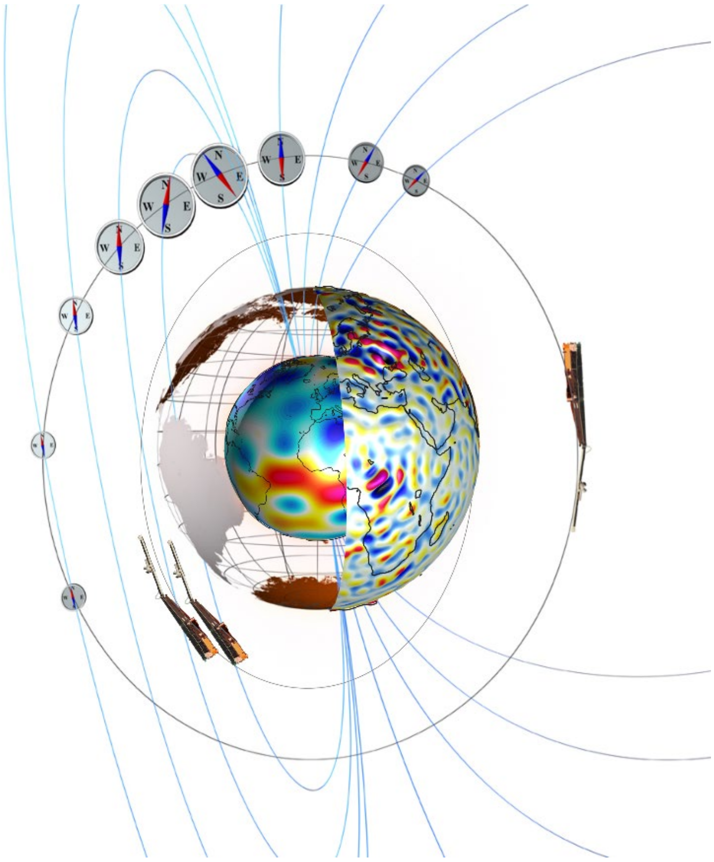
Data, Innovation, and Science Cluster

Swarm Ion Temperature Estimation Processing algorithm description



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Record of Changes

Reason	Description	Rev	Date
Initial vers.	Draft	1 dA	18 Sep 2020
Revised	Details about model function calls and ion temperature model added, as suggested by DTU	1 dB	13 Nov 2020
Release	Updated to version 1, signed	1	17 Jan 2022

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1 Introduction

The document provides information about the progressing algorithms, which are used to generate Swarm ion temperatures.

1.1 Scope and applicability

This document is a deliverable of the Swarm Ion Temperature Estimation 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 SITE 2.3.

2.2 Reference Documents

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

[RD-1] SW-TN-UoC-GS-001-2-3-SITE_Product_Defintition, SITE product definition document

[RD-2] SW-RN-IRF-GS-005, Extended Set of Swarm Langmuir Probe Data

[RD-3] SW-RN-UoC-GS-004, EFI TII Cross-Track Flow Data Release Notes

[RD-4] Weimer, D. R. (2005). Improved ionospheric electrodynamic models and application to calculating Joule heating rates. Journal of Geophysical Research, 110, A05306.

[RD-5] Picone, J. M., Hedin, A. E., Drob, D. P., & Aikin, A. C. (2002). NRLMSISE-00 empirical model of the atmos-phere: Statistical comparisons and scientific issues. Journal of Geophysical Research, 107(A12), 1468.

[RD-6] Drob, D. P., et al. (2015), An update to the Horizontal Wind Model (HWM): The quiet time thermo-sphere, Earth and Space Science, 2, doi:10.1002/2014EA000089.

[RD-7] Huba, J.D., G. Joyce, and J.A. Fedder (2000), Sami2 is Another Model of the Ionosphere (SAMI2): A new low-latitude ionosphere model, J. Geophys. Res., 105, 23,035.

[RD-8] 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-9] Lomidze, L., Burchill, J.K., Knudsen, D.J. and Huba, J.D., 2021. Estimation of Ion Temperature in the Upper Ionosphere Along the Swarm Satellite Orbits. *Earth and Space Science*, *8*(11), p.e2021EA001925.

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***
NRLMSISE	Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar Extended
HWM	Horizontal Wind Model

3 Processing algorithms

3.1 Outline

Processing software responsible for the Swarm ion temperature model estimation combines an ion energy balance equation with supporting observational and model data (Figure 1). It is implemented in Matlab, run on a UCalgary computer with Windows 10 OS, and produces ion temperature data at 2Hz rate together with other parameters as defined in RD-1.

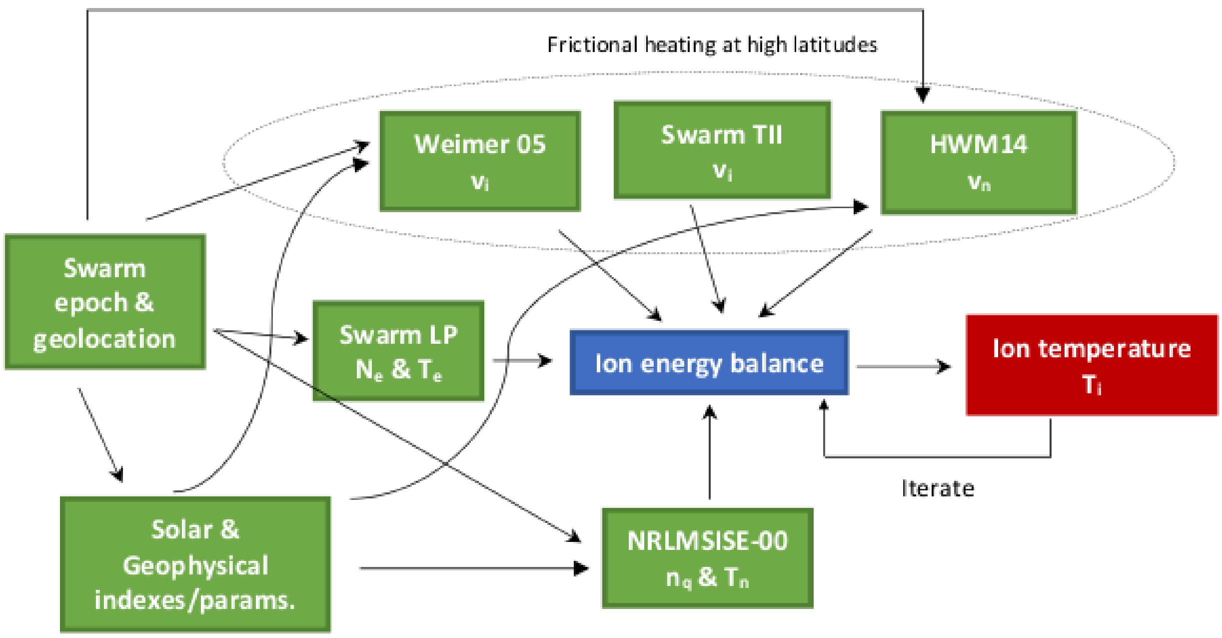

Figure 1: Schematic view of the different parts of ion temperature estimation algorithm and their relationship. Each box represents separate function, software code, or dataset, which are combined together by the main processing software [RD-9].

3.2 Observational data

3.2.1 Geophysical data

The processing begins with reading of pre-downloaded solar and geomagnetic ($F_{10.7}$, Ap, ap), solar wind (density and velocity), interplanetary magnetic field (IMF) B_y and B_z components, and auroral electrojet AL index data. They are loaded into the computer RAM and then used as inputs to run supporting empirical models: Weimer 2005, NRLMSISE-00 and HWM14. These geophysical data are available at https://celestrak.com/SpaceData/, http://wdc.kugi.kyoto-u.ac.jp, and https://spdf.gsfc.nasa.gov. In addition, loaded are hourly values of geomagnetic dipole tilt angle, which is the angle of the north magnetic pole to the GSM *z* axis (positive when the north magnetic pole is tilted towards the Sun). They are generated in advance using the Weimer 2005 model package available at http://doi.org/10.5281/zenodo.2530324 (see 'User's Guide for Weimer 2005' for details of a function call to calculate the tilt angle using IDL software package).

3.2.2 Swarm data

The next processing step is to select a particular date and read corresponding Swarm Langmuir Probe (LP) 2Hz electron density (N_e) and electron temperature (T_e) data from the corresponding daily CDF file. The data are taken from "Extended Set of Swarm Langmuir Probe Data" [RD-2], which are available at ftp://swarm-diss.eo.esa.int/Advanced/Plasma_Data/2_Hz_Langmuir_Probe_Extended_Dataset/. The parameters retained are satellite geolocation, epoch, electron density, electron temperatures from high- and low-gain probes, and flag bits. The flags are used to filter out unusable data as defined in RD-2 (marked with 'Don't use' in Table 3-3: Meaning of the flagbits). In addition, unphysical (N_e<0, T_e<0) and very high values (suspicious values [RD-2]) such as N_e>10^7 cm^{-3} and T_e>20,000 K are also excluded.

For the given date the software also checks if current baseline (e.g., 0302) 2Hz Swarm TII data [RD-3] are available, which are then read to obtain along-track (V_{ix}), cross-track (V_{iy}), and vertical (V_{iz}) components of plasma drift. The data are pre-downloaded from ftp://swarm-diss.eo.esa.int/Advanced/Plasma_Data/2Hz_TII_Cross-track_Dataset/New_baseline/. Separate function processes the TII data and provides three components of plasma velocity vector in a geographic (NEC) frame at high geomagnetic latitudes (>44° MLAT). In particular, the components of plasma drifts parallel (along-track) and perpendicular (cross-track horizontal and vertical) are used in combination with satellite velocity to obtain geographic east ($V_{i,E}$) and north ($V_{i,N}$) components of the plasma flow:

$$V_{i,E} = V_{ix}sin(\alpha) + V_{iy}cos(\alpha)$$

$$V_{i,N} = V_{ix}cos(\alpha) - V_{iy}sin(\alpha)$$

$$V_{i,C} = V_{iz}$$

where $\alpha = atan2(V_{sat,E}, V_{sat,N})$ is an angle between geographic north and the Swarm spacecraft along track direction, $V_{sat,E}$ and $V_{sat,N}$ are east and north components of satellite's velocity in the NEC frame.

Redundant along-track drifts from the horizontal and vertical TII sensors are averaged to estimate along-track drift. Only those cross-track drifts with quality 1 are retained. However, since along-track and vertical drifts currently have only quality 0, their values are retained if corresponding cross-track drift has quality 1. The drift values exceeding 4 km/s are ignored. If any of the drift components are missing no TII-based ion temperature is computed.

3.3 Supporting Models

3.3.1 Weimer 2005

The Weimer 2005 empirical convection electric field model [RD-4] consists of pre-compiled IDL code and is available at http://doi.org/10.5281/zenodo.2530324. The Matlab code, used for SITE, generates required inputs, calls Weimer 2005 IDL code to run it, and then reads and imports the outputs of magnetic east and north components of high-latitude electric field. Details of function calls in IDL to run Weimer 2005 are given in 'User's Guide for Weimer 2005'. The main ones include '`SetModel, By, Bz, Tilt, SWVel, SWDen, ALindex, /YZ`' to set the IMF conditions, and '`efield, MLAT, MLT, EmN, EmE, ALT`' (or '…`ALT, /south`' for the southern hemisphere) to get magnetic north (E_{mN}) and magnetic east (E_{mE}) components of electric field. Matlab command to call IDL code is '`system ('idl -e ".RUN PATH/my_idl_file.pro" ')`'.

The data required to run the Weimer 2005 model are magnetic latitude and local time, altitude, IMF By and Bz, solar wind velocity and density, dipole tilt, and AL index (Section 3.2.1). These all are taken to correspond to conditions (location, time, and geophysical conditions) of Swarm 2Hz LP observations. Magnetic latitude and local time are calculated using altitude adjusted corrected geomagnetic (AACGM) coordinates.

The resulting Weimer 2005 electric field components are used in conjunction with IGRF magnetic field data to compute geographic east, north, and vertical components of the high-latitude plasma drift as follows. First, magnetic east ($V_{i,weimer,mE}$), north ($V_{i,weimer,mN}$), and vertical ($V_{i,weimer,z}$) components of ion drifts are computed:

$$V_{i,weimer,mE} = -E_{mN} sin(I)/B$$

$$V_{i,weimer,mN} = E_{mN} sin(I)/B$$

$$V_{i,weimer,z} = -E_{mE} cos(I)/B$$

where *I* is magnetic inclination, and *B* is the magnitude of geomagnetic field. Then, the geographic east and north components of the drift are calculated:

$$V_{i,weimer,E} = V_{i,weimer,mN} sin(D) + V_{i,weimer,mE} cos(D)$$

$$V_{i,weimer,N} = V_{i,weimer,mN} cos(D) - V_{i,weimer,mE} sin(D).$$

Here *D* is the magnetic declination.

3.3.2 NRLMSISE-00 and HWM14

Densities and temperatures of neutral atmospheric species (H, He, O, N_2, O_2) are calculated along the Swarm satellite orbits using the empirical NRLMSISE-00 model [RD-5]. In addition, at high magnetic latitudes (>44° MLAT) the neutral wind horizontal velocity (zonal and meridional components) is computed by the HWM14 empirical model [RD-6]. The corresponding FORTRAN codes are available at https://ccmc.gsfc.nasa.gov/pub/modelweb/ and http://onlinelibrary.wiley.com/doi/10.1002/2014EA000089/full (supplemental information: ess224-sup-0002-supinfo.tgz), respectively. To obtain NRLMSISE-00 and HWM14 model data, FORTRAN commands '`Call GTD7(IYD,SEC,ALT,GLAT,GLONG,STL,F107A,F107,AP,MASS,D,T)`' and '`Call hwm14(IYD,SEC,ALT,GLAT,GLONG,STL,F107A,F107,AP,W)`' are made from Matlab via their corresponding pre-compiled executables. Details about `GTD7` and `hwm14` FORTRAN subroutines, required inputs, and instructions how to run the models are given in '*nrlmsise00_sub.for*' and '*hwm14.f90*', which are main files of NRLMSISE-00 and HWM14 models.

3.4 Swarm Ion temperature

The final step in the processing algorithm combines Swarm and data from empirical models with the ion energy balance equation, and estimates ion (O^+) temperatures (T_i) along the Swarm satellites. Specifically, the T_i solution is obtained from

$$\frac{7.7\times10^{-6} n_e n_i}{A_i T_e^{1.5}}(T_e - T_i) + \sum_q \frac{3k_B n_i m_i m_q}{(m_i+m_q)^2}\nu_{iq}(T_i - T_q) = \sum_q \frac{n_i m_i m_q}{(m_i+m_q)^2}\nu_{iq} m_q(\mathbf{v}_i - \mathbf{v}_q)^2 \qquad (1)$$

where *q* denotes summations over neutrals (H, He, O, N_2, and O_2), $n_i = n_e$ is O^+ number density and T_e is electron temperature, both measured by the Swarm LP; "*i*" refers to O^+ ions, $\mathbf{v}_i$ is the ion drift velocity either measured by Swarm TII or calculated using Weimer 2005 empirical model, $\mathbf{v_q}$ is the neutral wind velocity (assumed independent of neutral species) obtained from the HWM14 model, A_i is the mass of O^+ ions in atomic mass units, m_i is the mass of O^+ ion, m_q is the mass of neutral type "q". $\nu_{iq} = \nu_{iq}(n_q, T_q, T_i)$ denotes ion-neutral collision frequency (in s^{-1}), which for H, He, N_2, and O_2, is calculated by [RD-7]

$$\nu_{iq} = 2.69 \times 10^{-9} \frac{\alpha_{0q} n_q}{{\mu_A}^{0.5}} \cdot \frac{m_q}{m_i + m_q}$$

and

$$\nu_{O^+O} = 4.45 \times 10^{-11} n_O {T_{\text{eff}}}^{0.5} (1.04 - 0.67 \log_{10} T_{\text{eff}})^2,$$

where n_q is the number density of neutral species q calculated using NRLMSISE-00 model, $\mu_A = A_i A_q / (A_i + A_q)$, $T_{\text{eff}} = (T_n + T_{O^+})/2$, T_n is the neutral temperature, and α_{0q} is the polarizability ($\alpha_{0H} = 0.667, \alpha_{0He} = 0.21, \alpha_{0O_2} = 1.59, \alpha_{0N_2} = 1.76$ [$\times 10^{-24} cm^3$]). More information about the corresponding assumptions in the ion temperature model are given in RD-1.

The main function is written in Matlab. The ion temperature model is iterative. Initially it assumes equal ion and neutral temperatures in the expression of O^+-O collision frequency and a linear equation for the ion temperature is solved. Then the temperature estimate is iterated until the difference between the two most recent estimates of ion temperature is less than 1 K. Typically three to four iterations appear sufficient.

The model inputs are number densities of thermospheric neutral species H, He, O, N_2, and O_2; neutral temperature (T_n); electron density and temperature (N_e and T_e); and three components (geographic east, north, and vertical) of velocity differences between neutrals and ions at high-latitudes. The latter are used to specify ion frictional heating at high latitude (the last term in equation (1)).

Ion frictional heating is estimated in two ways at high latitude, leading to two temperature estimates. One method uses measured TII drifts and the other uses empirical Weimer 2005 drifts. The two temperatures are the same at low and middle latitudes (≤44° MLAT), where frictional heating is neglected.

The values of N_e and T_e inputs, which are based on Swarm LP data, are corrected for systematic errors using the results of RD-8. The correction applies to both high-gain and low-gain T_e values.

Ion temperature is based on the high-gain LP probe measurement when available, and the low-gain probe measurement if only this latter is available. Note, the values of T_e are compared to T_n after the corrections to ensure they are physically meaningful, i.e. $T_e \geq T_n$. Otherwise, $T_e = T_n$ is assumed, which could lead to $T_i = T_n$ when the ion frictional heating is not considered. The values of estimated T_i are also checked and disregarded if they exceed T_e at middle and low latitudes, because at these latitudes the model assumes the electron gas to be the only heat source for ions.

All fields of output data, as defined in RD-1, are written in daily CDF files at the end of the processing cycle, and ion temperature calculation is then advanced to the next computation day.