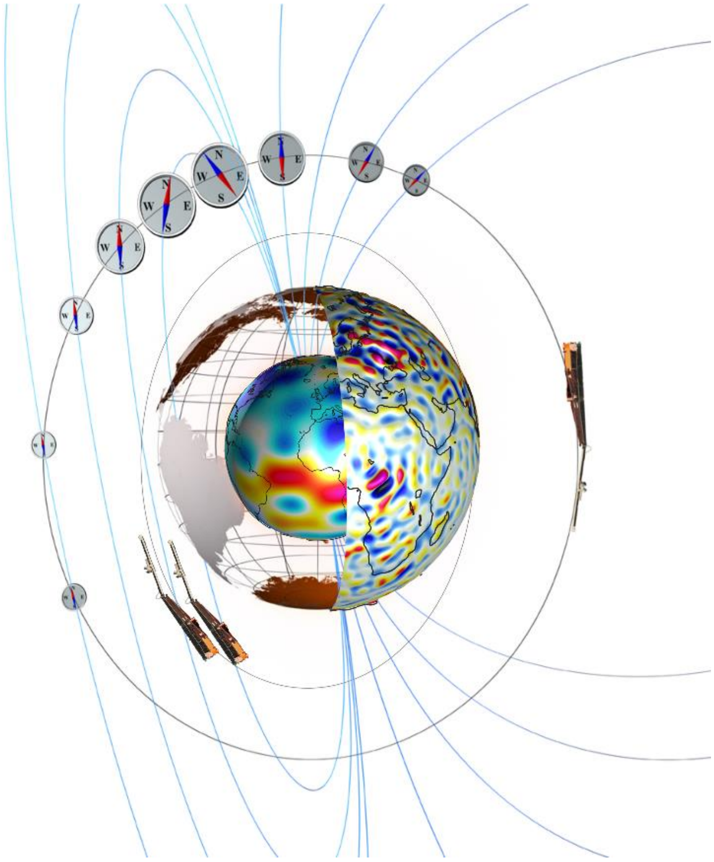
Langmuir Probe Level 1b Algorithm



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Record of Changes

Reason	Description	Rev	Date
Major update to DISC standard	This revision represents a major update, based on revision 2.5, available in the SVN: https://smart-svn.space-center.dk/svn/smart/SwarmESL-All/L1b_Technical/Releases_and_Related_Documents/IRF_PP/SW-TN-IRF-EF-003_level1b_algorithms.pdf?r=7493 The update is harmonising the document format, style and contents to match the other DISC L1b Algorithm documents. The changes that have been made to the algorithm as compared to revision 2.5 are described in section 1.4	3	2016-12-01
Minor update of Te algorithm	Instead of blending the results from 2 probes the T_e estimate from the high gain probe is used. The update is motivated in [RD-6]	3A dA	2017-04-19
Minor corrections	Minor corrections of inconsistencies and some clarifications in the algorithm description. Minor corrections to this table “record of changes” making it chronological as per DISC rules.	3A dB	2017-05-25
Clarify flags used	Flags used in algorithm are clarified	3A dC	2017-10-30
Minor correction	Correct a broken link and paragraph formatting, then released document	3A	2017-12-18
Clarify ion ram speed	Clarify assumptions about the ion ram speed and its relationship with the satellite orbital velocity in section 3.1.	3B	2018-04-27
Correct typo	Correct two minor typos in the last paragraph of section 3.1	3C	2018-04-27
Minor extensions	Added item in Chapter 1.4 about the computation of calibration offset Updated documentation in Chapter 2 Updated equation 14 and added new equation 16 Updated tables: Table 5-5, Table 5-11, Table 5-12, and Table 5-13 Minor corrections of inconsistencies and some clarifications in the algorithm description.	3D	2021-03-29

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1 Introduction

1.1 General

The EFIs on the Swarm satellites each feature two LPs. The main purpose of the LPs is to provide estimates of the ion and electron density and electron temperature, N_i, N_e and T_e, of the plasma around the satellites, as well as the electric potential of the spacecraft V_s. The actual probes are two spheres mounted on about 10 cm long stubs at the Earth-facing front edges of the satellites. Measured on board are probe currents and admittances as a response to a time varying bias that the LP electronics applies to the probes. By processing the raw L0 data on the ground N_i, N_e, T_e, and V_s are then estimated from the measured currents and admittances, the results are the main LP L1b product. N_i and N_e represent two different methods to estimate the plasma particle density.

1.2 Purpose and Scope

This document describes the algorithms for estimating the LP L1b products from the on-board measurements.

1.3 History

The electronic design of the Swarm LPs features a sinusoidal varying bias suitable for measuring not only currents, but also admittances. A comparable instrument has previously not been in orbit. A similar idea including tests in the laboratory have been presented [RD-2]. For Swarm the concept had been verified before launch using also a software instrument simulator, and an L1b algorithm had been developed, described in [RD-1].

After launch the LP algorithm was considerably modified and simplified for different reasons:

- only “harmonic submode” (HSM) data, where the above mentioned sinusoidal varying bias is applied, is used to produce L1b results;
- data from a classical “sweep submode”, measurements of the faceplate current, or other instrument modes are all not used for L1b LP products data, and applicable algorithms are not described in this version 3.0 document. Data in the sweep mode or via the faceplate current are or will be provided as “extended or advanced LP data sets”, and the algorithms are rather described in the respective release notes.

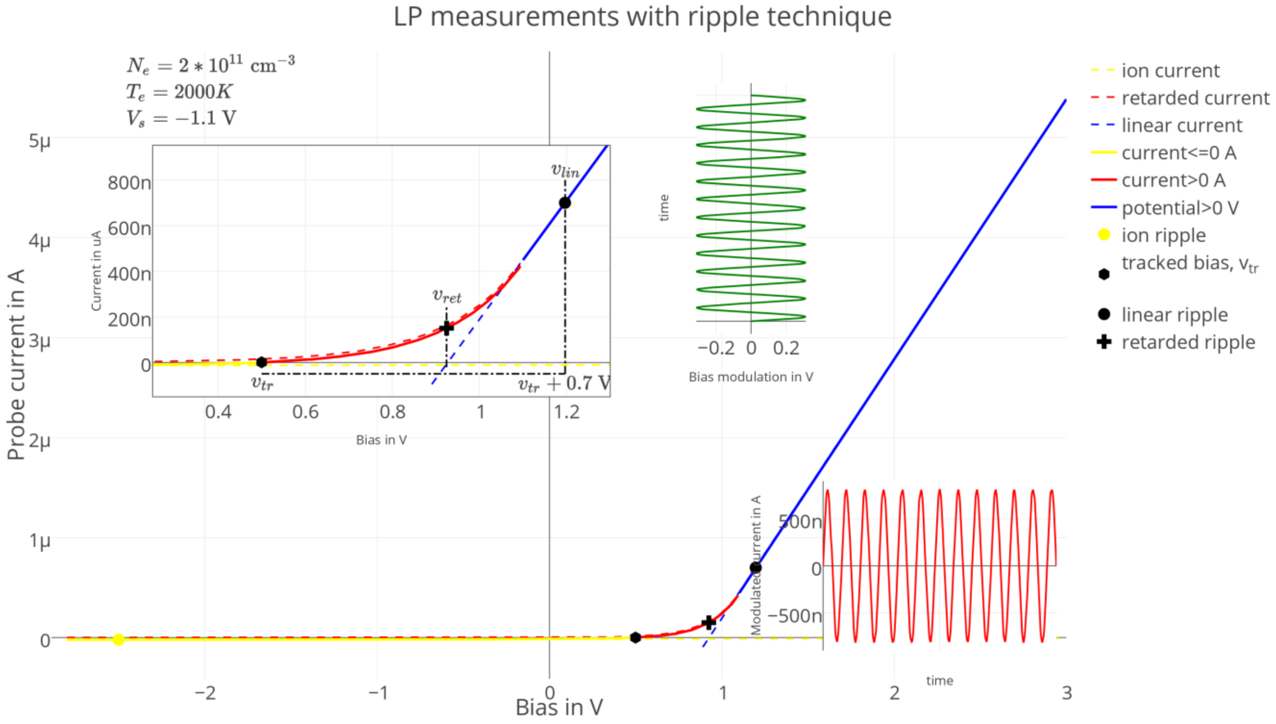

Figure 1-1: Schematic illustration of the harmonic submode.

The harmonic modulation of the bias resulting in a nearly harmonic current "ripple" is illustrated in the linear region at bias v_{lin}, but performed as well at biases v_{ion} and v_{ret}. The inset zooms into the region around the knee of the I-V curve, where the critical part of the on-board bias setting happens. For more details see [RD-5].

1.4 Changes to the algorithm

The following changes have been made to the algorithm as compared to revisions 2.5, [RD-1], and revision 3:

- Generally the use of both high and low gain probes for estimating a parameter is avoided. Independent estimates of the plasma parameters from both probes turned out to be more different than expected. The originally implemented linear transition avoided jumps and produced smooth time series, but artificial variations caused by a transition between probes could still not be excluded.
- The ion density N_i is estimated using the ion admittance, supplementing the electron density N_e from the linear electron current. For N_i always the high gain probe is used. Because the ion current/admittance is weak, an ADC overflow has never been observed. N_i is therefore particularly reliable at high densities, as they occur often on the dayside near the equator. Also the ion regime turned out to be much less affected by disturbances than the electron regimes. Errors of ion and electron currents should be uncorrelated, thus also the errors of N_i are only weakly correlated with those of T_e, N_e, and V_s .
- The orbital velocity needs to be retrieved from the MODx_SC_1B product and interpolated.
- In the previous version of the algorithm, for T_e the estimates from both probes had been blended together in order to avoid discontinuous jumps in the time series of data when ADC overflows occur. However, because of systematic differences between the T_e from different probes the transi-

tions exhibited smooth variations of T_e which had no physical origin [RD-6]. This transitional blending is now abandoned, instead the high gain estimate of T_e is used even when overflows are detected. To get estimates of T_e based on the low gain probe (if available), the advanced LP data set provided by IRF and distributed via the ESA PDGS can be used [AD-6]. In the L1b product the low gain estimate of T_e is dropped in only when the high gain data are flagged with errors, typically failed tracking.

- For T_e the low density equation from [RD-1] is no longer used, to reduce possible artificial variations of T_e when N_e changes.
- For the spacecraft potential V_s always the estimate from the gold-plated probe 2 is used, because it is observed to be more consistent.
- The results of sweeps are no longer used for L1b products. Sweep results turned out to be systematically different from harmonic mode results, the difference pattern is not yet understood. The satellites already send duplicated harmonic mode packets when sweeps occur, such that the harmonic mode analysis provides regularly sampled data even without the sweeps.
- The post-calibration of all parameters based on calculations with the instrument simulator was disabled, as it is uncertain whether the calibration matrices generated with the instrument simulator would be realistic and valid after these significant algorithmic changes. Instead a comparison of estimated N_i and T_e with data from incoherent scatter radars was used to establish similar calibration matrices in the CCDB [AD-3] from which a calibration correction is calculated [AD-4].
- Random errors, originally also obtained from the instrument simulator, are set to maximum values until statistical errors will be derived from the data themselves.

2 Applicable and Reference Documentation

2.1 Applicable Documents

[AD-1] SW-RS-DSC-SY-0007, Level 1b Product Definition, issue 5.3

[AD-2] SW-IF-EAD-GS-00017, Level 0 Data Products, issue 13

[AD-3] SW-TN-DSC-SY-0005_Level_1b_CCDB, issue 1B

[AD-4] SW-TN-IRF-GS-0010, Error estimates of LP L1b products, issue 1A

[AD-5] SW-TN-IRF-GS-0011, CCDB update for LP error estimates, issue 1A

[AD-6] SW-TN-IRF-GSSW-RN-IRF-GS-00, Extended LP Data Probes, issue 1A

2.2 References

[RD-1] SW-TN-IRF-EF-003, Level1b algorithm, issue 2.5

[RD-2] Siefring, C.L., Amatucci, W.E. and Rodriguez, P. (1998). Fast Electron Temperature Measurements with Langmuir Probes: Considerations for Space Flight and Initial Laboratory Tests. In Measurement Techniques in Space Plasmas: Particles (eds R.F. Pfaff, J. Borovsky and D.T. Young). https://doi.org/10.1029/GM102p0055.

[RD-3] H.M. Mott-Smith and I. Langmuir (1926), The Theory of Collectors in Gaseous Discharges, Phys. Rev.28, 727.

[RD-4] Fahleson, U. (1967), Theory of electric field measurements conducted in the magnetosphere with electric probes, Space Sci. Rev., 7: 238, https://doi.org/10.1007/BF00215600.

[RD-5] Knudsen et al. (2016), Thermal Ion Imagers and Langmuir Probes in the Swarm Electric Field Instruments, J. Geophys. Res. Space Physics, 122, 2655–2673, https://doi.org/10.1002/2016JA022571.

[RD-6] SW-TN-IRF-EF-008, Improving the Te algorithm, Issue 1

2.3 Abbreviations

Acronym ***or abbreviation***	***Description***
ADC	Analog Digital Converter
CCDB	Calibration and Characterization Data Base
DISC	Data, Innovation, and Science Cluster
EFI	Electric Field Instrument, including the TII and the LP
ESA	European Space Agency
eV	Electronvolt, a unit for energy, in the context of LPs used to indicate temperature, 1 eV is 11406 Kelvin
FPGA	Field-Programmable Gate Array
HSM	Harmonic Submode, the most important mode of the Swarm LP featuring sinusoidal (harmonic) modulations of the bias
ITRF	International Terrestrial Reference Frame
IRF	Swedish Institute of Space Physics (“Institutet för RymdFysik” in Swedish)
L0	Level 0 (satellite data), data from instruments such as voltages, currents, that normally need to be processed before general scientific use
L1b	Level 1b (satellite data), first level of processed satellite data released for general use
LP	Langmuir Probe, an instrument to measure density, temperature and potential in a plasma; on Swarm LPs are a part of the EFI
Matlab	A commercial programming environment for technical computing
N_e	Electron density
N_i	Ion particle density. In the environment of Swarm one can safely assume that ions with a single positive charged and electrons are the only charged particles. Then from quasi-neutrality it follows, that N_e and N_i differ only by an directly unmeasurably small amount, i. e., both should come equal. However, in practice this is not the case, for reasons discussed in the text

Acronym ***or abbreviation***	***Description***
NM	Normal mode, the mode of an instrument that is used most of the time to produce science data, in contrast to e.g. calibration or other testing modes
PP	Prototype Processor
SVN	SVN Repository with server located at DTU. For DISC members, presently, the following URLs apply: https://smart-svn.spacecenter.dk/svn/smart/SwarmESL-All
Swarm	Constellation of 3 ESA satellites, http://www.esa.int/Our_Activities/Observing_the_Earth/Swarm
TM	Technical Measurement, digital values
T_e	Electron temperature, when working with LPs, T_e is often indicated in units of eV
TII	Thermal Ion Imager, part of the Electrical Field Instrument
UoC	University of Calgary (CA)
Vs	Spacecraft potential, an electric potential, unit is Volts
XML	Extensible Markup Language

3 The Model for Swarm LP Measurements

Parameters controlled by the LP are written in green, quantities measured by the LP in blue, and L1b parameters to be estimated in red colours. In the following equations T_e is in units of eV, and the ratio of bias V to T_e is dimensionless. The final L1b product is in K.

In the "harmonic mode" a sinusoidal modulated bias (voltage) V_b is applied to the actual probe. In the presence of charged particles, i.e. a plasma, around the spacecraft an electrical current i flows and is measured. Owing to the harmonic modulation also the admittance $D = di/dV_b$ is measured. Three different currents contribute:

1) the *ion* current I_{ion}, with admittance D_{ion},
2) the *retarded electron* current I_{ret}, with admittance D_{ret}, and
3) the *linear electron* current I_{lin}, admittance D_{lin} ;

The principle is illustrated in Figure 1-1.

3.1 Ion current and admittance

The equations for these currents result from Mott-Smith and Langmuir's orbital motion limited theory [RD-3][RD-4]. For the ion current additional assumptions are:

- the plasma is cold, i.e. the convective ion velocity relative to the probe must be much larger than their thermal velocity;
- only O^+ ions are present;
- the ions move relative to the probe with the satellites' orbital speed u_i, about 7.5 km/s in the ITRF. The actual value is taken from the orbit determination with medium accuracy, which is calculated as a specific Swarm L1b product type named MODx_SC_1B.

Then the equations for the ion current and admittance are:

$$I_{ion} = \begin{cases} -\pi r_p^2 e u_i N_i \left[1 - \dfrac{(V_b + V_s)}{E_i}\right], & V_b + V_s < E_i \\ 0, & V_b + V_s \geq E_i \end{cases} \quad (1)$$

r_p is the probe radius, e the elementary charge and $E_i = e\frac{m_i}{2}u_i^2$ is the ion ram energy in units of eV. For oxygen ions $m_i = 15.999\ amu$, and

$$D_{ion} = \begin{cases} 2\pi r_p^2/(m_i u_i)N_i, & V_b + V_s < E_i \\ 0, & V_b + V_s \geq E_i \end{cases} \quad (2)$$

3.2 Retarded electron current and admittance

For electron currents the effect of photoelectrons are neglected. The equations for the retarded currents and admittances are

$$I_{ret} = \begin{cases} I_e N_e \sqrt{T_e}\exp[(V_b + V_s)/T_e], & V_b + V_s \leq 0 \\ 0, & V_b + V_s > 0 \end{cases} \quad (3)$$

where

$$I_e = 4\pi r_p^2 \sqrt{1/(2\pi m_e)} \quad \textbf{(4)}$$

m_e is the electron mass. The regime where $V_b + V_s \leq 0$ but there is a significant electron current due to their thermal energy is called *retarded*. The retarded admittance is

$$D_{ret} = \begin{cases} I_e \left(N_e/\sqrt{T_e}\right) \exp[(V_b + V_s)/T_e] \, , & V_b + V_s \leq 0 \\ 0 & , V_b + V_s > 0 \end{cases} \quad \textbf{(5)}$$

3.3 Linear electron current and admittance

The regime where $V_b + V_s > 0$ (but not too positive) is called *linear*. The equation for the linear or “saturation” current is

$$I_{lin} = \begin{cases} 0 & , V_b + V_s \leq 0 \\ I_e N_e \sqrt{T_e}[1 + (V_b + V_s)/T_e], & V_b + V_s > 0 \end{cases} \quad \textbf{(6)}$$

For the linear admittance

$$D_{lin} = \begin{cases} 0 & , V_b + V_s \leq 0 \\ I_e N_e/\sqrt{T_e}, & V_b + V_s > 0 \end{cases} \quad \textbf{(7)}$$

3.4 On-board bias setting

The LP electronics, which includes a microprocessor and an FPGA, sets for each HM measurement cycle (lasting 0.5 s) the probe bias V_b consecutively to three different values:

1. $V_b = v_{ion}$ at a large negative bias, such that the retarded current can be neglected, and the measured current and admittance are assumed to be from the ion current only, see equations (1) and (2).
2. $V_b = v_{lin}$ with $v_{lin} + V_s > 0$. Then the measured current and admittance are I_{lin} and D_{lin}, see equations (6) and (7).
3. $V_b = v_{ret}$ with $v_{ret} + V_s \leq 0$, but such that both ion and retarded current and admittance need to be retained. The measured current and admittance are $I_{ion} + I_{ret}$ and $D_{ion} + D_{ret}$, sum of equations (1)+(3) and (2)+(5).

The on-board bias setting attempts to ensure that the bias is set in the intended physical regimes and that the inequalities above in 2. and 3. are fulfilled in spite of the a-priori unknown V_s, and that particularly v_{ret} is in the “knee” (near the maximum of the 2nd derivative) of the LP current-voltage characteristics for optimal measurements. A successful on-board bias setting must result in v_{ion}<=v_{ret} and v_{ret}<=v_{lin}. Reasons for a failed on-board bias setting include:

- The on-board algorithm involves a tracked bias v_{tr}. It is set to zero, if the tracking fails.
- Occasionally v_{lin} comes out larger than 5 V, which will cause a 16-bit overflow in the LP electronics and an unusable actual bias.
- Occasionally v_{ret}>v_{lin}, probably caused by natural disturbances in the plasma or technical ones. This also cannot result in good measurements.

These conditions are detected by the L1b processor and the product is flagged as bad, see 5.2.1. In addition, overflow of the ADC can occur, is detected on-board and must be flagged in the L1b end product.

More details of the on-board processing can be found in [RD-5].

3.5 Parameter estimation

Three currents are measured (each at a different bias), and three admittances. In total there are six observations: i_{ion}, d_{ion}, i_{ret}, d_{ret}, i_{lin}, and d_{lin}. To i_{ret} and d_{ret} both the ion and retarded electron current contribute significantly, but we use the subscript $_{\text{ret}}$ to indicate the type of the largest contribution. According to the model the observations depend on the four parameters, N_i, N_e, T_e, and V_s which the L1b algorithm has to provide:

$$i_{ion} = -\pi r_p^2 e u_i N_i [1 - (v_{ion} + V_s)/E_i] \tag{8}$$

$$d_{ion} = \pi r_p^2 e u_i N_i / E_i \tag{9}$$

$$i_{ret} = I_e N_e \sqrt{T_e} \exp[(v_{ret} + V_s)/T_e] - \pi r_p^2 e u_i N_e [1 - (v_{ret} + V_s)/E_i] \tag{10}$$

$$d_{ret} = I_e \exp[(v_{ret} + V_s)/T_e]\, N_e/\sqrt{T_e} + \pi r_p^2 e u_i N_e / E_i \tag{11}$$

$$i_{lin} = I_e N_e \sqrt{T_e} [1 + (v_{lin} + V_s)/T_e] \tag{12}$$

$$d_{lin} = I_e N_e / \sqrt{T_e} \tag{13}$$

Within the here assumed model, the inequalities i_{ion}<=i_{ret}, i_{ret}<=i_{lin}, d_{ion}<=d_{ret}, and d_{ret}<=d_{lin} should all come out true. A standard approach would be to (non-linearly) fit the parameters to the observations. In practice, however, disturbances of unknown origin are not infrequently seen, with different occurrence and severity in the three regimes:

- The ion current at a large negative bias, v_{ion}, is the weakest current, nevertheless it is the least disturbed one.
- The linear electron current, at bias v_{lin}, seems most frequently disturbed, it is also the most likely one to have overflows in the ADCs.

Therefore, to minimize the effects of disturbances and overflows, we exploit that N_i can be obtained from the ion current. Assuming that the plasma is quasi-neutral, N_i could in principle substitute an estimate of N_e. In practice, however, also N_e is estimated indepently.For T_e the measurements from the retarded and ion regimes are sufficient, linear is not needed. The resulting equations are (without detailed derivation):

$$N_i = \frac{m_i u_i}{2\pi (e r_p)^2} d_{ion} \tag{14}$$

which is from equation (9),

$$T_e = \frac{i_{ret} - i_{ion} - d_{ion}(v_{ret} - v_{ion})}{d_{ret} - d_{ion}} \tag{15}$$

which is from equations (8-11),

$$N_e = \frac{1}{er_p}\sqrt{\frac{m_e}{8\pi e}}\frac{d_{lin}}{\sqrt{T_e}} \tag{16}$$

which is based on equations (4, 13) and using the just estimated T_e, and

$$V_s = \frac{i_{lin}}{d_{lin}} - v_{lin} - T_e \tag{17}$$

which uses equations (12-13). An alternative equation for V_s gave in simulations that were undertaken before the launch better results only for very low densities/weak currents:

$$V_{s,lne} = \frac{i_{lin} - i_{ret} + d_{ret}v_{ret} - d_{lin}v_{lin}}{d_{lin} - d_{ret}} \tag{18}$$

This estimate (18) is presently not used in the L1b processor, only equation (17) is used instead.

3.6 Two probes

In order to cover the complete range of densities in the ionosphere (roughly from 10^7 down to perhaps 10^2 per cubic cm) each satellite has two probes whose sensitivity for current measurements can be configured between two values. These are called “high gain” and “low gain”. Normally one of the probes is set to high gain, and the other to low. The L1b processor must detect, which probe is set to high and which to low. The equations to estimate N_e, T_e, and V_s are the same for high or low gain. To simplify the coding, both probes are used to estimate each one value, denoted N_e^h and N_e^l, T_e^h and T_e^l, and V_s^h and V_s^l. Typically the high gain probe suffers from ADC overflow in the linear regime, when the satellite crosses a high density region near the magnetic equator on the dayside once per orbit. In the lower density regions, i.e. most of the time, estimates from the high gain probe are less noisy and probably more accurate and correct. The estimates from both probes are often systematically different. Therefore T_e and N_e are estimated using the high gain probe. The estimates from the low gain probes are dropped in only in case of errors, such as ADC overflow. This, however, is flagged and therefore normally the low gain data get excluded by the user.

4 The Algorithm for the Harmonic Submode

Input for the processing of Swarm LP data consists of

1. The “raw” L0 data available in the instrument source packets of the EFI
2. Other parameters and constants used in the software.

The present algorithm is also documented via the Matlab function `sw_efi_langmuir.m` which is the core function of the LP PP code.

4.1 Error estimation

Errors can be categorised in *random* and *systematic*. Random errors are caused by unknown and unpredictable changes in the measurement, such as shot and thermal noise of the operational amplifiers of the instrument electronics. Systematic errors can originate also from the instrument but in the case of the LP measurements a significant source are neglected factors of the measurement model, for example, a not 100 % O^+ composition of the plasma or the effect of a wake behind the probe from the fast moving plasma. In principle systematic errors can be corrected which we synonymously call calibration. Generally it is expected that for the Swarm LPs systematic errors overwhelm the random ones.

The algorithm for error estimation is described in [AD-5]. It is assumed that the parameters N_e and T_e determine the error of N_e and T_e . Thus the CCDB contains matrices of error corrections (or in the case of random errors uncertainties) for N_e and T_e, where the matrix axes are N_e and T_e. Polygon stored in the CCDB indicate the area in N_e and T_e space where the error correction is considered valid.

5 Constants, Instrumental and Algorithmic Parameters

In `sw_efi_langmuir.m` algorithmic parameters and instrumental constants get assigned to Matlab variables (by code such as `probe_radius=0.004;`). In the following tables the column "Parameter" indicates the (usually concise) symbol used in equations and text of this document. Not all parameters show up in the equations or symbols. The column "Variable" indicates the variable name which is used in `sw_efi_langmuir.m` and other Matlab code of the IRF LP PP.

5.1.1 Physical constants

Table 5-1: Physical constants

Parameter	Variable	Description	Unit	Value
$\boldsymbol{m_e}$	`me`	Electron mass	kg	9.10938188e-31
$\boldsymbol{e}$	`qe`	Elementary charge	Coulomb	1.602176462e-19
$\boldsymbol{K/eV}$	`eV2K`	Conversion from eV to Kelvin	Kelvin/eV	11604.505
$\boldsymbol{amu}$	`amu`	Atomic mass unit	kg	1.66053892e-27
$\boldsymbol{O_{amu}}$	`o`	Mass of O^+ in amu	amu	15.999

5.1.2 Probe constants

Table 5-2: Probe constants

Parameter	Variable	Description	Unit	Value
$\boldsymbol{r_p}$	`probe_radius`	Probe radius	M	0.004
$\boldsymbol{a_f}$	`fp_area`	Faceplate area, not used for L1b	m^2	0.0840

5.1.3 LP Electronics constants

Table 5-3: LP electronics constants.

In each resistance matrix R_A, R_B, and R_C, the first row shows the values for probe 1, the second row for probe 2. The last row is for the faceplate, which is not used in L1b.

Parameter	Variable	Description	Unit	Value
$\boldsymbol{DACbits}$	`DACBits`	DAC nr of bits	n/a	16
$\boldsymbol{B_{min}}$	`VBmin_tm`	Minimum bias in TM units, -`(2^(DACBits-1)`	TM	-32768

Parameter	Variable	Description	Unit	Value
$\boldsymbol{VpTM\_DAC}$	`VpTM_DAC`	Volt per digital unit (TM)	V/TM	0.000152592547379986
$\boldsymbol{VB_{min}}$	`Blim_V_Low`	Minimum bias	V	-5.000152592547381
$\boldsymbol{VB_{max}}$	`Blim_V_High`	Maximum bias	V	+5.0
$\boldsymbol{R_A}$	`gainres`	Resistors determining the gain/ sensitivity in Ω, Swarm A*	Ω	$\begin{bmatrix} 67961.86 & 3315608.0 & 0.0 \\ 68341.76 & 3315081.0 & 0.0 \\ 1099.5 & 11037.63 & 100291.0 \end{bmatrix}$
$\boldsymbol{R_B}$	`gainres`	Resistors determining the gain/ sensitivity in Ω, Swarm B*	Ω	$\begin{bmatrix} 68222.2 & 3305020.0 & 0.0 \\ 68206.0 & 3319532.0 & 0.0 \\ 1100.0 & 11000.0 & 100000.0 \end{bmatrix}$
$\boldsymbol{R_C}$	`gainres`	Resistors determining the gain/ sensitivity in Ω, Swarm C *(row 1 for probe 1, row 2 for probe 2 , row 3 faceplate)	Ω	$\begin{bmatrix} 67879.1 & 3323814.0 & 0.0 \\ 67997.4 & 3313807.0 & 0.0 \\ 1100.0 & 11000.0 & 100000.0 \end{bmatrix}$

5.1.4 Algorithmic parameters

Table 5-4: Algorithmic parameters

Parameter	Variable	Description	Unit	Value
$\boldsymbol{O_{dion}}$	`HM_Dion_Offset`	Offset of the ion admittance	V/A	$1 * 10^{-10}$
$\boldsymbol{dT_{lgn}}$	`dT_lgn`	Offset of $T_{e,lgn}$for high N_e	K	400

$\boldsymbol{LD}$	Row 1, low gain:
	`HM_LG_N_Limit_Low`
	`HM_LG_N_Limit_High`
	Row 2, high gain:
	`HM_HG_N_Limit_Low`
		Range where the low density approximation of V_s is blended in.
		(row 1 low, row 2 high gain)
			cm^{-3}	$\begin{bmatrix} 57 & 138 \\ 1 & 3 \end{bmatrix} * 1000$

Parameter	Variable	Description	Unit	Value
	`HM_HG_N_Limit_High`			
$\boldsymbol{dmin}$	`HM_Vs_Dret_Limit`	Limit of difference in Dret and Dion for V_s above which method can be used	V/A	10^{-9}
$\boldsymbol{denom}$	`HM_Vs2_denominator_min`	Presently not used	V/A	10^{-6}
$\boldsymbol{dt1}$	`dt_one`	Time offset of the 1st N_e measurement from the full second	s	0.19706
$\boldsymbol{dt2}$	`dt_two`	Time offset of the 2nd measurement	s	0.69645
$\boldsymbol{Vl}$	`V_lim`	If V_s outside these limits, the result from high gain probe is used	V	] -6.5, 2.5 [
$\boldsymbol{Tl}$	`T_lim`	If T_e outside these limits, the result from the other probe is used	eV	] 0.01, 1.5 [

5.1.5 Full CCDB names of parameters used

The parameters in Table 5-1 to Table 5-4 are implemented in the Swarm CCDB, a collection of XML files, which are both human readable and easily accessible by computer code for retrieving parameters. The CCDB is documented in [AD-3]. Table 5-5 lists the association of LP variables with CCDB structures.

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Table 5-5: Association of variables with fully specified CCDB parameters.

Full CCDB parameter name	Variable	Note
`CCDB.Constants.me`	`me`	
`CCDB.Constants.e`	`e`	

Full CCDB parameter name	Variable	Note
`CCDB.Constants.k2`	`eV2K`	Inversed value of CCDB.
`CCDB.Constants.u`	`amu`	
`CCDB.Constants. m0_amu`	`o`	
`CCDB.EFI_LP.ProbeGains`	`gainres`	
`CCDB.EFI_LP.LP_SetupInstrument.probe_radius`	`probe_radius`	
`CCDB.EFI_LP.LP_SetupInstrument.fp_area`	`fp_area`	
`CCDB.EFI_LP. LP_SetupAlgorithms.DACBits`	`DACBits`	
`CCDB.EFI_LP.LP_SetupInstrument.VpTM_DAC`	`VpTM_DAC`	
`CCDB.EFI_LP.LP_SetupInstrument.VBmin`	`Blim_V_Low`	
`CCDB.EFI_LP.LP_SetupInstrument.VBmax`	`Blim_V_High`	
`CCDB.EFI_LP.LP_SetupAlgorithms.HM_Dion_Offset`	`HM_Dion_Offset`	
`CCDB.EFI_LP.LP_SetupAlgorithms.HM_HL_Dion_Transition_Low` `CCDB.EFI_LP.LP_SetupAlgorithms.HM_HL_Dion_Transition_High`	`HM_HL_Dion_Transition`	Combined as: [low, high]
`CCDB.EFI_LP.LP_SetupAlgorithms.HM_Te_Dion_Transition_Low` `CCDB.EFI_LP.LP_SetupAlgorithms. HM_Te_Dion_Transition_High`	`HM_Te_Dion_Transition`	Combined as: [low, high]
`CCDB.EFI_LP.LP_SetupAlgorithms.HM_N_Limit`	`HM_N_Limit`	
`CCDB.EFI_LP.LP_SetupAlgorithms.HM_Vs_Dret_Limit`	`HM_Vs_Dret_Limit`	
`CCDB.EFI_LP.LP_SetupAlgorithms.HM_Vs2_denominator_min`	`HM_Vs2_denominator_min`	

Full CCDB parameter name	Variable	Note
`CCDB.EFI_LP.LP_SetupAlgorithms.dt_one`	`dt_one`	
`CCDB.EFI_LP.LP_SetupAlgorithms.dt_two`	`dt_two`	
`CCDB.EFI_LP.LP_SetupAlgorithms.VS_Limit_Low` `CCDB.EFI_LP.LP_SetupAlgorithms.VS_Limit_High`	`V_lim`	Combined as: [low, high]
`CCDB.EFI_LP.LP_SetupAlgorithms.Te_Limit_Low` `CCDB.EFI_LP.LP_SetupAlgorithms.Te_Limit_High`	`Tlim`	Combined as [low, high]
`CCDB.EFI_LP.Te_Extreme`	`N/A`	For flagging extreme values of Te, unit eV
`CCDB.EFI_LP.LP_Post_Calibrations`	`N/A`	2d variable designating a matrix of cal values over a grid
`CCDB.EFI_LP. HM_TeNe_Cal_Limits`	`N/A`	2d variable designating a polygon limiting the validity of the calibration

5.2 Input from L0 instrument packets

The input from L0 packets is denoted according to [AD-2], column “PCF_DESCR”. Packets with SIDs 13 and 14 are relevant. For the bit format (integer, float, 8, 16, … bits) consult [AD-2]. The byte order is “little endian,” which practically all computers in use today have.

5.2.1 LP configuration

Information about the LP configuration is obtained from packets with PID 57 and SID 14. For each data packet the most recent preceding configuration packet has to be used. Configuration packets are nominally created every 128 s. When the EFI is powered on, a configuration packet should be sent before data packets. The time difference between a data packet and most recent preceding configuration packet should so never exceed 128 s.

Table 5-6: L0 LP configuration parameters

PCF_DESCR	Description	Unit
`EFI_CommonParam3`	Gain setting for each probe	N/A
`EFI_FixBiasIonPrb1`	Fixed ion bias probe 1	TM
`EFI_FixBiasIonPrb2`	Fixed ion bias probe 2	TM
`EFI_OptionsHarmonic`	Bit 2 on: Linear is offset from tracked Bit 2 off: Fixed linear bias	N/A
`EFI_FixBiasLinEPrb1`	Linear bias probe 1	TM
`EFI_FixBiasLinEPrb2`	Linear bias probe 2	TM

The linear bias is normally set relative to the tracked bias (contained in the data packets), and bit 2 of `EFI_OptionsHarmonic` is set. The L1b processor should also handle the unusual configuration that the linear bias is fixed and bit 2 of `EFI_OptionsHarmonic` is *not* set. In this case v_{lin} for each of the probes is `EFI_FixBiasLinEPrb1` or `EFI_FixBiasLinEPrb2` converted to physical V, see 5.2.3.

The configuration packets contain more information like ripple amplitude, frequency etc. which, however, is assumed to have no effect on L1b parameter estimates.

5.2.2 Harmonic submode data

The data of the harmonic submode are in packets with PID 57 and SID 13. Each packet contains the data from two cycles, at times *t1* and *t2*.

Table 5-7: Harmonic submode data

PCF_DESCR	Description	Unit
`EFI_LpBiasPrb1Sec0p5`	Tracked bias probe 1, t1	TM
`EFI_LpBiasPrb2Sec0p5`	Tracked bias probe 2, t1	TM
`EFI_Prb1BiasVRetESec0p5`	Retarded bias probe 1, t1	TM
`EFI_Prb2BiasVRetESec0p5`	Retarded bias probe 2, t1	TM
`EFI_StatusOverflowSec0p5`	Overflow indicator, t1	Counts
`EFI_Prb1CurrIonSec0p5`	Ion current probe 1, t1	TM
`EFI_Prb1CurrLinESec0p5`	Linear current probe 1, t1	TM
`EFI_Prb1CurrRetESec0p5`	Retarded current probe 1, t1	TM
`EFI_Prb1DerivatIonSec0p5`	Ion admittance probe 1, t1	AV^{-1}
`EFI_Prb1DerivatESec0p5`	Linear admittance probe 1, t1	AV^{-1}

PCF_DESCR	Description	Unit
`EFI_Prb1DerivatRetSec0p5`	Retarded admittance probe 1, t1	AV^{-1}
`EFI_Prb2CurrIonSec0p5`	Ion current probe 2, t1	TM
`EFI_Prb2CurrLinESec0p5`	Linear current probe 2, t1	TM
`EFI_Prb2CurrRetESec0p5`	Retarded current probe 2, t1	TM
`EFI_Prb2DerivatIonSec0p5`	Ion admittance probe 2, t1	AV^{-1}
`EFI_Prb2DerivatESec0p5`	Linear admittance probe 2, t1	AV^{-1}
`EFI_Prb2DerivatRetSec0p5`	Retarded admittance probe 2, t1	AV^{-1}
`EFI_LpBiasPrb1Sec1`	Tracked bias probe 1, t2	TM
`EFI_LpBiasPrb2Sec1`	Tracked bias probe 2, t2	TM
`EFI_Prb1BiasVRetESec1`	Retarded bias probe 1, t2	TM
`EFI_Prb2BiasVRetESec1`	Retarded bias probe 2, t2	TM
`EFI_StatusOverflowSec1`	Overflow indicator, t2	Counts
`EFI_Prb1CurrIonSec1`	Ion current probe 1, t2	TM
`EFI_Prb1CurrLinESec1`	Linear current probe 1, t2	TM
`EFI_Prb1CurrRetESec1`	Retarded current probe 1, t2	TM
`EFI_Prb1DerivatIonSec1`	Ion admittance probe 1, t2	AV^{-1}
`EFI_Prb1DerivatESec1`	Linear admittance probe 1, t2	AV^{-1}
`EFI_Prb1DerivatRetSec1`	Retarded admittance probe 1, t2	AV^{-1}
`EFI_Prb2CurrIonSec1`	Ion current probe 2, t2	TM
`EFI_Prb2CurrLinESec1`	Linear current probe 2, t2	TM
`EFI_Prb2CurrRetESec1`	Retarded current probe 2, t2	TM
`EFI_Prb2DerivatIonSec1`	Ion admittance probe 2, t2	AV^{-1}
`EFI_Prb2DerivatESec1`	Linear admittance probe 2, t2	AV^{-1}
`EFI_Prb2DerivatRetSec1`	Retarded admittance probe 2, t2	AV^{-1}

The overflow 16-bit word actually contains the 4-bit long count (max count = 15) of each probe 1 and 2 in each the retarded and linear subcycles, respectively, and is further decoded. For brevity we write

`EFI_StatusOverflowSec0p5` as `ofstat_t1` and `EFI_StatusOverflowSec1` as `ofstat_t2`. `>>` is the bitwise right shift operator, `&` the bitwise AND operator, and `0x0f` a number with all 4 bits set (all as in the C language).

Table 5-8: Overflow decoding

Decode statement	Description	Unit
`(ofstat_t1>> 4) & 0x0f`	Retarded overflow count probe 1, t1	counts
`(ofstat_t1     ) & 0x0f`	Retarded overflow count probe 2, t1	counts
`(ofstat_t1>>12) & 0x0f`	Linear overflow count probe 1, t1	counts
`(ofstat_t1>> 8) & 0x0f`	Linear overflow count probe 2, t1	counts
`(ofstat_t2>> 4) & 0x0f`	Retarded overflow count probe 1, t2	counts
`(ofstat_t2     ) & 0x0f`	Retarded overflow count probe 2, t2	counts
`(ofstat_t2>>12) & 0x0f`	Linear overflow count probe 1, t2	counts
`(ofstat_t2>> 8) & 0x0f`	Linear overflow count probe 2, t2	counts

5.2.3 Conversion to physical units

5.2.3.1 *Bias conversion*

Bias values in L0 packets need to be converted from TM to Volt, example:

$$v_{ion,p1} = (\mathrm{EFI\_FixBiasIonPrb1} + \mathrm{VBmin\_tm}) * \mathrm{VpTM\_DAC} \tag{18}$$

When the linear bias is relative to the tracked bias (as it is normally the case), the values need to be added before conversion to Volt, example for probe 1:

$$v_{lin,p1} = (\mathrm{EFI\_LpBiasPrb1Sec0p5} + \mathrm{EFI\_FixBiasLinEPrb1} + \mathrm{VBmin\_tm}) * \mathrm{VpTM\_DAC} \tag{19}$$

On-board 16 bit integers are used to control the bias. When setting the linear bias as an offset from the tracked bias, a digital overflow can occur. At the ground L1b processing this must be detected by asserting that the converted v_{lin} is less than +5 V. The 16 bit bias values in TM units must be read at the L1b processor into at least 32 bit integer variables (otherwise the digital overflow would occur also in the L1b processing with unpredictable outcome).

5.2.3.2 *Current conversion*

Currents are sampled at about 16 kHz per subcycle. The number of samples depends on the configurable duration of the subcycle. The values are down sampled and averaged on-board. Single precision floats are used for the averaged values. The scaling is the same as for the unsigned 16 bit bias values, but no offset must be applied.

Actually a voltage is measured which, to get the current, must be divided by the resistor determining the gain (or sensitivity, similar as in an Ohmmeter). Table 5-3 shows the resistor values. At low gain setting only the second resistor R_2(second column in the matrix) is coupled. At high gain setting both resistors R_1 and R_2 are coupled in parallel.

Therefore the **conversion of low gain currents** from TM to Ampere is

$$i_{xxx,lgn} = \mathrm{EFI\_Prb1CurrXXX} * \mathrm{VpTM_{DAC}}/R_2 \qquad \textbf{(20)}$$

and **for high gain currents** it is

$$i_{xxx,hgn} = \mathrm{EFI_{Prb1CurrXXX}} * \mathrm{VpTM_{DAC}} * (\frac{1}{R_1} + \frac{1}{R_2}) \qquad \textbf{(21)}$$

(xxx is ion, ret, or lin).

The gain/sensitivity setting for each probe is inferred from the "common parameter 3"/`EFI_Common-Param3` in the configuration packet, see Table 5-6, for brevity denoted **`gain`** in Table 5-9:

Decode statement	Description
`gain & 0x03`	Gain (1 or 2) of probe 1
`(gain >> 4) & 0x03`	Gain (1 or 2) of probe 2

Table 5-9: Gain decoding, 1=low, 2=high gain

If both probes have the same gain, then, for the L1b algorithm, probe 1 is assumed to be the high gain probe, and probe 2 the low gain, but the conversion of currents to Ampere is of course done according to the actual setting.

5.3 Computational algorithm

Steps:

1 Initialize LP constants and algorithm parameters (see Table 5-1 to Table 5-4), round the $dt1$ and $dt2$ (Table 5-4) to full Milliseconds;

2 While still data to process,

2.1 obtain for both probes the fixed ion bias, the linear bias, the option indicating whether the linear bias is an offset from the tracked bias (see Table 5-6), and the gain (see Table 5-9), all from the most recent L0 configuration packet. If applicable, the previous values can be reused;

2.2 obtain for both probes from the L0 harmonic submode packet the tracked bias and the retarded bias (see Table 5-7);

2.3 convert the ion, retarded, and linear bias to Volt using equations (18), for the linear bias, if applicable, add the tracked bias before conversion, equation (19). The result is v_{xxx} (xxx is ion, ret, or lin), for each probe;

2.4 obtain the ion, retarded, and linear currents (see Table 5-7);

2.5 convert currents to Ampere, equation (20), the results are i_{xxx} (xxx is ion, ret, or lin);

2.6 obtain the ion, retarded and linear real admittances (see Table 5-7), no conversion is needed, the result is d_{xxx};

2.7 add O_{dion} to the high gain probe d_{ion} (overwriting d_{ion}, see Table 5-4 for O_{dion});

2.8 obtain the satellite speeds v_1 and v_2 (magnitude of velocity vector) for the full seconds that bracket the LP HM measurement, interpolate the speed at the time stamp of the LP density measurement which is dt1 or dt2 from the full second: $u_i = v_1 + dtk * (v_2 - v_1), k = 1$ or 2;

2.9 calculate N_e according equation (14) using d_{ion} of the high gain probe. If the result is negative, use d_{ion} of the low gain probe;

2.10 prepare to calculate T_e according to equation (15) always using i_{ion} and d_{ion} from the high gain probe. Two values, $T_{e,hgn}$ and $T_{e,hl}$ are obtained by inserting the retarded currents and admittances from the high and low gain probes, respectively;

2.11 prepare to calculate T_e:

2.11.1 check if high gain $v_{tr,hgn} = 0$, i.e. failed tracking;

2.11.2 check if high gain $v_{lin,hgn} > 5.0$ Volt (overflowing 16-bit bias register)

2.11.3 check if $v_{ret,hgn} < v_{ion,hgn}$ (wrong ordering of ion and retarded bias)

2.11.4 check if $v_{ret,hgn} > v_{lin,hgn}$ (wrong ordering of retarded and linear bias)

2.11.5 check if $i_{ret,hgn} < i_{ion,hgn}$ (retarded current is wrongly less than ion current)

2.11.6 check if $d_{ret,hgn} < d_{ion,hgn}$ (retarded admittance is wrongly less than ion admittance)

2.12 set $T_e = T_{e,hgn}$, but if any of the checks 2.11.1-2.11.6 is positive/"yes" or if the computed $T_{e,hgn}$ is outside of valid region (see Tlim in Table 5-4), then $T_e = T_{e,lgn}$

2.13 determine flags for T_e, depending on which of the probes is used and which conditions are detected, see Table 5-12

2.14 The T_e result is now in eV, for output convert to Kelvin (see Table 5-1);

2.15 prepare to estimate V_s. Calculate, for both probes, $V_{s,1}$ according to equation (16);

2.16 calculate $V_s = V_s^l$ (preliminary tests showed that V_s from the low gain probe seems more consistent than that V_s from the high gain probe, but there are exceptions:);

2.17 if V_s from low gain is outside of valid region (see V_lim in Table 5-4) and V_s^h from high gain is not outside of valid region and none of the checks on the high gain probe (2.11.1-2.11.6) are positive then set $V_s = V_s^h$;

2.18 determine flags for V_s.

3 Go to step 2 or exit if no more data to process.

Normal mode packets are duplicated every 128 seconds, when sweeps occur. This allows to obtain seemingly regularly sampled harmonic mode data, and this was aimed to facilitate TII processing (which needs estimates of V_s strictly at 2 Hz sampling). In reality of course there is a data gap every 128 s. An "offset calibration" is done every six hours and normally lasts 3 seconds. Gaps from the offset calibration are not filled

5.4 L1b Output

5.4.1 Time stamped L1b parameters

The LP L1b parameters are N_e, T_e , and V_s. No errors are generally assigned to these parameters, but the error column in the output is set to the maximum value or (for certain latitudes) to a calibration offset as described in [AD-4]. The time stamps refer to the measurement of N_e or of the ion current. The timestamp of T_e would rather be associated with the retarded current measurement, which is roughly 200 ms later than the ion current. The offsets $dt1$ and $dt2$ of the LP N_e time stamps relative the packet time stamp, which is always the full second, is given in Table 5-4. The values were determined experimentally by correlating with 50 Hz VFM data at times when irregularities were present. They differ by about 20 ms from the values obtainable from the technical specifications of the LP instrument.

$dt1$ and $dt2$ should not be confused with `dt_LP` in [AD-1], where `dt_LP` is the offset relative to the TII timestamp.

5.4.2 Flags

Table 5-10: General LP flag indicating the source of the T_e measurement

Description	Flag_LP
High gain probe	1
Low gain probe	5
If sweep packet exists	9

The `Flag_LP` is set to 9, if a sweep packet for the same time and satellite exists. Then the harmonic mode packet is a duplication of the packet before the sweep.

Table 5-11: Flag for density estimates

Condition	Description	Flag_Ne
`N/A`	Nominal data, valid calibration error for this sample is computed	10
N_e,T_e `not in polygon`	Nominal data, but calibration error not computed/out of range	19
`N/A`	Nominal data, error for this sample is not computed	20
High-gain $N_e \leq 0$	The estimate is from low gain probe	30
$N_e < 0$	Negative density	40

In the following ROF_{hgn} denotes ADC overflow in the retarded regime at the high gain probe, ROF_{lgn} at the low gain probe (see tables Table 5-8 and Table 5-9). Overflows and failed tracking need to be flagged only when the corresponding probe is actually used for the estimate

Table 5-12: Flag for temperature estimate

Condition	Description	Flag_Te
`N/A`	Nominal data, valid calibration error for this sample is computed	10
N_e,T_e `not in polygon`	Nominal data, but calibration error not computed/out of range	19
$LOF_{hgn} > 0$	ADC overflow at the linear bias, high gain probe, tracking ok, should not affect T_e estimate	12
`N/A`	Nominal data, error for this sample is not computed	20

Condition	Description	Flag_Te
$\boldsymbol{LOF_{hgn}} > \mathbf{0}$	Error not computed, ADC overflow at the linear bias, high gain probe, tracking ok	22
$\boldsymbol{v_{tr,lgn}} = \mathbf{0}$	Failed 0-tracking low gain[1]	35
$\boldsymbol{T_e} > \mathbf{20000}\ \boldsymbol{K}$	Extreme value	36
$\boldsymbol{ROF_{lgn}} > \mathbf{0}$	Overflow low gain probe[1]	40
$\boldsymbol{T_e} < \mathbf{0}$	Negative temperature	40
The following values can be added:		
$\boldsymbol{ROF_{hgn}} > \mathbf{0}$	Overflow high gain probe[2]	1
$\boldsymbol{ROF_{lgn}} > \mathbf{0}$	Overflow low gain probe[1]	2
$\boldsymbol{v_{ret}} < \boldsymbol{v_{ion}} \vert \boldsymbol{v_{ret}} \geq \boldsymbol{v_{lin}}$	Wrong low gain bias setting[1]	4

[1] The condition is only flagged, if the high gain probe has an error, and the low gain probe gets used.

[2] The Te estimate can be treated as all right even when the high gain probe overflows

For flagging V_s also a possible linear overflow LOF_{hgn} and LOF_{lgn} is taken into account:

Table 5-13: Flag for spacecraft potential estimate

Condition	Description	Flag_LP_Vs
`N/A`	Default	20
$\boldsymbol{v_{tr,lgn}} = \mathbf{0}\ \&\ \boldsymbol{V_s^l}$ `is used`	Failed 0-tracking low gain	30
$\boldsymbol{v_{tr,hgn}} = \mathbf{0}\ \&\ \boldsymbol{V_s^h}$ `is used`	Failed 0-tracking high gain	30
$(\boldsymbol{ROF_{lgn}} > \mathbf{0}$ `or` $\boldsymbol{LOF_{lgn}} > \mathbf{0})\ \&\ \boldsymbol{V_s^l}$ `is used`	Overflow at retarded bias	25
$(\boldsymbol{ROF_{hgn}} > \mathbf{0}$ `or` $\boldsymbol{LOF_{hgn}} > \mathbf{0})\ \&\ \boldsymbol{V_s^h}$ `is used`	Overflow at linear bias	26

5.4.3 Coordinates, orbit velocity and sun position

The IRF LP PP produces geodetic coordinates and the Sun's zenith and azimuth (geodetic reference) from information that is read from the L1b MOD file providing coordinates in the ITRF at full seconds. The PP linearly interpolates the values for the LP time stamps, and then calculates geodetic and magnetic apex coordinates as well as the sun position. These coordinates are not part of the L1b product, but included only in the extended LP data set produced by IRF and distributed via the PDGS [AD-6] .

The orbital velocity, also retrieved from MOD files, is linearly interpolated to the LP time stamps (see step 2.8 in section 5.3) and then used for the calculation of N_i.