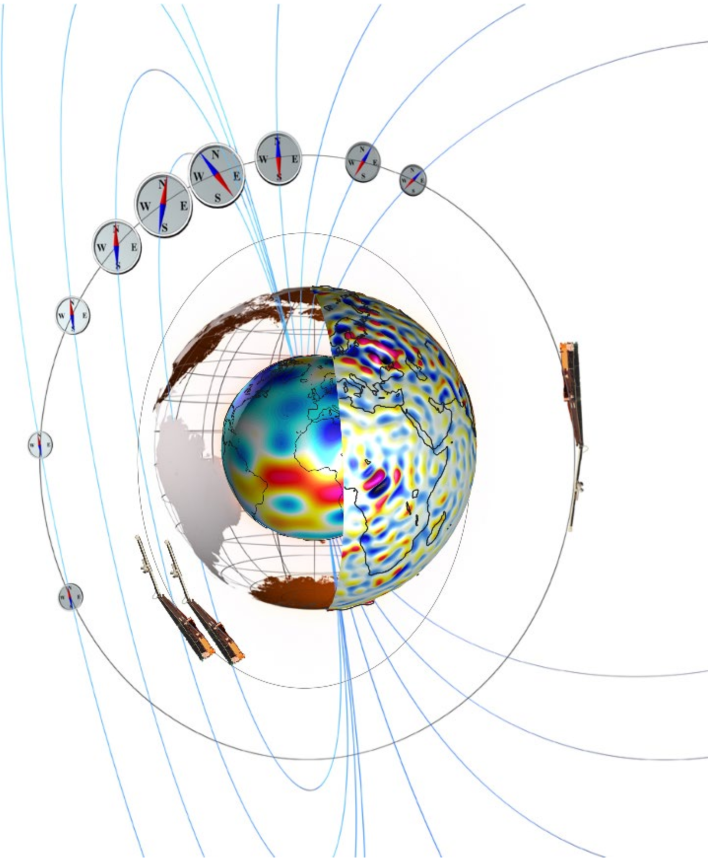
Statement of Work

Swarm DISC ITT 6.3

“Swarm climatological model of low- and mid-latitude toroidal magnetic fields”



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1 Introduction

This Invitation to Tender is issued by the Swarm DISC consortium on behalf of ESA within the reference frame of ESA contract 4000109587/13/I-NB, under the Swarm DISC Procurement Procedure described [RD-1].

1.1 Scope and Applicability

This document describes the activity to be executed and the deliverables required under the Swarm DISC ITT 6.3 – "Swarm climatological model of low- and mid-latitude toroidal magnetic fields".

It will become part of the contract and shall serve as an applicable document throughout the execution of the work (with possible amendments recorded during the negotiation meeting).

The document is structured as follows:

- Chapter 2 quotes applicable and reference documents (including applicable standards).
- Chapter 3 introduces the background and main objectives of the work, and presents the constraints on the system to be produced.
- Chapter 4 defines the work to be performed in the contract to produce the required output.
- Chapter 5 contains the requirements on deliverables and on general project management aspects.
- Chapter 6 contains schedule and milestones.

2 Applicable and Reference Documentation

2.1 Applicable Documents

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

[AD-1] ESA-EOPG-MOM-IF-17 Swarm SDPC to PDGS Interfacing Control Document (ICD)

2.2 Reference Documents

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

[RD-1] SW-RS-DTU-GS-003 rev. 2, Swarm DISC Procurement Procedure

[RD-2] Fillion, M., Hulot, G., Alken, P., & Chulliat, A. (2023). Modeling the climatology of low- and mid-latitude F-region ionospheric currents using the Swarm constellation. Journal of Geophysical Research: Space Physics, 128, e2023JA031344. https://doi.org/10.1029/2023JA031344

[RD-3] Olsen, N. (1997), Ionospheric F region currents at middle and low latitudes estimated from Magsat data, J. Geophys. Res., 102(A3), 4563–4576, https://doi.org/10.1029/96JA02949

[RD-4] Laundal, K. M., Finlay, C. C., Olsen, N., & Reistad, J. P. (2018). Solar wind and seasonal influence on ionospheric currents from Swarm and CHAMP measurements. Journal of Geophysical Research: Space Physics, 123, 4402–4429. https://doi.org/10.1029/2018JA025387

[RD-5] Vanhamäki, H., Juusola, L. (2020). Introduction to Spherical Elementary Current Systems. In: Dunlop, M., Lühr, H. (eds) Ionospheric Multi-Spacecraft Analysis Tools. ISSI Scientific Report Series, vol 17. Springer, Cham. https://doi.org/10.1007/978-3-030-26732-2_2

[RD-6] Alken, P., Maute, A. & Richmond, A.D. The F-Region Gravity and Pressure Gradient Current Systems: A Review. *Space Sci Rev* **206**, 451–469 (2017). https://doi.org/10.1007/s11214-016-0266-z

[RD-7] Alken, P., Maute, A., Richmond, A. D., Vanhamäki, H., & Egbert, G. D. (2017). An application of principal component analysis to the interpretation of ionospheric current systems: Tiegcm modeling, PCA, and data fitting. Journal of Geophysical Research: Space Physics, 122(5), 5687–5708. https://doi.org/10.1002/2017ja024051

[RD-8] G D Egbert, P Alken, A Maute, H Zhang, Modelling diurnal variation magnetic fields due to ionospheric currents, *Geophysical Journal International*, Volume 225, Issue 2, May 2021, Pages 1086–1109, https://doi.org/10.1093/gji/ggaa533

[RD-9] Maute, A., A. Richmond, F-Region Dynamo Simulations at Low and Mid-Latitude, Space Sci Rev (2017a) 206:471–493 DOI 10.1007/s11214-016-0262-3

[RD-10] H. Maeda, T. Kamei, T. Iyemori, T. Araki, Geomagnetic perturbations at low latitudes observed by Magsat. J. Geophys. Res., Solid Earth 90(B3), 2481–2486 (1985). doi:10.1029/JB090iB03p02481

[RD-11] Maute, A., & Richmond, A. D. (2017b). Examining the magnetic signal due to gravity and plasma pressure gradient current with the TIE-GCM. *Journal of Geophysical Research: Space Physics*, 122, 12,486–12,504. https://doi.org/10.1002/2017JA024841

[RD-12] Yamazaki, Y., & Maute, A. (2017). Sq and EEJ—A review on the daily variation of the geomagnetic field caused by ionospheric dynamo currents. Space Science Reviews, 206(1–4), 299–405. https://doi.org/10.1007/s11214-016-0282-z

2.3 Terminology

In this document the term '*shall*' indicates requirements which the proposed effort must meet, while '*should*' indicates a desirable feature.

2.4 Abbreviations

A frequently updated Acronyms and Abbreviations list for Swarm and related projects can be found here in the Swarm Data Handbook.

3 Background and Objectives

3.1 Background

In low Earth orbit, the magnetic field associated with ionospheric currents exhibits two primary components: a toroidal part linked to the radial component of field-aligned currents, and a poloidal part associated with both divergence-free horizontal currents in the lower ionosphere and the horizontal component of field-aligned currents. Olsen (1997) presented a model that accounts for both the toroidal and poloidal magnetic field disturbances based on measurements from the Magsat satellite. This model, derived in geographic coordinates, revealed the low-latitude current system driven by neutral winds (Sq, EEJ). Laundal et al. (2018) developed a similar model (AMPS) optimized to capture high-latitude currents. Their approach represents the magnetic field using spherical harmonics in magnetic apex coordinates with coefficients dependent on external parameters such as the interplanetary magnetic field and dipole tilt. More recently, Fillion et al. (2023) presented models focusing solely on the toroidal part of the magnetic field, derived from data within a limited altitude range. These models demonstrate that Swarm satellite data can provide detailed information about inter-hemispheric currents at low latitudes.

Using spatial information from a numerical model, Alken et al. [2017] developed a method to fit individual orbits of Swarm magnetic perturbations to principal component modes derived from the physics-based Thermosphere-Ionosphere-Electrodynamics GCMs (General Circulation Models). Egbert et al. [2021] extended this approach to capture daily magnetic variation by combining spatial and temporal principal component modes based on ground magnetometer and the spatial modes derived from Thermosphere-Ionosphere-Electrodynamics GCMs.

In general, the current flow in the ionosphere is complex and disentangling the source is a challenge. The wind dynamo is strong during the daytime especially in the E-region and responsible for a main part of the low- and mid latitude interhemispheric current flow. In addition, F-region winds generate characteristic low latitude current patterns [e.g., Maeda et al., 1995; Maute & Richmond 2017a] which models indicate close within a meridional plane (~ equatorward of 15° mag. latitude) through the E-region via vertical and field-aligned current. Smaller ionospheric current sources i.e., gravity and plasma pressure gradient driven current, are confined to low-latitude and part of this current can close via the E-region field-aligned current flow [e.g., Alken et al., 2017; Maute & Richmond 2017b]. In addition to the different current sources, the ionospheric current flow is 3D and varies with solar and geophysical conditions, season, longitude, and atmospheric forcing [e.g., Yamazaki & Maute, 2017].

The appeal of studying magnetic perturbations is that it captures variations even if the current is further away, however this also adds an additional layer of complication about how to remove the effect of certain current systems. Egbert et al. [2021] subtracted effects of external current sources i.e., magnetosphere including ring current. Fillon et al. [2023] used the Comprehensive Model (CM) [Sabaka et al, 2018]. In general, it is assumed that the models of the different internal and external current sources are accurate. However, potential biases could be introduced due to spatial-temporal data coverage and solar and geophysical conditions.

The mission objectives of Swarm, as well as already existing Swarm products are disseminated and described through https://earth.esa.int/eogateway/missions/swarm and included links.

Current Swarm data products are described in the Swarm Data Handbook and visualizations of most Swarm data products are available via the interactive 'VirES for Swarm' client. Tenderers are encouraged to visit VirES, to get an impression of the capabilities available.

This project shall deliver its products as part of the Level 2 distributed processing network, as a new product in the Swarm data processing chain (see Figure 1, and the applicable document [AD-1]). The products shall be suitable for generation on a regular basis pending availability of the required input products.

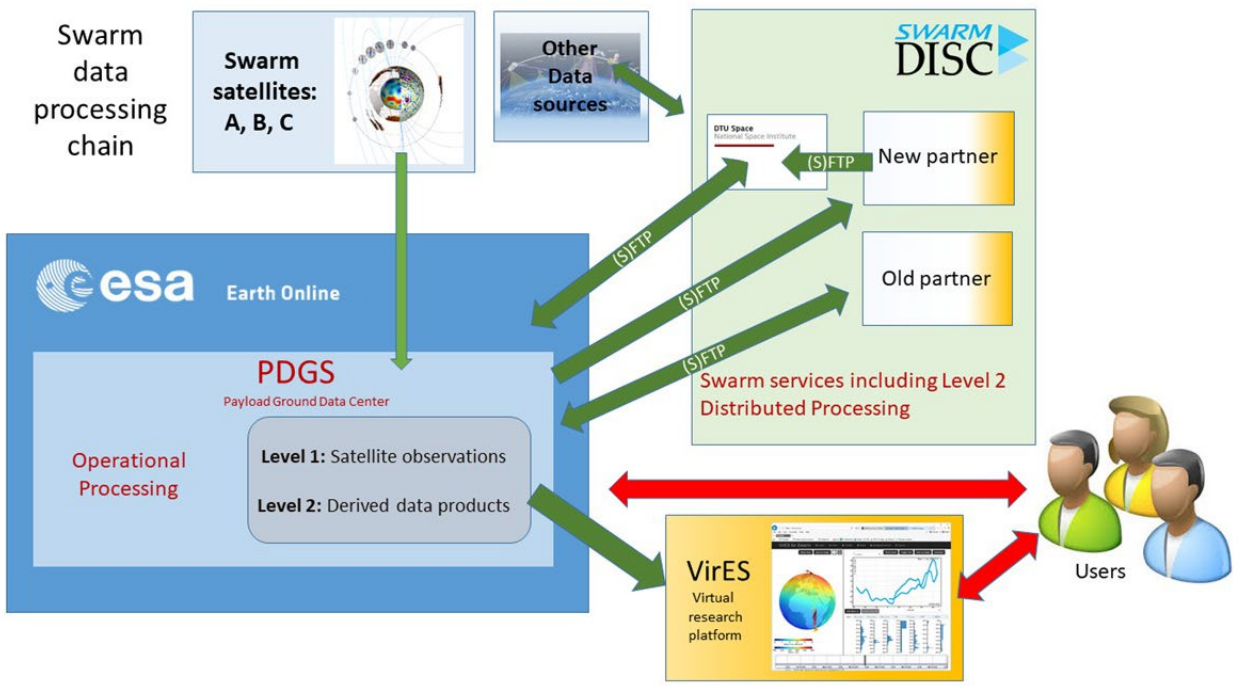

Figure 1 - Swarm data processing chain

3.2 Objectives of the Activity

The main objective of this activity is to develop a low- and mid-latitude model of the toroidal magnetic fields and its associated ionospheric current flow. This includes the coefficients associated with the parametrization as a data product and the associated forward model.

This activity *shall*:

- produce a climatological model of the toroidal magnetic field and its associated ionospheric current with
  - continuous variation in time (at least UT, seasons, and solar cycle)
  - continuous variation in longitude and latitude
  - continuous altitude variations at Swarm satellite height with the use of e.g.,
    - "thick-shell approximation", accounting for some altitude variation (e.g., Taylor expansion)

        - non-orthogonal 2D coordinates (QD-latitude/longitude, MIO_C and MIO_D product), or
        - full 3D non-orthogonal Apex frame (AMPS-type parameterisation extended to non-polar latitudes)
    - assessments of the effect on the climatological model of assumptions made about the poloidal field
- submit Python forward code to an open source repository, with visualization tools, links to descriptions of assumptions, data processing, description of output files, and user manual of tool box.
- deliver at least one publication for peer review and one presentation to a Swarm Data Quality Workshop or similar event.

A climatological model is here defined as a parameterized model based on a data set covering a significant and representative part of the solar cycle, which can describe the spatial-temporal variation beyond the original data-set coverage.

This activity *should*:

- provide the option to save output in commonly used data formats e.g., CDF or ASCII in the forward model.
- Provide output in both geographic and appropriate geomagnetic coordinate systems in the forward model.
- develop a climatological model that captures the influence of different processes, e.g., solar wind driving.
- consider potential visualization use cases for implementation in VirES and inclusion in SwarmPAL.
- submit inversion code to a public repository.

3.3 Assumptions and Constraints

Approval of deliverables will normally require 14 days for review by Swarm DISC Project Office. Approval of payment milestones is subject to approval of the related deliverables.

The tenderer shall show that they have access to the input data and that the project products preferably can be distributed in accordance with the ESA data policies.

The products shall be suitable for generation on a regular basis pending availability of the required input products. The new product shall be distributed through PDGS, but the tenderer may suggest using an additional alternative system (e.g. GitHub) for distribution as appropriate.

4 Work to be Performed

All deliverables described here will require an informal review – reviewer to be appointed by the Swarm DISC technical representative – and subsequent written approval.

The following sections describe the tasks anticipated to complete this project. Required output deliverables are listed in chapter 5.

4.1 Work Logic

The work to be performed shall cover the following tasks: Development and definition of the products including the forward code, a scientific validation of the developed products, the implementation of the products for ESA PDGS or other data system and verification and validation of the products performance, as well as preparation of the products for provision in an operational setting. The work shall also include the presentation of the results on international conferences and the compilation into a scientific publication.

The Contractor is expected to provide a brief summary of the project (about 200 words) to be published on the Swarm mission website a week after Kick Off at the latest.

4.2 Implementation

4.2.1 Task 1: Product definition

4.2.1.1 *Input*

- Statement of Work (this document)
- Scientific literature
- Satellite data products and their documentation
- Supporting data and models
- Proposal (should include a first iteration of the product definition and work plan)

4.2.1.2 *Task description*

Based on a review of the existing scientific literature and documentation of existing or recent Swarm products (see https://earth.esa.int/web/guest/missions/esa-eo-missions/swarm/data-handbook) and other relevant products and data sets, the Contractor shall update the product definition document.

The product definition should include descriptions of

- used data products, their temporal and spatial coverage and potential used parameters and version.
- description of used parametrization.
- data processing with information about employed models e.g., to describe certain magnetic variations, and a plan for assessing the quality of the resulting magnetic field and current model.
- output of forward model e.g., metadata with units, name.

4.2.1.3 *Deliverables*

- Product Definition Document (PDD) including specification of input data (TN-01)
- Literature survey

4.2.2 Task 2: Work plan

4.2.2.1 *Input*

- Statement of Work (this document)
- Proposal (should include a first iteration of the product definition and work plan)
- Product Definition Document

4.2.2.2 *Task description*

The Contractor shall propose a work plan for the implementation, verification, validation, and operation of the empirical model. The proposed work plan shall be supported by preliminary analysis results. The work plan shall include the identification of the satellite data and meta-data required for the analysis, as well as independent data or models to be used in the development of the model and for validation. One or more representative periods for initial testing and validation of the processor and resulting product shall be defined in the work plan. Satellite or ground based input data from sources other than existing Swarm products shall be described in the work plan, along with information on how to access this data.

The work plan should include details about the project's tasks, their timeline, and identify key personnel.

4.2.2.3 *Deliverables*

- Updated work plan

4.2.3 Task 3: Making data product

4.2.3.1 *Input*

- Product definition document
- Updated work plan
- Survey of data and existing tools and models
- Sample data sets for testing as well as full data set
- Validation plots based on the test data set
- Sample data set for validation
- Forward model code from Task 4

4.2.3.2 *Task description*

The contractor shall process the data and develop the parametrization to retrieve coefficients. The algorithms and resulting parametrization with coefficients shall be verified in an initial step using the forward model code for the test data. Adjustments to the parametrization should be made as necessary. The empirical model shall be validated on the full data set. Validation with additional data sources and against existing models should be performed. The final parametrization with the coefficients shall be described. The output of the forward model code applied to the test data set period shall be documented and be available to users.

The contractor shall assess the quality of the climatological model. The assumptions about e.g., poloidal field, external current sources, shall be documented and the effect on the model output assessed. The findings shall be summarized in the validation report.

4.2.3.3 *Deliverables*

- Description of the Processing Algorithms (DPA) and preferably submission of code to open source repository (TN-04)
- Validation plots based on the test data set (DL-01)
- Coefficients and the description of the parametrization and applied assumptions
- [optional] Inversion code submitted to public repository
- Validation Report.

4.2.4 Task 4: Making forward code

4.2.4.1 *Input*

- Parametrization with Coefficients
- Product definition document

4.2.4.2 *Task description*

The contractor shall develop a Python forward code with visualization tools, links to descriptions of assumptions and the data processing. The packages shall include a description of input values and output files format and fields with an example, and shall be documented in the user manual of the tool box. Examples of output files and visualization shall be included. The code shall be submitted to an open source repository, and the user manual shall be made publicly available.

4.2.4.3 *Deliverables*

- Python forward code with example scripts submitted to public repository
- Sampled input values, output files with visualization.
- User manual.

4.2.5 Task 5: Transfer of coefficients and documentation to ESA

4.2.5.1 *Input*

- Product Definition Document (TN-01)
- Work plan (TN-02)
- Interface Control Document (ICD) [AD-1]

4.2.5.2 *Task description*

The Contractor shall produce the output data, e.g., the coefficient files of the models, as well as a Product Definition Document ("PDD", TN-01) in the final product format which is as much as possible compliant with [AD-1] and distribute them via PDGS or via an alternative similar system as agreed with the Swarm DISC Project Office. The final output data should cover results from the full mission and be delivered by the Final Presentation. The Contractor shall prepare a plan for how continued operational provision of the data product could be supported beyond the end of the contract. This plan shall describe the support needed for maintaining an updated product with new mission data including answering user questions received by ESA EO helpdesk (second line support) in the event that a future operational phase is to be negotiated.

4.2.5.3 *Deliverables*

- Description of data transfer functionality and proposal for continued operation beyond project closure (TN-06)

- Products based on full mission data delivered to PDGS or other data system (DL-02)
- Final data set

4.2.6 Task 6: Final presentation

4.2.6.1 *Input*

- All outcomes from the project

4.2.6.2 *Task description*

- Preparation and submission of publication for peer review on the outcome of this project
- Presentation of project achievements at a Swarm Data Quality Workshop or similar event to be agreed with the Swarm DISC Project Office towards the end of the project.
- Delivery of all documentation to Swarm DISC. Note that the PDD, DPA, and Validation Report will be made publicly available on the Swarm web page.

4.2.6.3 *Deliverables*

- One publication submitted for peer review
- Presentation of project achievements at Swarm DQW or similar event
- Final project documentation delivered electronically to the Swarm DISC Project Office in searchable PDF format

5 Requirements for Management, Reporting, Meetings, and Deliverables

The following are the requirements for management, reporting, meetings and deliverables applicable to the present activity.

5.1 Management

MG-01	The Contractor shall assign a responsible project manager as point of contact with the DISC Project Office / ESA.
MG-02	A point of contact shall be assigned for each subcontractor, if any, but generally any correspondence with the project will be via the project manager assigned in MG-01
MG-03	All correspondence between the project and ESA must be via – or if agreed by DTU in copy to – the Swarm DISC Project Office, with attention to the DISC project manager by email or letter post: Klaus Nielsen klausn@space.dtu.dk: Swarm DISC Project Office DTU Space Centrifugevej, Building 356 DK-2800 Kgs. Lyngby Denmark Fax: +45 4525 9701

5.2 Reporting

GR-01	The Contractor shall submit all documents to the DISC Project Office in a searchable, non-protected PDF format, as well as their native format.
GR-02	The Contractor shall ensure that electronic documents do not contain any harmful code (e.g. virus)
GR-03	The Contractor shall produce a short quarterly progress report (or at other intervals as agreed), communicated to the Swarm DISC Project Office via SVN and email. This report shall contain highlights of recent achievements, status on work progress, references to publications or presentations, new challenges, etc. Swarm DISC will provide a reporting template.
GR-04	The Contractor shall consider public outreach opportunities that may arise from this project. Ideas should be reported to the DISC Project Office who will liaise between the project team and ESA's communications team.

5.3 Meetings

ME-01	The Contractor shall organize a Kick Off meeting via telecon where key persons are introduced and the project schedule is presented.
ME-02	The Contractor shall at the Mid Term Review present highlights of recent achievements, status on work progress, and plan for the remaining part of the project to the Swarm DISC Project Office via telecon. The presentation should preferably be comprised of a limited number of slides provided to DTU one week before the telecon. ESA reserves the right to participate.

ME-03	The Contractor shall prepare a presentation of the final result (DL-09) and present it to the Swarm DISC community at a suitable event (Data Quality Workshop or conference) in Europe to be agreed with the Swarm DISC Project Office.
ME-04	The Swarm DISC Project Office and ESA reserves the right to call up ad hoc meetings at any time for justified reasons.
ME-05	The Contractor shall provide minutes of the meetings. The DISC Project Office shall provide a template.

5.4 Technical Documentation

The individual deliverables referred to in the task descriptions above and listed below can be submitted either as individual documents (technical notes) or as sections in a combined project report. The latter will take the form of a living document to be submitted in revisions according to the schedule outlined in section 6.2 below. Submitting parts of the Project Report as journal publications is also acceptable.

TN-01	Product Definition Document (PDD) including specification of input data
TN-02	Work plan
TN-03	Literature survey
TN-04	Description of the Processing Algorithms (DPA) and preferably submission of code to open source repository
TN-05	Validation report
TN-06	Description of data transfer functionality and proposal for continued operation beyond project closure

5.5 Other Deliverables

DL-01	Validation plots based on the test data set
DL-02	Coefficients and the description of the parametrization and applied assumptions
DL-03	Inversion code submitted to public repository [Optional]
DL-04	Python forward code with example scripts submitted to public repository
DL-05	Sampled input values, output files with visualization
DL-06	User manual
DL-07	Products based on full mission data delivered to PDGS or other data system
DL-08	Final data set
DL-09	One publication submitted for peer review

DL-10	Presentation of project achievements at Swarm DQW or similar event
DL-11	All technical notes, presentations, publications and other relevant project documentation delivered electronically to the Swarm DISC Project Office in searchable PDF format.

6 Schedule and Milestones

6.1 Schedule

SC-01	The Contractor shall establish a schedule that is consistent with the planned start of work and the milestones in section 6.2. Any deviation shall be identified and duly justified.
SC-02	The Contractor shall during execution monitor the major milestone schedule. Deviations shall be reported with justification to the DISC Project Office as soon as identified.
SC-03	In the event that delays to milestone deliveries are anticipated, this shall be reported to the Swarm DISC Project Office as soon as possible.

6.2 Milestones

Milestone	Description	Suggested timeline (months)
MIL-01	**Project Kick Off**	KO
MIL-02	**Delivery 1** • Literature survey • Survey of existing data and tools • Product definition document (PDD) • Work plan (updated)	KO+2
MIL-03	**Delivery 2 – Mid-Term Review** • Working version of forward code with functional example • Coefficients (close to final) • Validation report (interim) including preliminary assessments of the effect on the climatological model of the assumptions about the poloidal field • Test data set	KO+7
MIL-04	**Delivery 3 – Final delivery** • Validation report (Final) • Submission of python code plus documentation • Plan for continuation and integration • Coefficients based on full mission data	KO+11
MIL-05	**Final Presentation** All technical notes (updated if necessary), presentations, publications, and other relevant documentation delivered electronically to the Swarm DISC Project Office in searchable PDF format (DL-10)	KO+12