Near Earth Electron Environment Modelling Tool
User/Software Requirements Document

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ABSTRACT

The document describes the User and Software Requirements for an operational Modelling Tool of the physical environment in near-Earth space. The use of the Modelling Tool is expected primarily to be (post-)analysis of spacecraft anomalies, where the actual physical conditions in the vicinity of the spacecraft are important parameters in trying to solve the cause of an observed anomaly. A secondary (in this work) use of the Modelling Tool is assumed to be prediction of hazardous conditions for operative spacecraft, to be monitored and predicted in real-time for spacecraft operators.

The document describes one possible solution for building a working Modelling Tool, and discusses alternative approaches, where appropriate. Rough estimates of resources (manpower and computer) for developing and running such a Modelling Tool are given.

Contents

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1. INTRODUCTION

This document defines the User and Software Requirements for an operational software tool for forecasting hazardous space weather conditions in space environment. The document is the final report of Work Package WP 320 of ESA / ESTEC contract work 'Study of plasma energetic electron environment and effects' (ESA / ESTEC / Contract No. 11974 / 96 / NL / JG(SC)).

1.1 Purpose

1.1.1 Purpose of the Document

This document describes the User Requirements and Software Requirements, following documents ESA-PSS-05-02 and ESA-PSS-05-03, respectively, for an operational tool for 1) post-event analysis of conditions during observed spacecraft anomaly events, and 2) prediction of conditions that are hazardous for spacecraft.

1.1.2 Intended readership

The document is intended for

- persons responsible for planning of operational forecasting systems
- software developers,

and together with the technical report "State of the art of space weather modelling" (Koskinen and Pulkkinen, 1998) forms an information package for a feasibility study of developing such system.

1.2 Scope of the Software

The software will use observational data from the sun, the solar wind, and different regions of the magnetosphere as input. It will use an integrated set of numerical models to give user-dependent relevant parameters at a given time and place in pre-defined regions of the Magnetosphere.

The primary uses of the software are in

(1) (post-)analysing spacecraft anomalies after one has been identified, and in

(2) predicting conditions hazardous for spacecraft.

The software can also be used in the design phase of new spacecraft for predicting statistical occurrence of different conditions during spacecraft lifetime, and thus setting constraints for spacecraft design.

The benefits of such a modelling tool are many. At present, spacecraft anomalies cannot be predicted better than as probabilities over an extended period of time. These estimates are either based on data from previous missions, or statistical behaviour of the Solar-Terrestrial system (so called climatology approach). With a modelling tool, physical conditions along spacecraft orbit during its lifetime can be estimated with better accuracy.

For operational spacecraft, the modelling tool allows for forecasts of hazardous conditions. By avoiding critical operations when hazardous conditions are predicted, this may save from anomalous effects harming the spacecraft, and at best save the spacecraft from being lost.

When an anomaly has occurred, a modelling tool allows for a detailed post-analysis of the event. At present, there are no models that would give the external physical conditions at the time of an anomaly, and one has to rely on on-board measurements of external conditions. Since the on-board instrumentation for measuring external conditions typically gives very few parameters, if such instruments at all exist, one cannot conclude with confidence what has caused an observed anomaly. With the modelling tool, the post-analysis can be based on more data, which helps in the design of future spacecraft.

The modelling tool also allows for estimating occurrence probabilities of the most hazardous ("worst case") conditions, e.g., in terms of radiation from different sources, and thus vulnerable parts of hardware can be designed according to either maximum, mean, or optimum conditions, whichever is considered most appropriate.

Different users have different needs for the output in terms of access times, required parameters, and user interface. Even if only specifying the two different uses mentioned above, the User and Software Requirements differ. Thus we shall deal with these two uses separately.

The final product shall include, for both user groups,

- a distributed system for collecting data from observation sites in space as well as on the ground,
- software for converting these input into a form to be used by the modelling tool,
- the (physics-based) state-of-the-art simulation model, used for the interpolation / extrapolation of, and forecasting from, the observational data, and
- a dedicated user interface for each user group, giving output with an accuracy and in a format best suitable for different uses.

The first of the above items is an essential requirement for making the modelling tool. However, it is not an integral part of the system. Instead, organisations responsible for collecting the data shall also be responsible for delivering verified data for input in the modelling tool.

The second item shall include interpolation routines, both in space and time, to adjust the input data in the format used by the modelling tool. This software shall be called the modelling tool data front end hereinafter.

The third item includes the most critical software of the modelling tool. It will be called the modelling tool core in this document.

The last item is the user interface software.

1.3 Definitions, acronyms and abbreviations

3D	Three-dimensional
AE8	Trapped electron model
AP8	Trapped proton model

ARMA	Auto-Regressive Moving Average
CRRES	US Air Force satellite
Dst	Magnetic storm-time index
ENA	Energetic Neutral Atom
HMR	Heppner-Maynard-Rich (model for ionospheric electric field)
IGRF	International Geomagnetic Reference Field
IMF	Interplanetary Magnetic Field
Kp	Planetary magnetic activity (K) index
MHD	Magnetohydrodynamics
MSFM	Magnetospheric Specification and Forecast Model
MSSL	Mullard Space Sciences Laboratory (UK)
NSSDC	National Space Science Data Center (US)
R_E	Radius of the Earth (about 6370 km)
REM	Radiation Environment Monitor
SEDAT	Space Environment Database and Analysis Tool
SPENVIS	Space Environment Information System
SREM	Space Radiation Environment Monitor
SSC	Storm Sudden Commencement
STP	Solar Terrestrial Physics
TREND	Trapped Radiation Environment Model Development
WWW	World Wide Web

anomaly event	An event when anomalous behavior of a system or sub-system of a spacecraft has been observed
core modelling tool	combination of physics-based models, translated into operational software, performing the calculations for predicting physical conditions at a given place, from available input data
data front end	part of the modelling tool of this document, software performing necessary formatting and interpolation of data received from observation sites

1.4 References

Applicable documents:

ESA-PSS-05-02 Guide to the user requirements definition phase.

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WWRefTsyganenko `http://www-istp.gsfc.nasa.gov/Modeling/group.html`

1.5 Overview of the Document

The document is organised following the guidelines given in ESA-PSS-05-02 and ESA-PSS-05-03, with User Requirements and Software Requirements documents combined into one single document.

Section 2 of this document gives the general description of the User and Software requirements, as well as a description of the model. In Sections 3 and 4 specific requirements as set by two different groups of Users (defined in section 2.2) are described. Section 5 includes Specific requirements for the Software, corresponding to User Requirements specified in Sections 3 and 4. In Section 6, the requirements are presented in the form of the Requirements traceability matrix, summarising how each user requirement is met in the software requirements.

2. GENERAL DESCRIPTION

This section gives the general description of the User and Software requirements, following guidelines given in documents ESA-PSS-05-02 and ESA-PSS-05-03, respectively.

2.1 URD: Product perspective

Up to now, no modelling tool similar to the one described in this document has been developed in Europe. There exist numerous physical research models for different parts of the Solar-Terrestrial system, which are in scientific use. Integrating these to an operational modelling tool, with near-real-time input from space, has been done for U.S. Air Force contract in Rice University (the Magnetospheric Specification and Forecast Model, MSFM, Freeman et al., 1994), but that model is not available for users outside that group.

Predictive models, using Non-linear ARMA or Neural Network approaches, are able to forecast geomagnetic activity parameters both in the short-term and asymptotically. These models may thus be used for operational forecasting of increased probability of hazardous events. However, they do not fulfil the requirements of prediction of local physical conditions. For these requirements, a physics-based model is needed.

Essential parts of the physics-based modelling tool include:

- Solar and solar wind monitors. The model accuracy relies on continuous monitoring of the conditions in the sun and the solar wind. Without adequate coverage of observations, no model will have the desired accuracy. Solar and / or solar wind monitors are also needed for predictive models.
- Model for solar wind behaviour. Disturbances originated in or on the Sun propagate to the magnetosphere with the solar wind, and thus a model of the solar wind is necessary. For modelling of Solar Energetic Particle Events, this is extremely important, since those particles may enter near-Earth environment in a time scale of the order of 20 minutes, after an eruption has been observed on the surface of the sun.
- Model for solar wind - magnetosphere interaction. The magnetosphere is a complicated system of different time and spatial scales, demanding careful connection of different models, such as
    - model for the large scale behaviour of the Magnetosphere,
    - empirical models for magnetospheric configuration,
    - models for the trapped energetic particle environment,
    - ionospheric models, and
    - atmospheric models.

The present state of the availability and maturity of different models for operational use is discussed in Koskinen and Pulkkinen (1998). In general, it varies from poor to fair, and the transformation of the parts to an integrated operational system has not been initiated.

Three-dimensional magnetohydrodynamic (3D MHD hereinafter) models are used in solar-terrestrial physics (STP) research, and their maturity in describing large-scale phenomena in the magnetosphere is evolving rapidly. These models are self-consistent, taking into acccount the limitations of their applicability. However, for the purpose of analysing spacecraft anomaly events, MHD models have a number of serious drawbacks. Firstly, the present day models still have problems in timing of events. Even if the prediction of the dynamics is quantitatively correct, the timing is often badly erroneous, and thus not suitable for accurate post-analysis. Reasons for these problems are being investigated. Secondly, even between different implementations of 3D MHD models, there are substantial discrepancies between the results (see WWWRefCompare for sample comparison). Thus, before the actual reasons for these discrepancies are solved, selection between one implementation against another, as being more accurate or reliable, cannot be well justified, and the maturity cannot be proven. Thirdly, and most importantly, as energetic (few tens of keV) particle fluxes are today considered as the factor best correlating with spacecraft anomalies, this parameter has to be available from the model. 3D MHD models only give averaged fluid parameters (plasma density, temperature, velocity, and electric and magnetic fields) as output, and it is by definition impossible to calculate, e.g., electron fluxes in a given energy range from the model. The field parameters can be used as input to other models, describing particle behaviour, but a 3D MHD model alone is not sufficient as a modelling tool.

As discussed above, the maturity of the different physics models for the Solar-Terrestrial interaction is very much varying. Only 3D MHD models are truly self-consistent, and it is not foreseen that self-consistent global scale models will be available in the near future either. For the purposes of this work, solar and solar wind propagation models are not yet mature to be included in the model. Research models consisting of empirical or semi-empirical descriptions of magnetospheric configuration can, at the time of writing of this document (May 1998), describe the large-scale behaviour of the Magnetosphere with an accuracy that can be considered sufficient for building a modelling tool. This is not to say that the models were "ready" in the sense that no further development shall be made, but that in describing a modelling tool they can be used as a defining the approach and region of applicability.

As a conclusion, we shall assume a model consisting of a combination of separate physics-based models inside the magnetospheric boundaries, as the approach for the physics-based modelling tool described in this document.

2.2 URD: User characteristics

Two different groups of users of the software have been identified. These are:

1. Study engineers or scientists, and design engineers
2. Satellite operators

These groups have somewhat different needs for the software, and will thus be dealt with separately.

2.2.1 User characteristics: Study and design engineers

Study engineers and / or scientists work on post-analysis of observed anomalies on spacecraft, called anomaly events in this document. This group will use the Modelling Tool to reconstruct the conditions in the space environment in the vicinity of the spacecraft at the time of an observed anomaly. These users have education in physics or engineering, often at doctoral level, and the actual physical conditions in the environment of the spacecraft, at the time of the anomaly, are of interest. It is assumed to be up to the users to make their conclusions from the physical data given by the modelling tool. These kind of studies usually take up to a few weeks, and thus the accuracy of the modelling is more critical than a fast response time. Since these users use the tool only occasionally, the interface shall be user-friendly and self-explaining.

Design engineers may use the modelling tool for predicting statistical occurrence of different conditions (e.g., certain levels of radiation) along spacecraft orbit during its lifetime. Precise conditions at a given time and location are not necessarily required, since statistical ('typical') data are to be used as input. Design engineers are professionals in spacecraft design, but not necessarily in space physics. The results of the modelling tool thus have to be translated into occurrence probabilities of radiation doses and other relevant parameters to be defined with the users. The design groups do not use the tool routinely after constraints have been fixed, and thus the user interface has to be user-friendly and easy to familiarise with.

2.2.2 User characteristics: Satellite operators

Satellite operators are people working on daily on-line operation of spacecraft, including orbit control, communications and maintenance of the satellite. These users work in a real-time environment, having to make decisions of action immediately, and thus needing a reliable software tool with a user-friendly, satellite-specific user interface. These people are responsible for taking care of any action for recovery after an anomaly on the spacecraft has been observed. The people in this group usually have a technical background for operating the spacecraft. Users in this group are not assumed to know the cause and effect relationships between different conditions and the spacecraft in detail, but to be concerned about the kind of anomaly that could be expected.

2.3 URD: General constraints

In general, the modelling tool has to be

1. Fault-tolerant in terms of input data and run-time instabilities in the physics-based model.

Bad or missing input data shall not cause the running of the modelling tool to stop, nor shall ill-posed physical conditions cause program error. However, these situations have to be clearly indicated to the user, so that the user knows that the results have to be interpreted with extreme care.

2. Flexible in terms of input.

Input data available from any part of the magnetosphere, on ground, or from the solar wind, shall be possible to include in the input data set used by the tool. An obvious example is data from spacecraft, whose instrumentation and positions are variable. If conflicts between data from different sources exist, the modelling tool shall indicate such occasions. Also, any input data *not* available shall be allowed to be omitted, instead of critical input parameters, defined in section 2.11. These kind of situations are expected from observations from spacecraft, where data dropouts are common and full coverage of all possible input scarce. The modelling tool shall adapt to existing data, and not be critically dependent on single observation, with the exception of input parameters defined as critical.

3. User-friendly.

The modelling tool shall have a dedicated user interface for each identified group of users, and, for operational use, for each satellite.

4. Reliable in terms of quality of output.

As already stated in item (2) above, missing or probably erroneous input data shall be indicated as lowering the quality of the output, so that no false conclusions of the cause of an anomaly are made, no over-design or too small margins will result for design of future spacecraft (user group 1), and no false expectations of necessary actions to be taken are made (user group 2). Obviously the quality of the output depends on the quality of the data, and a measure of the reliability of the output data shall be given for all users. This requirement implies careful validation and acceptance testing of the model, specified in more detail in section 5.6.

Partly these requirements are for the physical models, partly for the modelling tool and its implementation on a computer system. Again, the two are intimately interrelated.

2.4 URD: Assumptions and dependencies

It is assumed that when the modelling tool is developed, there exist

1. sufficient amount of observational sites in the critical regions of the modelled system to provide necessary input data for the modelling tool, and a coordinated system for collection of that data for modelling
2. powerful enough computers to perform the desired calculations in the required response time (group 1), or in the lead time for forecasting (group 2).

Assumption 2 implies that Neural Network or other predictive model is to be used for forecasting (group 2). This is because present (May 1998) cannot perform the calculations of physics-based models fast enough for forecasting. Thus a predictive model is assumed for group 2 for the rest of the document.

2.5 URD: Operational environment

The modelling tool will run in a distributed net of computers, with different tasks in different phases of the modelling in the most appropriate hardware and location.

The observations are verified and pre-processed at the organisation responsible for the observation in (near) real-time. The data is then transferred through a network (e.g. internet or a dedicated link) to the modelling centre.

The physics-based model, used for post-analysis, requires a fast computer, beyond desktop workstation, with large memory and fast links to organisations providing input data. (The hardware requirements are discussed in sections 2.12 and 5.5) For ensuring the smooth operation of the modelling tool, dedicated professionals both for computer operation and result verification and interpretation are needed at the centre.

Predictive models (trained Neural Network) can be run on fast workstations, and the actual modelling software can be run either at the modelling centre, or at the end user's organisation. For predicting hazardous conditions for satellite operators in real time, the only technically feasible approach today is a predictive model, and that is what is assumed in this document. In each case, the verification, selection and integration of input data for the modelling tool is to be done at the modelling centre.

The parameters and format of the output depend on the needs of the end user, and the User Interface part of the modelling tool will be run locally in the workstation of the end user. The results from the physical (or predictive) model are distributed through a data network to the users for post-processing.

The modelling tool core shall include the different physics models discussed in section 2.1, and thus the most natural choice is to distribute the responsibility of development work of the modelling tool to institutions where expertise and resources are available. However, for practical reasons, the final product (core modelling tool) shall be integrated to one place.

2.6 SRD: Relation to current projects

Currently there are several groups around the world, including Europe, working on software models that could be included as partial models in the modelling tool. These models and groups are discussed more in detail in WP310–TN. These research projects are run independently of this project. In the development of the modelling tool, the feasibility of integration of the different research models to the modelling tool has to be investigated, and negotiated with each group separately. Below we give a (non-exhaustive) list of European groups, in alphabetical order by the name of the institution, working on research models relevant to this project.

BIRA / IASB, Brussels, Belgium,

> Research and modelling of radiation belts, TREND, TREND-2, TREND-3, and development of the SPENVIS model, supported by ESTEC.

CERT / ONERA, Toulouse, France,

> Research and modelling of energetic particle behavior in the inner magnetosphere, Salammbô model (Beutier et al., 1995; Bourdarie et al., 1997).

CESR, Toulouse, France

> Research and modelling of magnetospheric and ionospheric dynamics.

CNRS / CETP, Versailles, France

> Research and modelling of magnetospheric and ionospheric dynamics (Peymirat et al., 1996)

FMI, Helsinki, Finland

> Research and modelling of the magnetosphere, e.g., time-dependent modelling of magnetic fields (Pulkkinen et al., 1992), drift modelling of particles in time-varying magnetic and electric fields (Toivanen et al., 1998), global 3D MHD simulations of magnetospheric dynamics (Janhunen, 1996). Main contractor of the SPEE project (this project), supported by ESTEC.

IRF, Lund, Sweden

> Modelling of magnetic storms (Dst index) using solar wind data and dynamic Neural Networks (Wu and Lundstedt, 1997), University of Lund space weather research centre.

MPAe, Katlenburg-Lindau, Germany

> Magnetospheric research on wide range of fields, including modelling of energetic particle behavior in the magnetosphere, TREND-3 project supported by ESTEC.

MSSL, University College London, UK

> Applied space plasma physics research, radiation belt dynamics and modelling research, TREND-2, and 3 projects supported by ESTEC.

2.7 SRD: Relation to predecessor and successor projects

The development of the modelling tool is not directly related to any preceding or, at present knowledge, successing project. However, it includes components that can be related to previous projects supported by ESTEC,such as REM (Radiation Environment Monitor), SEDAT (Space Environment and Data Analysis Tool, `http://www.wdc.rl.ac.uk/sedat/`), SPENVIS (Space Environment Information System, `http://www.spenvis.oma.be`), SREM, and the TREND-models (TREND, Trapped Radiation Environment Model Development, TREND-2 (Lemaire et al., 1995), and TREND-3). Much research work has been done on the energetic particles in the inner magnetosphere, which is also one important part of the present project. The feasibility of carrying the research work done during those projects over to developing the modelling tool shall be investigated.

2.8 SRD: Function and purpose

The software ('modelling tool') serves as a tool to predict space environment conditions that are hazardous for operational spacecraft. It consists of functional blocks, responsible for acquisition, verification and preparation of data ('data front end'), 'core modelling tool' software, including the physics based models that calculate the required output parameters from the input parameters, and the user interface software, dedicated for each user group. The function and purpose of the software are discussed above in section 2.1 above, and the 'core modelling tool' is described in section 2.11.

2.9 SRD: Environmental considerations

The operational environment of the modelling tool has been discussed in section 2.5 above. The modelling tool consists of three logically and physically independent software: the 'data front end', the 'core modelling tool', and output software. These three may be run in different systems, depending on the final implementation. The 'data front end' is the interface towards the organisation responsible for the acquisition and verification of the data for the modelling tool. Thus this part shall be connected with fast and reliable connections to these organisations, and compatibility with those systems has to be guaranteed. This part of the software also may perform searches in data bases, including proxy data for the model. The 'core modelling tool' performs the calculations of the physics-based model, and thus requires computers with fast calculating capacity. Depending on the final implementation, a supercomputer with parallel or vector processing capability may give the highest performance. The user interface (UI) depends on the needs of the user group, and may be run on the end users' desktop workstations. If this approach is selected in the implementation, the UI shall be written keeping portability to commonly used operating systems and hardware in mind.

2.10 SRD: Relation to other systems

The modelling tool has interfaces towards other systems from in its input and output phases of operation. The data collection and verification is assumed to be carried out by the organisations responsible for the observations, and thus the modelling tool has to be connected to the systems of those organisations. The hardware and software compatibility with possibly a large number of different environments, and smooth operation of the connections between the modelling centre and the data providing organisations shall be guaranteed. Secondly, the end users of the modelling tool shall not be assumed to use the tool in the modelling centre, where the 'core modelling tool' is run. Thus the user interface shall be assumed to use existing networks to transfer data to the end user interface software, run in a remote system. These connections to remote systems require using standard, vendor- and operating system independent interface protocols in the input and output interfaces.

2.11 SRD: Modelling tool description

The modelling tool is a system of independent, interacting software, and of manual phases of work (data verification) in a distributed environment. The data collection and verification are done by the organisation responsible for operating the instrumentation. The input data are fed to the data front end of the modelling tool. This software converts the data to the input data format of the modelling tool, and performs, e.g., interpolation routines, when needed.

After verification and preparation the data are fed to the core modelling tool. The selection of the structure of the modelling tool is a trade-off between possibility to upgrade with more recent (advanced) partial models and computational efficiency. A completely modular program cannot be optimised to the same level as a model where the computational algorithms are selected according to the functional forms of the physical models.

The block diagram of the modelling tool described in section 2.1 is shown in Figure 1.

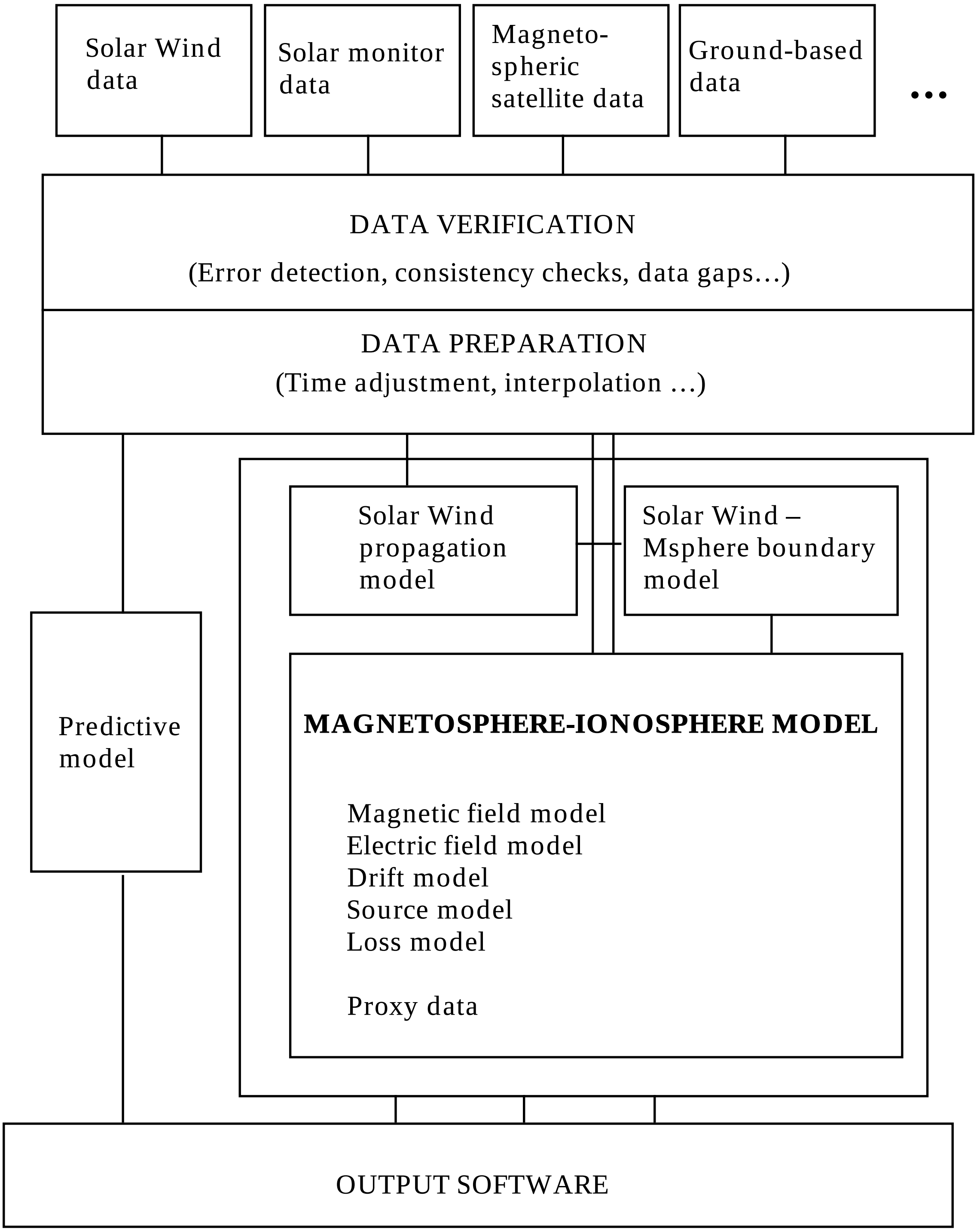

Figure 1. Block diagram of an ideal modelling tool.

Figure 1 assumes a complete set of physical models, starting from the Sun, and down to the ionosphere, to be included in the modelling tool. However, as discussed above, all the partial models of the Solar-Terrestrial system are not yet mature to be implemented in an integrated model, and thus we shall restrict us to a more limited model, a magnetosphere-ionosphere interaction model, in the detailed description. The block diagram of such model is given in Figure 2.

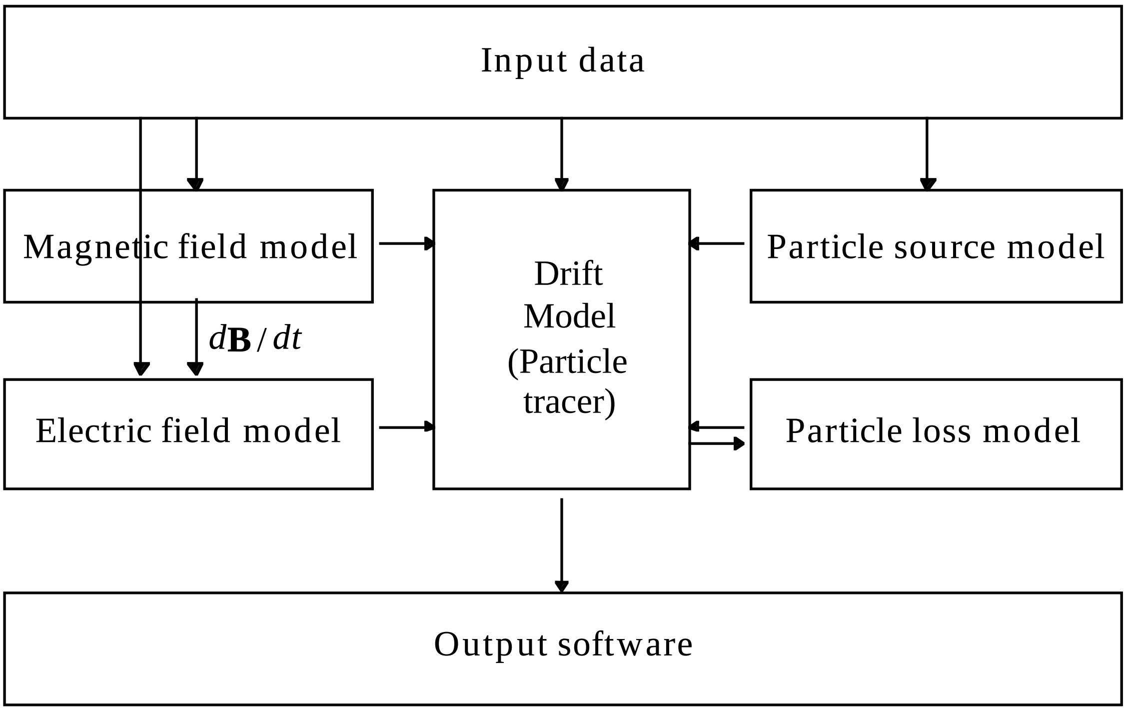

Figure 2. Block diagram of the magnetosphere-ionosphere model (modelling tool core) of Figure 1.

Specifically, the following requirements apply to the modules of the magnetosphere-ionosphere core modelling tool:

- The modelling tool shall include a (dynamic) magnetic field model, run with (near-real-time) physical parameters.
- The modelling tool shall include an electric field model, including electric fields emerging from time-variation of the magnetic fields, to be combined with the output of the magnetic field model, for particle drift calculations.

〈 The modelling tool shall include a particle drift model (particle tracer).

- The modelling tool shall include models for particle sources (either model or proxy data from a data base), and for loss of particles.

The modelling tool core passes its output to the dedicated output software. Output software shall depend on the User group, and whether interactive or batch processing is used.

In the following, the essential building blocks, as well as their relations will be described in detail. We shall start with the skeleton of the magnetosphere, the magnetic field model, and go towards more particle-flux-specific models in order electric field model, particle drift model (particle tracer), models for particle heating, and particle source and loss models.

2.11.1 Magnetic field model

Dipole and eccentric dipole

There are numerous alternatives for choosing a magnetic field model for the modelling tool. The most simple models are the *dipole* and *eccentric dipole* models. These are static models, describing the non-variable component of the

Earth's internal field. The advantage of these models is that they can be expressed in a clear analytic form. As a consequence, manipulation of the equations governing particle behaviour in combined magnetic and electric fields is often possible and substantial speed up of the numerical calculations may be obtained. The major disadvantage of these models is the small region of applicability of the (eccentric) dipole magnetic field. The magnetospheric magnetic field deviates from the dipole field already at the distance of the geostationary orbit, especially close to the noon-midnight meridian. Thus these models do not describe the true magnetic field very well. Also closer to the Earth, to correctly describe high energy particle precipitation to low altitudes above the South Atlantic Anomaly a more advanced model has to be used.

IGRF

The next in order of increasing complexity is the *International Geomagnetic Reference Field* (IGRF). This model includes higher harmonics of the internal field, and it is also updated regularly, thus following the slow variations of the internal field. However, as for the (eccentric) dipole field model, the applicability of this model is also limited to close distances from the Earth, up to roughly 5 Earth radii on the equator.

The IGRF model (coefficients and routines for expansion) is available from the NSSDC data centre.

Hilmer-Voigt

The magnetic field model by Hilmer and Voigt (Hilmer and Voigt, 1995) combines the dipole magnetic field of the Earth with magnetospheric field components caused by electric currents in different parts of the magnetosphere. The model is described in Hilmer and Voigt (1995), and it is also used, with some modifications, in the MSFM model of U.S. Air Force / Rice University. In the following, a short summary of the model is given.

The current systems included in the model are the equatorial ring current (RC), the cross-tail current (TAIL), and the Chapman-Ferraro current at the magnetopause (CF). Thus the combined magnetic field is the sum of the four components

$$\mathbf{B} = \mathbf{B}_{\mathrm{dipole}} + \mathbf{B}_{\mathrm{RC}} + \mathbf{B}_{\mathrm{TAIL}} + \mathbf{B}_{\mathrm{CF}}.$$

Using these source fields, the model computes the total field configuration.

The input parameters used by the Hilmer-Voigt B-field model to set the magnitude, location and extent of the source current systems are:

1 The dipole tilt angle (the angle between the axis perpendicular to the Sun-Earth direction, pointing to the North. Positive values correspond to the northern hemisphere being tilted towards the Sun). The calculation of this parameter is straightforward when the date and time are known.

2 The magnetopause standoff distance. This parameter is used to set the size of the magnetosphere by adjusting the strength of the Chapman-Ferraro currents. The magnetopause standoff distance can be approximated by simply calculating the pressure balance between the dynamic pressure of the solar wind, and the magnetic pressure of the magnetospheric magnetic

field. Alternatively, a more advanced model, such as Shue et al. (1997) can be used for calculating the standoff distance from solar wind parameters.

3 The geomagnetic index *Dst*, describing the magnitude of the ring current.

4 The midnight equatorward boundary of the diffuse aurora. This parameter is used to indicate the degree of stretching of the magnetotail magnetic field. This parameter is used to define where the tail current sheet must be positioned so that the inner edge footprint maps to the right latitude in the ionosphere. This parameter is to be inferred either from ground-based observations, or satellite measurements of precipitating particles in the midnight sector.

In the practical implementation of the MSFM, the model magnetic field values have been pre-calculated and tabulated in the computational grid of the model, for a range of input parameters, to save computing time.

The main advantage of the Hilmer-Voigt model is that the input parameters are directly measurable, and thus adjust the magnetic field to the prevailing conditions, with several parameters that can be verified. The region where the model can be used, well covers the inner magnetosphere, up to nearly subsolar point towards the Sun, and down to approximately 30 R_E towards the tail.

The Hilmer-Voigt model is not publicly available.

Tsyganenko 1987, 1989, 1995, 1997

The different versions of the Tsyganenko magnetic field models (Tsyganenko, 1987; Tsyganenko, 1989; Tsyganenko, 1995; 1997) are widely in use among the scientific community. They are all available on the WWW (WWWRefTsyganenko), and due to the large number of users, they have been thoroughly tested, and the strengths and weaknesses of the models are relatively well known.

For a modelling tool, the main weakness of the Tsyganenko models is that they only use global parameter(s) (typically magnetic activity, and in the later (1995, 1997) versions also solar wind parameters) to adjust the magnetic field configuration. Thus, even if local measurements of magnetic field (or other parameters describing or affecting local magnetic field configuration) were available, they cannot be used as input for the field model. Also, like all statistical models, the models have been averaged over large amount of events, and thus extreme configurations are not reproduced.

The basic principle of the models is very similar to the Hilmer-Voigt model: the magnetic field in the magnetosphere is calculated from electric currents inside and at the boundaries of the magnetosphere. The approach in the Tsyganenko models is to use vector potentials to describe the currents and magnetic fields. This approach ensures that the magnetic field remains divergence-free.

The input parameters for the two most recent versions are, in addition to the point in space where the magnetic field is to be calculated:

Tsyganenko 1989:

Magnetic activity index *Kp*, and optionally either geodipole tilt angle , or date and time (for calculation of the geodipole tilt angle), Tsyganenko 1995, 1997:

> Magnetic activity index *Dst*, Solar Wind pressure, IMF B_y and B_Z, and optionally either geodipole tilt angle , or date and time (for calculation of the geodipole tilt angle).

The user may also choose whether to use the dipole or IGRF internal magnetic field model. A package of routines (in FORTRAN) performing coordinate transformations and, e.g., tracing of magnetic field lines, is provided together with the Tsyganenko models (WWWRefTsyganenko).

Modified versions of the models have been developed for specific scientific research uses (e.g., Pulkkinen et al., 1992; substorm modelling). These models, however, are not publicly available.

2.11.2 Electric field model

For the selection of the electric field model for the modelling tool there are essentially two alternative approaches: (1) Specifying the electric field in the equatorial plane of the magnetosphere, and using mapping along magnetic field lines for the rest of the modelling region, or (2) specifying the electric field in the high-latitude ionosphere, and using mapping towards the equatorial plane for calculating the electric field in other parts of the model. Approach (1) has been used in the model Salammbô (Bourdarie et al., 1997; and references to older versions therein), whereas the latter option (2) has been used in the MSFM model. Both approaches exclude the effects of inductive electric fields (governed by $\nabla \times \mathbf{E}_{\mathrm{ind}} = -d\mathbf{B} / dt$), which are important in the dynamics of particles.

The choice is not obvious. The motivation for using the equatorial electric field in Salammbô is that the model used has a simple analytical form (Volland-Stern-model, Volland, 1973; Stern, 1975)

$$\mathbf{E} = -\nabla \phi,$$

$$\phi = A r^{\gamma} \sin \varphi,$$

where φ is the azimuthal angle, r the radial distance, specified on the equatorial plane, and A is an empirically determined coefficient fixing the intensity of the electric field (e.g. Eijiri, 1978)

$$A = \frac{0.045}{(1\text{-}0.159\,\mathrm{Kp} + 0.0093\,\mathrm{Kp}^2)^3}$$

in kV / R_E^2, and *Kp* being the magnetic activity (K) index. The shaping factor $\gamma = 2$. This model can easily be implemented in the code, and analytic manipulation is straightforward. On the other hand, the Volland-Stern model is very much simplified, and does not correctly account for small-scale structures of equatorial electric field, nor does it correctly describe the region between the corotation-dominated electric field (up to 5 R_E) and the convection-dominated electric field (tailward of 10 R_E).

In the MSFM model, the authors use the Heppner-Maynard model (Heppner and Maynard, 1987; Rich and Maynard, 1989) that specifies the ionospheric potential pattern at latitude above 60 degrees (thus excluding innermost part of the magnetosphere, inside 4 R_E). The Heppner-Maynard-Rich (HMR) model uses spherical harmonics in magnetic local time and latitude, to describe the variation of the potential pattern of the Heppner-Maynard model, as a function of IMF. For southward IMF, explicit variation with geomagnetic activity is also included., and in the MSFM model the HMR model was modified to accept the Polar Cap potential drop as an extra input parameter. The HMR model is available from the authors.

Neither of the models discussed above include time variation of the electric field, nor inductive electric fields due to magnetic field variation. The modelling tool shall be able to model transient effects like Storm Sudden Commencements (SSC), that cause rapid heating of plasmaspheric plasma to keV and even MeV energies, and auroral substorms, that cause flux dropouts and energetic particle injections at geostationary orbit. Both phenomena are, according to present knowledge, due to inductive electric fields (electric fields caused by time variation of the magnetic field, $d\mathbf{B}/dt$). Those variations are not included in the present magnetic field models (with the exception of some research models).

Particle energisation in the inner magnetosphere due to an SSC was successfully modelled by Hudson et al. (1997), who used magnetic and electric fields obtained from a 3D MHD simulation of a SSC event, and calculated particle energisation in those fields. The electric field that was used essentially reproduced the inductive electric field caused by the compression of the magnetospheric magnetic field during the SSC event. The applied azimuthal electric field produces first inward and then outward acceleration of particles, causing acceleration and deceleration, respectively, due to conservation of the first magnetic invariant in an increasing and then decreasing magnetic field.

The Salammbô model (Bourdarie et al., 1997; and references therein) originally used the dipole magnetic field and the Volland-Stern electric field model. In later versions, the Volland-Stern electric field model has been modified to include time variation of the convection electric field (Bourdarie et al., 1997). With this modification, and adding a new low-energy (temperature 8 keV) particle source at the near-Earth magnetotail (at a distance of 9 R_E), particle injection features during strong magnetic activity were modelled. The latest version (Bourdarie et al., 1998) includes also a ring current term and a simple model for magnetotail currents. Flux dropouts observed at geostationary orbit during substorm expansion phase were modelled using a time-varying magnetotail current location. In this simulation, the injection front of the previous model (Bourdarie et al., 1997; see above), was not included. On the other hand, to reproduce the flux dropouts, only minor modifications to the magnetic field are needed, since the geostationary orbit is located in a region, where particle orbits are sensitive to even small changes in the magnetic field (P. Toivanen, private communication, 1998)

The recent studies by Toivanen et al. (1998) also show that even moderate temporal changes in the magnetic field, when translated to inductive ($d\mathbf{B}/dt$) electric field, cause substantial variations in particle distributions during substorm cycles. Thus a model neglecting these terms clearly is not sufficient, if high accuracy is desired.

2.11.3 Particle drift model

Particles in combined magnetic and electric fields experience different kinds of drift motions, in addition to their rapid gyration around the magnetic field line and their motion along the magnetic field (e.g., Northrop, 1963). These drifts depend on the strength, temporal variation, and spatial gradients of the fields. In addition to these relatively slow drift motions, the particles may also experience acceleration by electric fields parallel to the magnetic field, as well as acceleration by wave electric fields.

The basic equation governing the motion of charged particles in combined electric and magnetic fields is the Lorentz equation

$$m\frac{d\mathbf{v}}{dt} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}).$$

However, in large-scale modelling, the fast gyromotion around magnetic field direction is not of importance, and can be neglected: One obtains a number of equations governing the motion of the particle gyrocenter (also called guiding center). These are the large scale drifts. The equations governing the first-order drift motions are as follows.

ExB drift

In combined electric and magnetic fields all particles drift with the same velocity, given by

$$\mathbf{V}_{\mathrm{ExB}} = \frac{\mathbf{E} \times \mathbf{B}}{B^2}$$

where, $\mathbf{E}$ is the electric field, $\mathbf{B}$ the magnetic field, and $\mathbf{V}_{\mathrm{ExB}}$ the E×B-velocity. This drift is perpendicular to both the magnetic and electric fields. For a complete description, the electric field shall include both static and time-varying electric fields.

Polarisation drift

When the electric field is varying in time, the time variation causes a drift motion, described by

$$\mathbf{V}_{\mathrm{p}} = \frac{1}{\Omega B}\frac{d\ \mathbf{E}_{\perp}}{dt}$$

here Ω is the particle gyrofrequency $\Omega = qB/m$ which includes particle charge. Thus particles with opposite charges drift to opposite directions and a net electric current is created. In most applications (slowly varying fields) this drift is small compared to the other drifts. However, during SSC's and substorm expansion phase, the inductive part of the electric field may vary in short time scales, and this drift may be even dominant in limited regions of the magnetosphere.

Gradient drift

In inhomogeneous magnetic fields (such as the magnetospheric field), particles experience a gradient force, driving them to the direction of weakening magnetic field. This force results a guiding center drift, described by

$$\mathbf{V}_{\mathrm{grad}} = \frac{m v_{\perp}^2}{2qB^3}(\mathbf{B} \times \nabla B)$$

where $v_{\perp}$ is the perpendicular (to the magnetic field) component of the velocity of the particle. This drift is proportional to (1) the (perpendicular) kinetic energy, and (2) charge of the particle. Higher energy particles drift faster, and electrons and (positive) ions in opposite directions. A net electric current is created.

Curvature drift

When the magnetic field lines are curved, particles experience a centrifugal force, which leads to the curvature drift

$$\mathbf{V}_{\mathrm{curv}} = \frac{m v_{\|}^2}{q} \frac{\mathbf{R}_{\mathrm{c}} \times \mathbf{B}}{R_{\mathrm{c}}^2 B^2},$$

where $\mathbf{R}_{\mathrm{c}}$ is the radius of curvature (vector) of the magnetic field, and $v_{\|}$ is the particle velocity component parallel to the magnetic field. This drift is proportional to the parallel component of the particle kinetic energy, and again to particle charge.

There are also numerous different equations that combine, e.g., the magnetic drifts, using variables and formalism most suitable for the particular problem. Those can be found in plasma physics textbooks (e.g., Northrop, 1963); here we have only given the basic formulas, not to restrict the selection of the numerical scheme.

2.11.4 Particle tracer

In a model, particle drifts are governed by the electric and magnetic fields. For performing the drift calculations, two different approaches have been used.

One possibility is to use the Hamiltonian formalism, as in Salammbô. One does not solve the drift equations (given above) for each particle, but uses instead the adiabatic invariants in the Hamiltonian equations of motion, and solves the Fokker-Planck (diffusion) equation for the time evolution of the particle distribution function. Knowing the relation between the distribution function and particle flux, one can calculate the corresponding measurable parameters from the distribution function.

This approach is efficient when the magnetic and electric field configurations have (simple) analytic forms (like a dipolar magnetic field, and Volland-Stern electric field), leading to well-defined and well-behaved adiabatic invariants. In more complicated magnetic field geometries (like any non-dipolar magnetospheric field), the same analytic expressions are not valid. One has then to integrate the adiabatic invariants in the model fields numerically, and the calculations become very time-consuming.

Another approach is to use a set of "test particles", which may represent an ensemble of particles with given energies and pitch angles at a given place, and follow their drift paths with integration of the drift equations of motion in time. The electric and magnetic fields are simultaneously updated according to their (measured or modelled) time evolution during the event. This approach is used in the MSFM model, and, e.g., in the drift modelling by Toivanen et al. (1998;

see also Toivanen, 1995). Special care has to be taken to ensure that the integration scheme conserves the constants of motion: In the case of a model that is not self-consistent, this has to be regularly checked.

In the Toivanen et al. model the particle orbits are averaged over one bounce period (time which it takes for a particle to travel from the equator to one mirror point above the ionosphere, to the other mirror point, and back to equator). Thus the smallest time step is the highest energy electron bounce period. Ions drift a substantial distance in the azimuthal direction during one bounce period, and this approach is not accurate for ion drifts. The bounce averaged formalism does not describe particle energisation due to electric drifts accurately: only upper and lower limits of energies are available. On the other hand, diffusion due to wave electric fields and / or pitch angle scattering are straightforward to implement.

The practical implementation of the test particle approach is partly documented in the MSFM documents, but some of the equations (some of which critical) are referred to as being found in Freeman et al. (1984), which is not available. The Toivanen et al. model is a research model, not intended for operative use.

2.11.5 Particle heating due to plasma waves

In addition to drifting in the magnetic and electric field, particles also gain energy in interactions with plasma waves. Good models for the existence or heating efficiency of plasma waves in different parts of the magnetosphere do not exist. The Salammbô group uses a diffusion coefficient, based on simple assumptions of azimuthally constant heating region at the outer edge of the plasmasphere to describe wave-particle heating. The values for the diffusion coefficient were calculated using results from Lyons et al. (1972) and Thorne et al. (1973), and the results show general agreement with data. However, these values are only applicable for this very limited region, and for other parts of the magnetosphere similar models do not exist.

2.11.5 Boundary conditions: Particle sources

There are a number of statistical models for the particle environment in different parts of the magnetosphere. Probably the best modelled regions are the radiation belts, for which the NASA radiation belt models (AE8 for electrons and AP8 for protons; see Vette, 1991), models developed under ESTEC Contracts (TREND, TREND-2, see Lemaire et al., 1995, and TREND-3), and data from the CRRES spacecraft (Gussenhoven et al., 1996) are available. Limited data from geostationary spacecraft (GOES series) and low-orbiting spacecraft (Defense Meteorological Satellite Program, DMSP) are also available.

An important reservoir of plasma is the plasmasphere. There are models for the plasmasphere, and the average properties at the equator are relatively well known (e.g., Carpenter and Anderson, 1992: an empirical model for equatorial electron density). Lambour et al. (1997) used a modified version of the MSFM model to model the behaviour of the plasmasphere following storm sudden commencements, with the Carpenter and Anderson model as an initial condition.

The plasma sheet is another important source of particles, especially during magnetically active periods. Unfortunately there are no good models for the plasma sheet. The most coherent set of studies of plasma sheet properties, based on measurement on board the AMPTE / IRM spacecraft, is summarised in Baumjohann (1993; and references therein).

The ionosphere is also an important source of plasma for the magnetosphere. However, its role is more of constantly filling the reservoirs of the plasma sheet and plasmasphere, and thus of lesser importance for this work.

It is important to keep in mind that variations of, e.g., energetic electron flux, from statistical values can be as high as several orders of magnitude during disturbed conditions. Thus even proxy data from data bases of previous missions may be misleading. Obviously, the best plasma source boundary condition for a model is an in situ measurement.

2.11.6 Boundary conditions: Particle loss model

In first order approximation, particles are lost either through precipitation to the ionosphere / neutral atmosphere, charge exchange, or by drifting to dayside and lost to non-closed orbits.

The simplest model for precipitation to ionosphere can be obtained by removing particles that have their magnetic mirror points below a given altitude. This is equivalent to assuming a completely absorbing ionosphere. A more accurate (and physical) model, using an exosphere neutral gas model, and friction model to describe the interaction of energetic particles with neutrals, has been successfully implemented in the Salammbô model (see Beutier et al., 1995)

Energetic Neutral Atom (ENA) production through charge exchange is generally accepted to be an important mechanism for ring current energy dissipation. The efficiency of charge exchange as a loss process depends on neutral (hydrogen) density, and the details of the charge exchange process. Modelling of ENA production during magnetic storms has been presented (e.g., Roelof et al., 1985; Roelof, 1987). However, these studies concentrated on the microscale interactions and their relation to ENA production, and thus are not suitable as such a large-scale operational model.

Energetic particle loss by drift is automatically included in a complete drift model: When particles drift to non-closed orbits, they are lost from the model.

2.12 SRD: Resource estimates

2.12.1 Computer resources

The modelling tool, if based on a particle drift model approach, sets high requirements on computing power. Memory resources are not extensive (on a 3D particle drift code one has 12 variables / test particle), but the computations take a long time. The Toivanen et al. (1998) particle drift code used the Tsyganenko 1989 magnetic field, with modifications corresponding to the time-varying magnetic field during substorms, and inductive electric fields calculated from the variation of magnetic field. For modelling of 11 hours of real time (one orbital period of the CRRES satellite) by backward calculation of the drifts of 100 test particles from the substorm onset to the measurement during previous orbit, one needs approximately 16 hours of computer time on a fast workstation / server machine (P.K. Toivanen, private communication, 1998).

Most of the time in a drift model is spent on the tracing of the magnetic field lines of the model, and the more complicated the model is, the slower the calculation. It is estimated that tracing the field lines of the Tsyganenko 1996 model takes approximately 10 times more time than tracing the Tsyganenko 1989 model (N.A. Tsyganenko, private communication, 1998). The tracing part of the code is also a part that cannot be vectorised, and thus not much better performance is expected even on a vector processor.

2.12.2 Manpower resources

Present research models have been developed gradually, as research projects, during several years, and are still in continuous development. In general, approximately one third of the development project consists of planning, one third actual programming, and one third tests and, finally, "production" runs. For research models, each "production" run of the model can also be considered as one more test.

The effort needed for developing a physics-based model of the dynamics of the magnetosphere is extremely difficult to estimate. However, to give an idea of the order of magnitude of the work needed, we give three sample cases:

The development of the 3D MHD model by Janhunen (1996) was started in 1995, and the model (now in third generation) is still in continuous development. The model today consists of about 35000 lines of code (in C++), including visualisation. Recently almost 95 % of the development work of the code has been directed towards better numerical stability and computational efficiency.

Another example, the drift model by Toivanen (1995; Toivanen et al., 1998) was originally developed in one year by one person. That version of the model did not include the time-varying magnetic field, nor the inductive part of the electric field, which both are essential for a complete description of the dynamics. Finding a workable solution for the implementation of these two physical phenomena into an efficient computer code, coding, and testing, took then almost two years.

The first results of the Salammbô model were published in 1995 (Beutier et al., 1995). Since then, the model has been gradually developed, and still, after 3 years from the first results, modifications are made to make the accuracy better (in terms of both qualitative and quantitative agreement with observations). Updating the model with some of the Tsyganenko magnetic fields has also been considered, but not implemented.

The research modelling projects typically are, or at least include, work directed towards a doctoral thesis, and thus one could argue that the persons working on the model development perhaps are not the most skilled professionals, neither in physics, nor in computational mathematics. We would not, however, draw this conclusion. Fact is, that there often are no better specialists on those fields, and the support by the research groups is enough to guarantee continuation of work. Of course, one can benefit a lot if there is support from specialists available, when needed, but we do not think that would speed up the progress by a factor of two.

It *is* in principle quite straightforward to translate the basic physics equations to a numerical computer code, but to make the model give physical (and even quantitatively correct) results in an acceptable computing time, quite a lot of technical problems have to be solved. This is analogous to building an instrument for space measurements: The basic design is quite straightforward, but to take into account all the limitations of mass, power, and telemetry, and still get useful results, one has to work a long time. Usually the problems are solved in an iterative manner (by trial and error) and finding the right solutions to the problems requires a lot of thinking. In conclusion: A computer engineer, even if highly skilled, cannot translate the physics equations to an efficient working model without help from physicists, who know the problem, and maybe skilled mathematicians, specialised in computational mathematics. In an ideal situation, of course, some of these properties are combined in one person.

3. SPECIFIC REQUIREMENTS - User group 1

This section includes Specific User Requirements for user group 1 (study/ design engineers) as defined in section 2.2.1. User Requirements are numbered with UR-EN-NNN, where EN stands for engineers, and NNN is number from 001 onwards.

UR-EN-001 It shall be possible to use data from any part of the modelled region as input for the modelling tool.

SOURCE: AM

UR-EN-002 It shall be possible to run the program with only the data defined as essential.

SOURCE: AM

UR-EN-003 For any analysis, the modelling tool shall use all available data as input, to guarantee highest possible quality of output.

SOURCE: AM

UR-EN-004 It shall be possible to use data from particle monitors of previous spacecraft as proxy input data.

SOURCE: E.Daly, ESTEC, Nov. 1997

UR-EN-005 The modelling tool shall output confidence levels of the output parameters.

SOURCE: E.Daly, H.Evans, ESTEC, Nov. 1997

UR-EN-006 The modelling tool shall be able to output energy spectra (flux vs. energy) of energetic ions and electrons (energy ranges and species depending on analysis) for any time and place in the modelled region.

ESSENTIAL

SOURCE: E.Daly, H.Evans, Nov. 1997

UR-EN-007 When requested, the modelling tool shall be able to calculate distribution function parameters: Te, ne, from the energy spectra, assuming Maxwellian, bi-Maxwellian, kappa, and piecewise exponential distributions.

SOURCE: E.Daly, Nov. 1997

UR-EN-008 The modelling tool shall be able to predict short time scale (from the order of 10 minutes) changes in plasma environment.

ESSENTIAL

SOURCE: E.Daly, Nov. 1997

UR-EN-009 The modelling tool shall be able to calculate accumulation of charge by high-energy particles (50 keV -> MeV) during 2-3 day period of activity.

SOURCE: E.Daly, Nov. 1997

UR-EN-010 The modelling tool shall be available interactively through network access.

ESSENTIAL

SOURCE: E.Daly, H.Evans, Nov. 1997

UR-EN-011 The modelling tool shall be available in a batch mode through network access.

SOURCE: E.Daly, H.Evans, Nov. 1997

UR-EN-012 For batch processing (through network access) the system shall notice the user by e-mail about the start and finish of the processing.

SOURCE: E.Daly, Nov. 1997

UR-EN-013 The system shall indicate to the user if there are internal inconsistencies in the input data set that is being used.

SOURCE: A. Hilgers, Oct. 1998

UR-EN-014 The modelling tool shall be able to model the plasmapause position.

SOURCE: A. Hilgers, Oct. 1998

UR-EN-015 User documentation shall include a user manual, as well as a document describing the (physics of the) partial models, and other related possible partial models.

4. SPECIFIC REQUIREMENTS - User group 2

This section includes specific User Requirements for user group 2 (satellite operators) as defined in section 2.2.2. User Requirements are numbered with UR-OP-NNN, where OP stands for operators (or operative use), and NNN is a number from 001 onwards.

UR-OP-001 The modelling tool shall include longer term (24 hours) and short-term (4 hours) predicting capability.

SOURCE: AM, G. Töyrä, April 1998

UR-OP-002 The modelling tool shall view on-line on the end user's terminal the present conditions (nowcasting) at spacecraft location.

SOURCE: AM

UR-OP-003 The modelling tool shall view on-line on the end user's terminal the predicted conditions at spacecraft location (forecasting).

ESSENTIAL

SOURCE: SOW

UR-OP-004 The modelling tool shall give warnings of hazardous conditions at spacecraft location 2 hours before predicted occurrence.

ESSENTIAL

SOURCE: G. Töyrä, May 1998

UR-OP-005 The modelling tool shall give an estimate of the probability of hazard.

SOURCE: AM

UR-OP-006 When predicted, the modelling tool shall give an estimate of the time of hazard occurrence.

SOURCE: PM 2

UR-OP-007 When predicted, the modelling tool shall give an estimate of the duration of hazardous conditions.

SOURCE: PM 2

UR-OP-008 The modelling tool shall give estimate of the reliability of the prediction.

SOURCE: A.Hilgers, E.Daly, ESTEC, Nov. 1997

UR-OP-009 The user interface (UI) of the modelling tool shall be tailored according to the project (UI of the spacecraft control centre).

SOURCE: AM

UR-OP-010 The UI shall include a simple (e.g. traffic-light type green / yellow / red) indicator for hazard, for simple interpretation of the output.

ESSENTIAL

SOURCE: PM 2

UR-OP-011 The meaning of different hazard indicator signals of UR-OP-010 shall be clearly and unequivocally defined, to avoid misunderstandings.

ESSENTIAL

SOURCE: G. Töyrä, April 1998.

UR-OP-012 Gap in input data shall be indicated as a warning in output.

ESSENTIAL

SOURCE: PM 2

5. SPECIFIC REQUIREMENTS - Software

This section includes Software Requirements for the modelling tool translated from the specific User Requirements of the preceding two sections (3 and 4), and implied from the Model Description in section 2.11.

5.1 Functional requirements

5.1.1 Post-analysis

SR–EN–001 The modelling tool shall include a possibility to use proxy data from in situ measurements on previous missions, as input data.

SR–EN–002 The modelling tool shall include a dynamic (time-varying) model for the magnetosphere magnetic field.

SR–EN–003 The modelling tool shall include a dynamic (time-varying) model for the magnetosphere electric field.

SR–EN–004 The modelling tool electric field model shall include inductive electric fields calculated from the time variation of the magnetic field.

SR–EN–005 The modelling tool shall include a model for particle losses in the modelling region.

SR–EN–006 The modelling tool shall calculate energy vs. flux spectra for electrons in the energy range from 1keV to 50 keV, at a given time and place inside the modelling region.

SR–EN–007 The modelling tool shall include a numerical fitting routine (adjustable by the user) to calculate moments of particle spectra, assuming Maxwellian, bi-Maxwellian, Kappa, and piecewise exponential shapes for the distribution.

SR–EN–008 The modelling tool shall have possibility of adjusting parameters of the physical model to fit to in-situ data obtained inside the modelling region.

SR–EN–009 The physical time step of the modelling tool shall not be longer than 10 minutes.

SR–EN–010 The modelling tool shall include a routine to calculate accumulated charge, using local particle spectra along a specified spacecraft orbit as input.

SR-EN-014 The modelling tool shall perform an internal consistency check for input data.

SR-EN-015 If the input data is internally inconsistent, the modelling tool shall give a warning to the user.

SR-EN-016 The modelling tool shall include the plasmaspheric particle population as a default particle source.

5.1.2 Operative use

SR–OP–001 The modelling tool shall include long term (24 hours) and short term (4 hours) warning capability.

SR–OP–002 The modelling tool shall output present probability of hazardous conditions (nowcasting) capability.

SR–OP–003 The modelling tool shall output predicted probability of hazardous conditions (forecasting) at spacecraft location.

SR–OP–004 The modelling tool shall calculate the time of occurrence of anomaly, predicted from the input (solar wind) data.

SR–OP–005 The modelling tool shall estimate the duration of hazardous conditions (based on input characteristics compared to previously analysed events).

SR–OP–006 The modelling tool shall indicate missing or erroneous input data as a warning in output.

5.2 Performance requirements

SR–OP–007 The modelling tool shall give a warning in 2 hours before the predicted occurrence of hazardous conditions in 95 % of cases.

5.3 Interface requirements

SR–OP–008 The modelling tool User Interface shall be dedicated to and be defined in collaboration with the end user.

SR–OP–009 The modelling tool User Interface shall include a simple (for example, a green / yellow / red-type) indication of hazard probability.

SR–EN–011 The modelling tool shall have an interactive and a batch mode interface.

SR–EN–012 In batch mode, user shall be notified when the processing starts and ends.

5.4 Operational requirements

SR–OP–010 The modelling tool shall run 24 hours a day without end user interference.

5.5 Resource requirements

N / A

5.6 Verification requirements

SR–OP–011 / SR–EN–013

The modelling tool shall be extensively tested against analysed cases, in different magnetospheric conditions, to be able to give reliability estimates for predictions.

SR-EN-017 Interoperability of independent partial physical models shall be tested and validated.

5.7 Acceptance test requirements

- The acceptance test shall include verification of model results with known cases, leading to estimates of model performance, occurrence probability, and reliability estimates.

5.8 Documentation requirements

SR-EN-018 Documentation for each partial physical model has to be available, describing: assumptions, name and type of input and out put parameters, range of applicability, and known limitations.

SR-EN-019 Documentation of the relations of each partial models with other implemented (partial) physical models (or references) shall be available.

5.9 Security requirements

- No special requirements.

5.10 Portability requirements

SR–OP–012 The modelling tool shall be written in standard vendor-independent programming language.

5.11 Quality requirements

- No special requirements.

5.12 Reliability requirements

- No special requirements.

5.13 Maintainability requirements

- No special requirements.

5.14 Safety requirements

- No special requirements.

6. REQUIREMENTS TRACEABILITY MATRIX

6.1 User Group 1: Study / Design Engineers (EN)

	SR-EN-001	SR-EN-002	SR-EN-003	SR-EN-004	SR-EN-005	SR-EN-006	SR-EN-007	SR-EN-008	SR-EN-009	SR-EN-010	SR-EN-011	SR-EN-012	SR-EN-013	SR-EN-014	SR-EN-015	SR-EN-016	SR-EN-017	SR-EN-018	SR-EN-019
UR-EN-001								X						X			X		
UR-EN-002								X											
UR-EN-003								X											
UR-EN-004	X																		
UR-EN-005													X				X		
UR-EN-006		X	X	X	X	X											X		
UR-EN-007							X												
UR-EN-008									X										
UR-EN-009										X									
UR-EN-010											X								
UR-EN-011											X								
UR-EN-012												X							
UR-EN-013														X	X				
UR-EN-014													X			X			
UR-EN-015																		X	X

6.2 User Group 2: Satellite Operators (OP)

	SR-OP-001	SR-OP-002	SR-OP-003	SR-OP-004	SR-OP-005	SR-OP-006	SR-OP-007	SR-OP-008	SR-OP-009	SR-OP-010	SR-OP-011	SR-OP-012	SR-OP-013
UR-OP-001	X												
UR-OP-002		X											
UR-OP-003			X										
UR-OP-004							X						
UR-OP-005											X		
UR-OP-006				X									
UR-OP-007					X								
UR-OP-008											X		
UR-OP-009								X					X
UR-OP-010									X				
UR-OP-011									X				
UR-OP-012						X							