Statement of Work

Swarm DISC ITT 5.1

"A processor for modelling the high-latitude ionospheric electrodynamics based on Swarm magnetic field and plasma data"

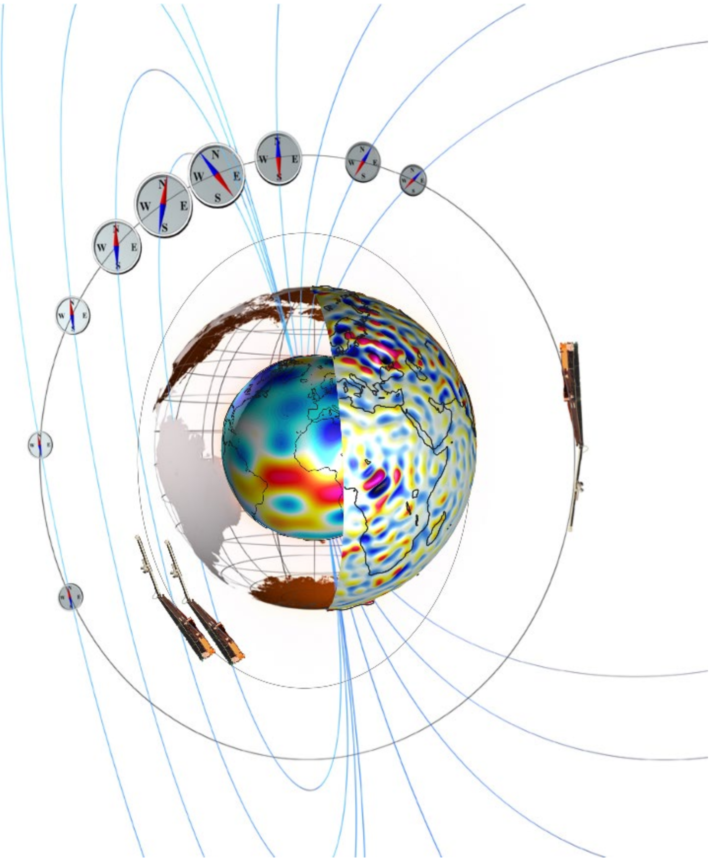

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Table of Contents

1 Introduction 7

1.1 Scope and Applicability 7

2 Applicable and Reference Documentation 7

2.1 Applicable Documents 7

2.2 Reference Documents 7

2.3 Terminology 8

2.4 Abbreviations 9

3 Background and Objectives 10

3.1 Background 10

3.2 Objectives of the Activity 11

3.3 Assumptions and Constraints 12

4 Work to be Performed 13

4.1 Work Logic 13

4.2 Implementation 13

4.2.1 Task 1: Product definition and development 13

4.2.1.1 Input 13

4.2.1.2 Task description 13

4.2.1.3 Deliverables 13

4.2.2 Task 2: Work plan 13

4.2.2.1 Input 13

4.2.2.2 Task description 14

4.2.2.3 Deliverables 14

4.2.3 Task 3: Development of the forward model 14

4.2.3.1 Input 14

4.2.3.2 Task description 14

4.2.3.3 Deliverables 14

4.2.4 Task 4: Product validation 14

4.2.4.1 Input 14

4.2.4.2 Task description 15

4.2.4.3 Deliverables 15

4.2.5 Task 5: Transfer of code and documentation to ESA 15

4.2.5.1 Input 15

4.2.5.2 Task description 15

4.2.5.3 Deliverables 15

4.2.6 Task 7: Final presentation 15

4.2.6.1 Input 15

4.2.6.2 Task description 16

4.2.6.3 Deliverables 16

5 Requirements for Management, Reporting, Meetings, and Deliverables 17

5.1 Management 17

5.2 Reporting 17

5.3 Meetings 17

5.4 Technical Documentation 18

5.5 Other Deliverables 18

6 Schedule and Milestones 19

6.1 Schedule 19

6.2 Milestones 19

List of Figures

Figure 1 - Swarm data processing chain 11

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 5.1 – "A processor for modelling the high-latitude ionospheric electrodynamics based on Swarm magnetic field and plasma data".

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] Amm, O. (2001) 'The elementary current method for calculating ionospheric current systems from multisatellite and ground magnetometer data', *Journal of Geophysical Research: Space Physics.* Wiley-Blackwell, 106(A11), pp. 24843–24855. doi: 10.1029/2001JA900021.

[RD-3] Amm, O. et al. (2015) 'A method to derive maps of ionospheric conductances, currents, and convection from the Swarm multisatellite mission', *Journal of Geophysical Research: Space Physics.* Wiley-Blackwell, 120(4), pp. 3263–3282. doi: 10.1002/2014JA020154.

[RD-4] Green, D. L. et al. (2007) 'Technique: Large-scale ionospheric conductance estimated from combined satellite and ground-based electromagnetic data', *Journal of Geophysical Research: Space Physics,* 112(A5). doi: 10.1029/2006JA012069.

[RD-5] Heelis, R. A. and Maute, A. (2020) 'Challenges to Understanding the Earth's Ionosphere and Thermosphere', *Journal of Geophysical Research: Space Physics.* doi: 10.1029/2019JA027497.

[RD-6] Laundal, K. M. et al. (2018) 'Solar Wind and Seasonal Influence on Ionospheric Currents From Swarm and CHAMP Measurements', *Journal of Geophysical Research: Space Physics.* John Wiley & Sons, Ltd, 123(5), pp. 4402–4429. doi: 10.1029/2018JA025387.

[RD-7] Öztürk, D., Garcia-Sage, K. and Connor, H. (2020) 'All Hands on Deck for Ionospheric Modeling', *Eos,* 101. doi: 10.1029/2020EO144365.

[RD-8] Palmroth, M. et al. (2020) 'Lower thermosphere - ionosphere (LTI) quantities: Current status of measuring techniques and models', *Ann. Geophys. Discuss.* Copernicus Publications, 2020, pp. 1–73. doi: 10.5194/angeo-2020-42.

[RD-9] Reistad, J. P. et al. (2019) 'Separation and Quantification of Ionospheric Convection Sources: 1. A New Technique', *Journal of Geophysical Research: Space Physics.* John Wiley & Sons, Ltd, 124(7), pp. 6343–6357. doi: 10.1029/2019JA026634.

[RD-10] Richmond, A. D. (2021) 'Joule Heating in the Thermosphere', in Wang, W., Zhang, Y.-L., and Paxton, L. J. (eds) *Space Physics and Aeronomy Vol. 4: Upper Atmosphere Dynamics and Energetics.* Washington, D.C.: American Geophysical Union.

[RD-11] Weimer, D. and Edwards, T. (2021) 'Testing the electrodynamic method to derive height-integrated ionospheric conductances', *Annales Geophysicae,* 39(1), pp. 31–51. doi: 10.5194/angeo-39-31-2021.

[RD-12] Weimer, D. R. (2005) 'Improved ionospheric electrodynamic models and application to calculating Joule heating rates', *Journal of Geophysical Research: Space Physics,* 110(A5). doi: 10.1029/2004JA010884.

[RD-13] Billet, D. D. et al. (2022) 'High-resolution Poynting Flux Statistics from the Swarm Mission: How Much is Being Underestimated at Larger Scales?', *ESSOAr*, https://doi.org/10.1002/essoar.10511165.1 (preprint; under review)

[RD-14] Knipp, D., Kilcommons, L., Hairston, M., & Coley, W. R. (2021) 'Hemispheric asymmetries in Poynting flux derived from DMSP spacecraft', *Geophysical Research Letters*, 48, e2021GL094781. https://doi.org/10.1029/2021GL094781

[RD-15] Pakhotin, I. P., Mann, I. R., Xie, K., Burchill, J. K., & Knudsen, D. J. (2021) 'Northern preference for terrestrial electromagnetic energy input from space weather', *Nature communications*, 12(1), 1–9.

[RD-16] Vanhamäki, H., Aikio, A., Kauristie, K., Käki, S., and Knudsen, D. (2021) 'Statistical estimates of auroral Pedersen conductance using electric and magnetic measurements by the Swarm spacecraft' *EGU General Assembly 2021,* online, 19–30 Apr 2021, EGU21-12569, https://doi.org/10.5194/egusphere-egu21-12569, 2021

[RD-17] Richmond, A.D. (1992) 'Assimilative mapping of ionospheric electrodynamics' *Adv. Space Res.*, 12(6), 59-68, https://doi.org/10.1016/0273-1177(92)90040-5

[RD-18] Knipp, D., Kilcommons, L., Hairston, M., & Coley, W. R (2022) 'DMSP Poynting Flux: Data Processing and Inter-spacecraft Comparisons' [Submitted to] *Journal of Geophysical Research,* https://www.essoar.org/doi/10.1002/essoar.10510229.1 (preprint; under review)

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

Ionospheric conductance in the high latitude E region is an important parameter for describing auroral electrodynamics. It feedbacks to magnetospheric currents and is an essential factor when calculating Joule heating. Joule heating and Poynting flux are central in understanding high latitude dynamics and quantifying the energy transfer between the magnetosphere and the ionosphere/upper atmosphere. However, due to the lack of regular in situ observations of the E region ionosphere, the conductance cannot be determined directly. Thus, its estimation relies on indirect observations or on proxies.

The thermosphere-ionosphere research community has recently expressed a clear need for improved, observation-based estimates of key ionosphere-thermosphere parameters — e.g. electric potential (Richmond, 1992), Joule dissipation, Poynting flux, and ionospheric conductances (Heelis and Maute, 2020; Öztürk, Garcia-Sage and Connor, 2020; Palmroth et al., 2020; Richmond, 2021; Weimer and Edwards, 2021).

Several efforts have been undertaken to derive these quantities. A combination of empirical models of electric potential and magnetic field perturbations has been used by Weimer and Edwards (2021) to derive a model of ionospheric conductance, following the original work of Amm (2001) as well as, e.g., Green et al. (2007) and Amm et al. (2015).

- Vanhamäki et al. (2021) used 5 years of electric field and magnetic observations by the Swarm mission for a statistical study of the height-integrated Pedersen conductivity at high latitudes.
- Knipp et al. (2021; 2022) applied 9 years of plasma drift and magnetic variation data from the DMSP satellite to derive time series of the high latitude Poynting flux and suggested that larger solar illumination in the Northern Hemisphere causes larger flux input than in the Southern hemisphere.
- Pakhotin et al. (2021) and Billet et al. (2022) used a dedicated time period of Swarm magnetic and electric field observations to investigate hemispheric difference of the Poynting flux as well as the effects of small-scale fluctuations of the Poynting flux on the total energy budget transferred by the Poynting flux.
- Laundal et al. (2018) derived a Swarm-based Average Magnetic Field and Polar Current System (AMPS) model and also revealed the hemispheric difference in the field-aligned currents.

Using a global network of bi-static coherent radars, measuring ion drifts in the high latitude regions of both hemispheres the SuperDARN (Dual Auroral Radar Network JHU/APL) has since many years been able to provide maps of ionospheric convection in response to solar wind parameters. The derived maps are of global character, and are created by fitting all available ion drift observations to an empirical model convection pattern. Based on such maps SuperDARN also provides the total polar cap potential, an important parameter for the understanding of Solar wind and magnetosphere interaction.

Some of the mentioned studies are focused on deriving time series of Poynting flux or conductance, other studies provide models which are derived from different data sources. In addition, their derivation algorithms are not open access.

This tender invites proposals for deriving empirical models for the high latitude electric potential, Pedersen and Hall conductance, the Joule heating and the Poynting flux. The model shall include variations in location, time, season, hemisphere, solar flux, the interplanetary magnetic field or other geomagnetic activity indicators. The model shall be consistently derived and shall be based on Swarm observations. The results of the derived models are expected to be validated against independent measurements or models. A code to generate model predictions (forward code) shall be provided. Providing the inversion code as open source to the community, e.g., in a developer environment, will enhance the merits of the offer. While the call is focused on utilizing the Swarm data, proposals based on a combination of other data with Swarm data are welcome.

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

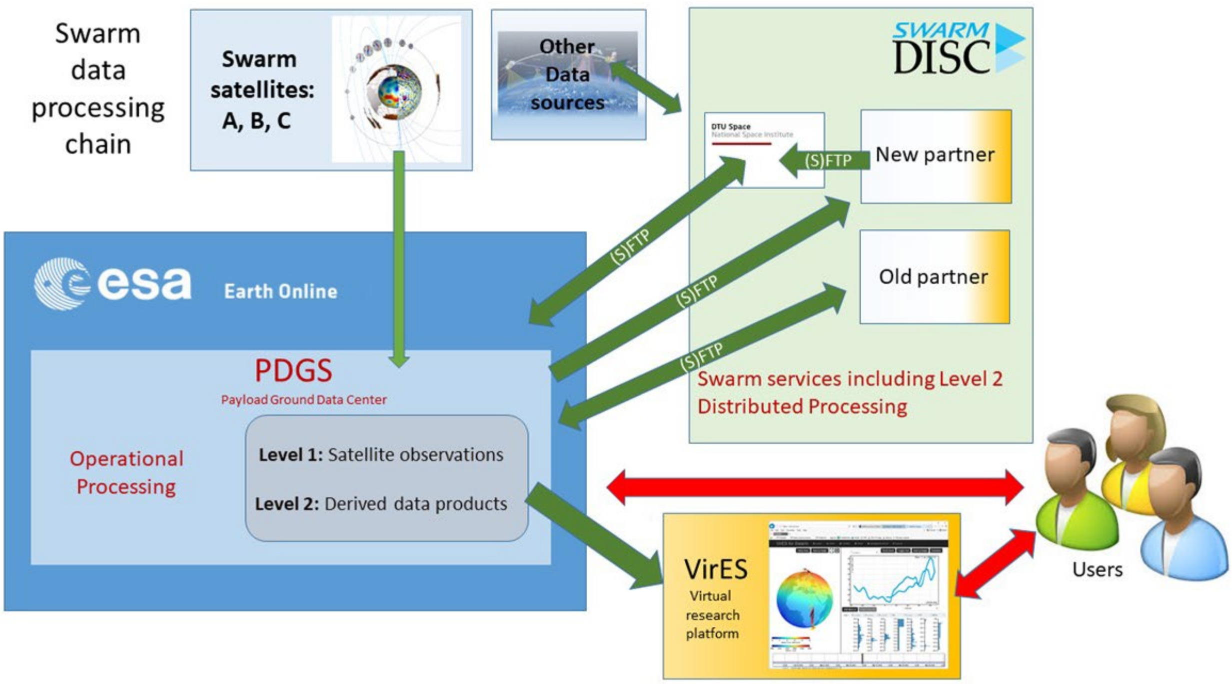

Figure 1 - Swarm data processing chain

3.2 Objectives of the Activity

The main objective of this activity is to provide electrodynamic parameters of the high-latitude ionosphere.

This activity *shall*:

- derive empirical models for
  - the high latitude electric potential,
  - Pedersen and Hall conductance,
  - the Joule heating taking into account neutral wind, and
  - the Poynting flux

The models *shall*:

- include variations in location, time, season, hemisphere, solar flux, and also be dependent on geo-magnetic activity
- be consistently derived
- be based on Swarm magnetic field and ion drift data, but can be complemented by other data sources
- be validated against independent measurements or models.

A code to generate model predictions (forward code) shall be provided.

The project shall deliver at least one publication for peer review and one presentation to a Swarm Data Quality Workshop or similar event.

This activity *should*:

- provide the inversion code as open source to the community, e.g., in a developer environment, which will enhance the merits of the offer
- primarily utilize the Swarm data, however, proposals based on a combination of other data (e.g. ground-based or satellite) with Swarm data are welcome
- harness public outreach opportunities that may arise from this new product
- consider potential visualization use cases for implementation in VirES.

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 can be distributed through PDGS, but the tenderer may suggest using an alter-native similar system 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 model, 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 and development

4.2.1.1 *Input*

- Statement of Work (this document)
- Scientific literature
- Satellite data products and product 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), the Contractor shall define new high-level products, which are to be derived from empirical models of the high latitude electric potential, Pedersen and Hall conductance, the Joule heating taking into account neutral wind, and the Poynting flux.

4.2.1.3 *Deliverables*

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

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)

4.2.2.2 *Task description*

The Contractor shall propose a work plan for the implementation, validation, and operation models to be developed for producing the new products. 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 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.

4.2.2.3 *Deliverables*

- Updated work plan (TN-02)

4.2.3 Task 3: Development of the forward model

4.2.3.1 *Input*

- Product Definition Document (TN-01)
- Work plan (TN-02)
- Input data products

4.2.3.2 *Task description*

The Contractor shall implement the processor at its premises, according to the work plan. The processor shall be implemented to produce the output data, in accordance with the Product Definition Document. The processor shall accept user input of parameters including variations in location, time, season, hemisphere, solar flux, the interplanetary magnetic field or other geomagnetic activity indicators. The processor shall accept programmatically generated input. The Contractor shall document the algorithms that are applied in the processor in a technical note. The Contractor is strongly encouraged to adopt an open source approach for the code development. The Contractor shall collect all necessary input data to run the processor for a test period, and generate and deliver a first test data set.

4.2.3.3 *Deliverables*

- Description of the Processing Algorithms (DPA) and preferably submission of code to open source repository (TN-03)
- First test data set (DL-01)

4.2.4 Task 4: Product validation

4.2.4.1 *Input*

- Product Definition Document (TN-01)
- Work plan (TN-02)

4.2.4.2 *Task description*

The Contractor shall compare the new product with data from Swarm and other data sources and model outputs as applicable, such as the SuperDARN Convection Model (http://superdarn.thayer.dartmouth.edu/index.html), or the SWMF (Space Weather Modelling Framework) including its ionospheric potential solver (IE) of the University of Michigan (https://ccmc.gsfc.nasa.gov/models/SWMF~20180525/), to demonstrate the validity of the model output, and to the extent possible assess the accuracy of the model. The output of the activity shall be documented in a validation report, which shall include a description of the dataset used in the validation.

The Contractor is encouraged to consider potential visualization use cases for implementation in VirES and interact as early as possible with the VirES team in support of a potential implementation.

4.2.4.3 *Deliverables*

- Validation report (TN-04)

4.2.5 Task 5: Transfer of code 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 and the forward code to run the models, as well as a descriptive file (e.g., readme.txt) 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 appropriate.

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-05)
- Products based on full mission data delivered to PDGS or other data system (DL-02)

4.2.6 Task 7: 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 (DL-03)
- Presentation of project achievements at Swarm DQW or similar event (DL-04)
- Final project documentation delivered electronically to the Swarm DISC Project Office in searchable PDF format (DL-05)

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 interval 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.

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-04) 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.

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.

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

5.5 Other Deliverables

DL-01	First test data set
DL-02	Forward code and coefficient files
DL-03	One publication submitted for peer review
DL-04	Presentation of project achievements at Swarm DQW or similar event
DL-05	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 • Product Definition Document (TN-01) • Updated work plan (TN-02)	KO+2
MIL-03	Delivery 2 – Mid Term Review • Updated work plan (TN-02) • Description of the Processing Algorithms (TN-03) • Initial Forward code and coefficient files (DL-01) • Initial Validation report (TN-04)	KO+7
MIL-04	Delivery 3 – Final delivery • Updated Product Definition Document (TN-01) • Updated Description of the Processing Algorithms (TN-03) • Validation report (TN-04) • Description of model output data transfer functionality and proposal for continued operation beyond project closure (TN-05) • Forward code and coefficient files (DL-02) • One peer reviewed publication submitted (DL-03)	KO+11
MIL-05	Final Presentation All technical notes, presentations, publications, and other relevant documentation delivered electronically to the Swarm DISC Project Office in searchable PDF format (DL-04, DL-05).	KO+12