Part B

FP7-SPACE-2010-1

A new, ground based data-assimilative model of the Earth's Plasmasphere – a critical contribution to Radiation Belt modeling for Space Weather purposes

PLASMON

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Introduction

In this project we address space weather models to improve specification and prediction capabilities, with emphasis on the linkage of the different physical processes that occur simultaneously or sequentially in many domains in accordance with *Work Programme 2010, Cooperation, Theme 9 SPACE* call.

At the end of the project we will provide real time data of plasmaspheric densities, a data-assimilative model of the plasmasphere and a model of Relativistic Electron Precipitation (REP) losses. All these data, models and information will significantly contribute to European capacity to estimate and prevent damage of space assets from space weather events as well as to improving forecasting and predicting of disruptive space weather events.

The data, models and forecasting capabilities will be available for European and international actors in the field.

No such data and models are available to date, neither separately nor as a complex service or method which we will develop in the project.

As *security of space assets from space weather events* is a global challenge and thus difficult to confine any activity into the EU, therefore – completely conforming to the *call -,* we will involve partners from other space-faring nations (USA, New Zealand, and South Africa) as well as IPCP partner (South Africa). Without their specific expertize or the utilization of their special geographic (geomagnetic) location(s), the project objectives cannot be achieved.

ESA SSA preparatory programme – which is in the middle of its first phase – is currently identifying European Space Weather *assets,* operational services; services and methods that are potentially operational. No complex service or method such as proposed here is currently in the list of space weather-related assets of ESA.B1. Concept and objectives, progress beyond state-of-the-art, S/T methodology and work plan

1.1 Concept and objectives

1.1.A Concepts

All space weather models and forecasting methods are dependent on data input for either boundary conditions or the specification of parameters needed by the model. These data at best come from in-situ observations or a statistical model parametrized by some geomagnetic indices, and at worst simply "guessed" to be some representative value.

In-situ observations (satellite measurements) suffer from inherent weaknesses. One, very few platforms give comprehensive measurements of particles, waves and fields. Two, the data availability is very often limited in space and time; at best there will be a handful of observations of a given parameter at any given time throughout all of geospace. Three, with very few exceptions (GOES data), data are not generally available in real or even near-real time, limiting their use for forecasting. Four, the high costs of satellite fabrication and launch make it unlikely that these limitations will be overcome any time soon.

However, there is a complementary or alternative approach to provide data sources for space weather models: ground based measurements. Clearly the combination of ground and space based measurements would provide the best result, but the ground based measurements have several advantages over the space based ones. Generally, they are cheap, and they can produce continuous temporal and spatial coverage. As they generally have access to the Internet providing real-time data presents few problems.

In this project we will develop and/or upgrade ground based systems to provide key parameters used in comprehensive radiation belt models that are unlikely to ever be provided by space-borne systems, but are vital for any realistic radiation belt model.

We address here '**Security of space assets from space weather events'**, particularly the topic *space weather models to improve specification and prediction capabilities.*
One of the most significant hazard to Earth-orbiting satellites is posed by high fluxes of relativistic electrons. These fluxes contribute to the total radiation dose to the satellite and thus its lifetime, or to deep-dielectric charging, where penetrating electrons gives rise to potential differences, which in turn can lead to intense voltage discharges and surges of electric energy deep inside the electric circuits of the spacecraft – causing severe damage to various subsystems. Such discharges can produce short-lived (fractions of a microsecond) but intense (several Amperes) current pulses.

The temporal evolution of trapped relativistic electron fluxes in the radiation belts is highly dynamic and poorly understood, and is currently topic of intense scientific research which has led to the development of several radiation belt models (the Los Alamos DREAM project, the ONERA Salammbo code, the UCLA radiation belt code, the NERC-BAS radiation belt code).
Reeves [1998] found that geomagnetic storms produce all possible responses in the outer belt flux levels, i.e., flux increases (53%), flux decreases (19%), and no change (28%). The dynamics of these particles is the result of a complex interplay of acceleration, loss and transport processes; and for all these processes the underlying mechanism has a strong dependence on the distribution of the overlapping background cold plasma in the *plasmasphere*: Acceleration and loss are due to resonances with variety of plasma waves – both the generation of these waves and the resulting resonance conditions depend on the ambient plasma density and composition. Transport is due to resonances with ULF wave modes, which depend on mass loading of field lines and thus also on the ambient plasma density.

The plasmasphere itself is also a dynamic region being permanently influenced by the region below (ionosphere) and above (outer magnetosphere) and is controlled by the relative intensities of the solar wind-imposed electric field and the co-rotation electric field. The plasmasphere plays a central role in magnetosphere-ionosphere dynamics. Apart from hosting the waves which are responsible for the acceleration, decay and transport of radiation belt particles, the plasmasphere also plays an important role in spacecraft charging effects, and it is a significant contributor to TEC which contributes to GPS inaccuracies and communications problems. At the simplest level the plasmasphere is controlled by three factors: a global convection electric field, outflow/inflow from/to the ionosphere, and diffusive equilibrium. Therefore the dynamics of the plasmasphere requires monitoring, modeling and forecasting. Fundamental parameters of the plasmasphere are the plasma distribution, density and composition. To obtain this distribution, we will use a combination of ground based networks, and ground based techniques, in combination with a data-assimilative model of the plasmasphere.

One network (AWDANet) measures Very Low Frequency (VLF) waves to capture and analyze *whistlers*, another network (EMMA) measures Ultra Low Frequency (ULF) signals to capture and analyze *Field Line Resonances* (FLR). Methods based on the two phenomena are capable of providing plasmaspheric densities. The two methods are complementary to each other due to the spatial and temporal occurrences of whistlers and FLRs. *Monitoring* of the plasmasphere by whistlers and FLRs will be the basic objective (1.1.B.1 and 1.1.B.2) of this project, while the third (data-assimilative modeling of the Earth's plasmasphere, 1.1.B.3) uses these data to provide a hi-fidelity model. The fourth objective (identifying electron loss to the atmosphere from the different regions of the plasmasphere, 1.1.B.4) demonstrates one application of the new plasmasphere model in providing value added information on the loss processes for use in radiation belts models making use of measurements by a third ground based network (AARDDVARK)

1.1.B Objectives

1.1.B.1 Objective 1: Automatic retrieval of equatorial electron densities and density profiles by Automatic Whistler detector and Analyzer Network (AWDANet)

The cold electron density distribution of plasmasphere cannot be easily measured routinely, but is a key parameter for modeling of the plasmasphere and radiation belts. Whistlers have been regarded as cheap and effective tools for plasmasphere diagnostic since the early years of whistler research, but it never became a real operational tool since “reducing” whistler data to equatorial densities was very labor intensive. Recently the Space Research Group of Eötvös University has developed a new, experimental Automatic Whistler Detector and Analyzer (AWDA) system [Lichtenberger et al. 2008] that is capable of detecting whistlers and we plan to use this system to process lightning whistlers with no human interaction. A network formed by AWDA systems (AWDANet) is evolving and now covers low, mid and high magnetic latitudes [Lichtenberger et al. 2008]. Currently, the automatic analyzer works only for low latitude whistler, which can provide equatorial electron density only for a very limited range of L-shells (L=1.8-2.8). A recent developments in whistler inversion methods for multiple-path whistler groups propagating on mid and high latitude [Lichtenberger, 2009] will allow us to retrieve electron density profiles automatically for wide range of L-values, with low latitude whistlers practically covering the whole plasmasphere. The AWDANet (Figure 1) will be extended to have better spatial and temporal coverage and thus will be able to provide density profiles for different MLTs which can be used as a data source for space weather models. We will

- extend the AWDANet to have better MLT and latitudinal coverage,
- develop an automatic whistler analyzer (AWA) method based on our new whistler inversion method,
- implement the AWA in AWDANet nodes and
- develop AWDANet to work in quasi-real-time mode of operation.

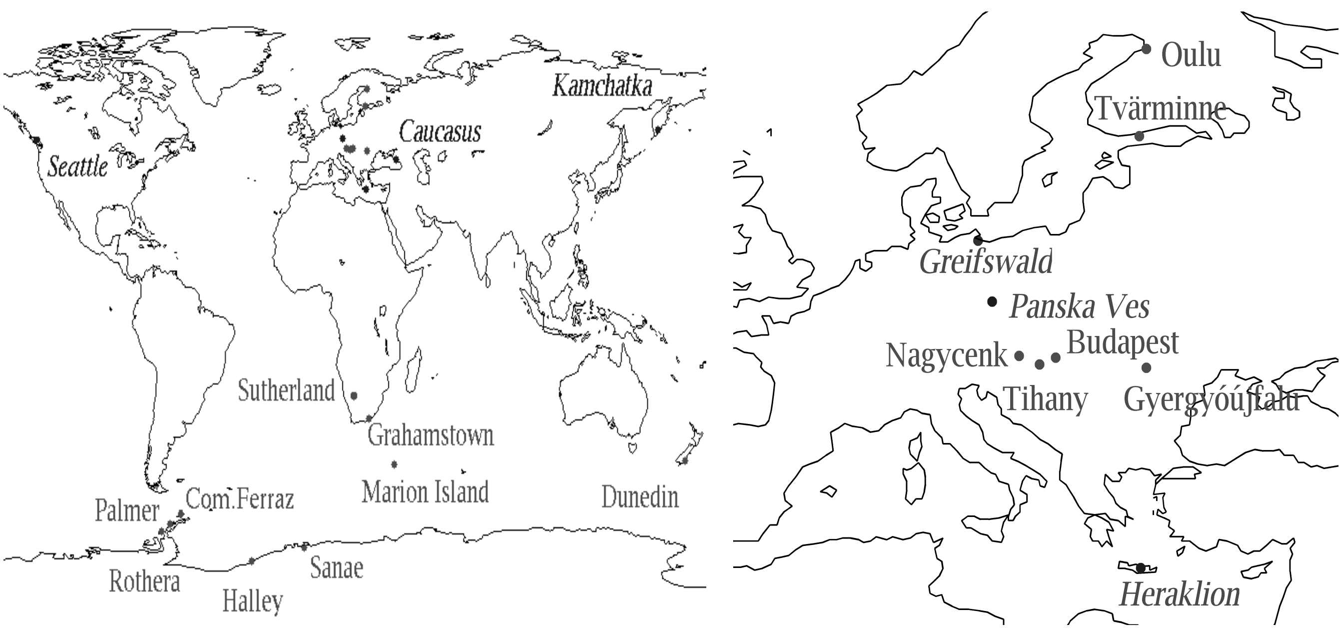


Figure 1. Left panel: AWDANet nodes all over the world. Right panel: European stations. Site names in italic are planned stations. We will plan to setup an additional station in North America (mid-Canada) and in NW Europe (Scotland), the exact location is not yet defined.

1.1.B.2 Objective 2: Retrieval of equatorial plasma mass densities by SEGMA and MM100 magnetometer arrays and cross-calibration of whistler and FLR method

Thanks to the recent developments in magnetometry (reduction of noise), data acquisition (resolution and timing) and the theory (wave propagation, event detection, models, inversion) of magnetohydrodynamic (MHD) waves, the routine monitoring of the cold plasma mass density of the plasmasphere became possible. Although the preparation of such monitoring systems in Europe has started, the efforts have so far been made separately in different countries. University of L'Aquila established the SEGMA (South European GeoMagnetic Array), [Vellante et al, 2004], while Eötvös Loránd Geophysical Institute (Hungary) initiated the MM100 array [Heilig et al., 2007a, 2007b], both in 2001. One of the main goals of both arrays was to monitor the plasmaspheric mass density based on the detection of geomagnetic field line resonances (FLRs). None of these 'monitoring' systems, however, became operational in the sense that they never produced quasi real time products.

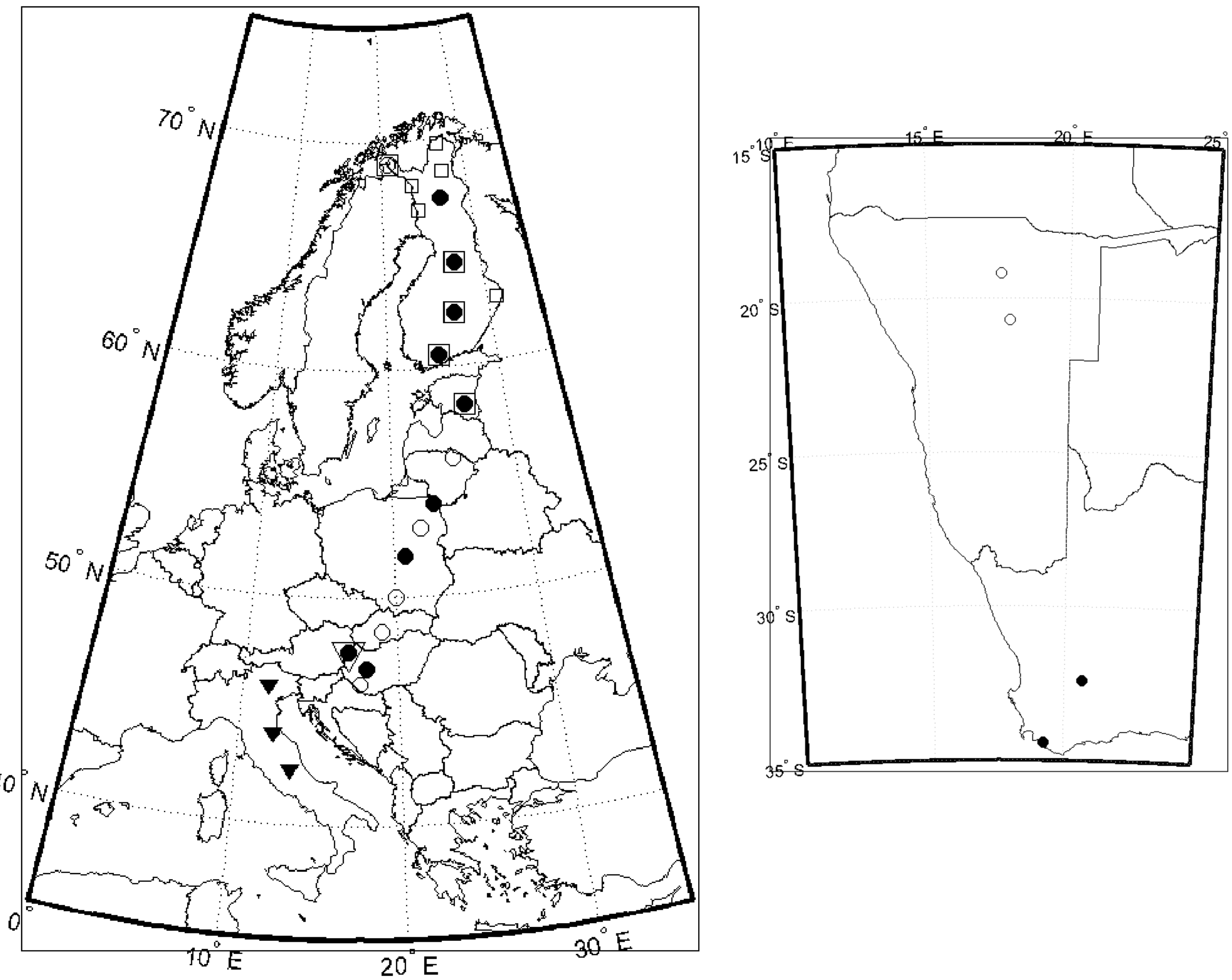


Figure 2. EMMA stations across Europe (left panel). Full/open triangles represent SEGMA stations, full circles: MM100 stations, open squares: IMAGE stations in Finland, open circles: planned new EMMA stations, the exact locations of which have not yet been defined. SA stations in Southern Africa (right panel), full/open circles: existing/planned SA stations.

Data are transferred a few times a year, and processed on a non-regular basis. The latitude coverage is also not sufficient to monitor the whole plasmasphere. In contrast to the whistler method the FLR method can be used to infer the plasma mass density even in the plasmatrough and to also identify the location of the plasmapause. In the context of the current project we plan to unify the isolated European efforts to call into being a joint European network, EMMA (European quasi-Meridional Magnetometer Array,) with stations ranging from Italy

to the northern Finland (L-shells 1.6 – 6.7) (Figure 2).
We intend to use and upgrade existing magnetometer networks (IMAGE), which were originally established for other purposes and other requirements (resolution, sampling rate, timing), but the data of which can be exploited for plasmasphere observations, as well. In accordance with these goals we will

1. unify and extend the SEGMA, MM100 and IMAGE networks into EMMA (including stations in Southern Africa maintained by HMO) to have better latitudinal coverage,
2. develop an automatic FLR identification (FLRID) method based on previous experience and recent improvements,
3. develop an automatic FLR inversion (FLRINV) method based on most recent achievements including error estimations,
4. develop all EMMA stations to work in quasi-real-time mode of operation,
5. evaluate relative abundances of heavy ions in the plasma composition from simultaneous determinations of mass density (FLR method) and electron density (whistler method)

1.1.B.3 Objective 3: Data assimilative modeling of the Earth's plasmasphere

Even dense measurements only sample the plasmasphere at limited resolution in both space and time. For example, FLR data only provide measurements during the daytime, and only at the local time of the observatory pairs, whereas whistlers provide the best measurements during the night time, and again only at the MLT and L-shells of the observatories. The same restrictions apply to, and are usually more severe, in the case of satellite measurements. Yet determining the effect of wave-particle interactions on the radiation belts require a continuous map of the plasma density in both time and space. In order to provide such a complete map it becomes necessary to interpolate between measurements, again in both time and space. A good approach to this interpolation is data assimilation. The basic idea behind data assimilation is the combination of a physical model of the system with observations relevant to constraining the physical system. The most sophisticated data assimilation schemes preserve the internal physical consistency of the model while matching it optimally to the data, in time and space. This combination of observation and a physical model should, in theory, perform better than either by itself. This is actually the case, as demonstrated by many examples ranging from radar tracking of aircraft [Kalman, 1960] to routine weather forecasting [Evensen, 2008]. A good data assimilation scheme essentially fits a time-dependent model to a time-series of uncertain observations. It can be visualized as a feedback system in which the measurements provide error signals, which adjust free, or poorly determined, inputs to the model. In the case of the plasmasphere these include the electric field, the refilling and loss rate, and possibly some composition information. Specifically this is carried out by simulating the measurements from the model and comparing those to the observations, taking into account complicated relationships such as the fact that future measurements can constrain past drivers of the model.
At New Mexico Tech we are working with data assimilation schemes to combine plasmaspheric measurements with a numerical physics-based plasmasphere model. The two data assimilation schemes which we are pursuing are Ensemble Kalman filtering [Evensen, 2003] and particle filtering Arulampalan et al., 2002, Nakano et al., 2008]. As part of this project we will develop the necessary means to incorporate FLR measurements and whistler measurements into the assimilation scheme. There are two approaches to this, and we will pursue both. The simplest approach is to estimate equatorial and/or field-line-integrated mass and electron density from the measurements using a nominal model [Lichtenberger, 2009]. This will be the simplest to incorporate as it just requires matching the model plasma densities to those measurements. A more involved approach computes the FLR frequencies from the model using first principles or simplified solvers. In the case of FLR measurements it requires solving an eigenvalue equation, [e.g. Denton, 2000] and in the case of the whistler measurements it requires estimating the whistler parameters. We will also undertake incorporating composition information into the model. When the composition changes slowly over time it is possible to estimate it through the data assimilation even when there is only limited overlap between FLR and whistler measurements.

1.1.B.4 Objective 4: Modeling REP losses from the radiation belts using the AARDDVARK network

During a geomagnetic storm the length of time during which space assets are in danger is determined by the efficiency of the loss mechanisms, particularly through relativistic electron precipitation into the atmosphere. The primary mechanism for this precipitation is the interaction of several wave modes with resonant electrons, which leads to scattering into the atmospheric loss cone. The nature of the wave activity and the interactions between the waves and radiation belt particles are strongly governed by the properties of the plasmasphere. In this work package we will use the assimilative model of the plasmasphere to identify regions where plasmaspheric structures such as the regions occurring on, inside, and outside of the plasmaspause and/or composition changes are likely to result in enhanced electron losses. We will monitor the occurrence and properties of REP using the ground based AARDDVARK network.
There is evidence that different wave activity and varying radiation belt losses occur due plasmaspheric structures. For processes that occur inside of the plasmapause we would anticipate that plasmaspheric hiss would be the dominant loss mechanism, while outside the plasmapause chorus would be expected to dominate. In addition electro-magnetic ion-cyclotron (EMIC)-driven precipitation associated with the plasmaspause itself can lead to intense bursts of very strong relativistic precipitation from the radiation belts as we have previously shown, and could provide radiation dose hazards for astronauts in (very) low Earth orbit. We will use the AARDDVARK data to determine the electron precipitation flux levels that are associated with the different regions of the plasmasphere, identifying subionospheric transmitter-receiver propagation paths that are influenced solely by processes that occur either inside, or outside of the plasmaspause. In order to achieve this aim we would map the regions of plasmaspheric structures into the Earth-ionosphere waveguide in order to know which part of the AARDDVARK network they would be monitored by; plan to build up the AARDDVARK network to provide additional receiver pairs located such that they combine together to monitor a constant L-shell; include data from riometers and pulsation magnetometers in case studies; and ultimately develop a REP loss module to add on to the plasmasphere model including an indication of radiation dose hazard. This analysis would rely on development of quasi-constant L-shell monitoring paths in the AARDDVARK network.

1.2 Progress beyond the state-of-the-art

1.2.1 Objective 1

Though whistlers had already been discovered by the end of 19th century, they did not play a significant role in upper atmospheric physics till 1953, when Storey [1953] demonstrated the existence of the protonosphere (what we now call plasmasphere) by lightning-generated VLF waves (whistlers). He showed that the propagation time delay of a frequency in the whistler wave is proportional to plasma density on the propagation path. Some years later, the discovery of nose whistlers [Helliwell et al., 1956] and the development of their propagation theory [Smith et al., 1960] opened the possibility of using whistlers to determine the electron density distribution along the propagation path of the waves. Since then, whistlers have been regarded as cheap and effective tools for plasmasphere diagnostics. Park [1972] developed a consistent method for the determination of electron densities from nose whistlers, and Bernard's [1973] and Tarcsai's [1975] works made it possible to use midlatitude whistlers for diagnostic purposes using nose extension methods leading to routine whistler analysis. Whistlers were used to determine equatorial electron density profiles [e.g., Park, 1974; Tarcsai et al., 1988]; for measurements of ionosphere-plasmasphere coupling fluxes [Park, 1970]; for measurements of east–west electric fields and plasma bulk motions in the plasmasphere [Carpenter et al., 1972; Thomson, 1976; Carpenter and Seely, 1976] based on drifting whistler paths; discovery of plasmapause by knee whistlers [Carpenter, 1963], and for development of an empirical model of equatorial electron density in the magnetosphere [Carpenter and Anderson, 1992], to mention only a few important applications. These classical whistler propagation methods enable us to determine the cold plasma densities in the magnetosphere. Recently, hot/warm plasma effects related spatially to radiation belts and ring current and temporally to geomagnetic disturbances and space

weather have become a major field of space physics. There are many points where whistlers may also play an important role in these scenarios, either directly through whistler(wave)induced particle scattering [Helliwell et al., 1973; Rycroft, 1973] leading to ionospheric disturbances or indirectly through radiation belts/ring current models [e.g., Beutier and Boscher, 1995; Fok et al., 2001], where cold plasma density is a key input parameter. The analysis of a whistler usually consists of the following steps: (1) searching for whistlers in raw data, (2) scaling the whistler traces obtaining frequency-time (f-t) pairs on dynamic spectra, and (3) applying a model using the scaled f-t pairs to calculate plasma and propagation parameters (L value of field line, equatorial electron density n_{eq} and tube electron content N_T). All research described in the previous paragraph was done by manual analysis of whistlers. Manual analysis refers to the fact that steps 1 –3 above have to be performed by the researchers. Computers helped to make these steps less tedious but could not eliminate the need for the human mind in whistler analysis: whistlers are now stored digitally and not on analogue tapes; spectrograms are used to help in search of whistlers; scaling is done on computer screens and not on sonograms with pencils and rulers; models are coded into computer programs; and there is no need to use nomograms anymore. These tedious human efforts needed in whistler analysis prevented whistlers from fulfilling the old expectation of becoming a cheap and effective tool for plasmaspheric diagnostics.
Therefore the 'traditional' methods of whistler analyzes have not led to use them for monitoring the plasmasphere, this can clearly be seen from the dates of publication in the previous paragraph. Recent we have developed an *automatic whistler detector* (AWD) system [Lichtenberger et al., 2008] , it is capable to detect whistlers in the raw VLF signal. Now a network of such a systems is established and the AWDs detect whistler traces between100,000-6,000,000/year, depending on the location of the detector. A new whistler inversion methods has been developed [Lichtenberger, 2009]. This new method is based on recent theoretical improvements of wave propagation model [Ferencz et al, 2001] and empirical enhancements of field aligned density distribution [Denton et al., 2004]; and is extended with a new multiple path whistler group model. The latter makes possible not only the retrieval of equatorial electron density *profiles*, but the development of an *automatic whistler analyzer* (AWA) method. The combination of AWD and AWA leads to the unique *Automatic Whistler Detector and Analyzer* (AWDA) system, a complete network of such a system, the *AWDANet,* will be able to fulfill the objective: the **retrieval of equatorial electron densities and density profiles automatically**. No such or similar system exists and no one is planned to setup up to our best knowledge. Furthermore, a *service* based on AWDANet would be inevitable for ESA SSA System as well.

1.2.2 Objective 2:

The possibility to monitor the magnetospheric cold plasma mass density by ground-based recordings of ULF waves is based on the circumstance that the geomagnetic field lines, stimulated by compressive MHD waves propagating through the magnetosphere, behave like vibrating strings with their feet tied with the ionosphere. The normal mode frequencies of these oscillations, usually referred to as field line resonance (FLR) frequencies, depend on the magnetic field length, strength and plasma mass density distribution along the field line. Assuming well established magnetospheric field models and reasonable functional dependencies of the plasma mass density along the field lines, an estimate of the mass density at the apex of the field line (in the case of a dipole magnetic field the equatorial plasma mass density, ρeq) can be derived. Although the idea that ULF waves detected on the ground can be used to remote sense the magnetospheric plasma density dates back to the seventies of the last century [Troitskaya and Gul'elmi, 1970], only in the last few years, with the development of specific techniques, this method has become effective and several research groups are planning to use it in a systematic way.
The standard method for determining FLR frequencies consists in performing a cross-spectral analysis between the magnetic signals recorded at two ground stations nearly aligned along a same magnetic meridian and closely separated in latitude (typically 1-3 degrees). In this way the peculiarities of the source wave are removed and the FLR properties are extracted. This method, first introduced by Baranski et al. [1985] as the amplitude gradient method (AGM), became more popular and efficient when Waters et al. [1991] proposed the use of the "cross-phase"; or phase gradient method (PGM). The technique identifies the resonance frequency of the field line whose footprint lies mid-way between the two stations as the frequency at which the cross-phase difference between the north-south (H) component of the magnetic signals maximizes. It has been applied successfully for

identifying the plasmapause [Menk et al., 2004], constructing an empirical model of the equatorial plasmasphere mass density [Berube et al., 2005], investigating: a) the magnetospheric dynamics during geomagnetic storms [Chi et al., 2000; 2005], b) the annual variation in plasmaspheric density [Berube et al., 2003; Vellante et al., 2007], c) the solar irradiance control [Vellante et al., 2007]. Based on the PGM automated processes have been developed [Berube et al., 2003], which in theory made the quasi real-time density monitoring of the magnetosphere possible.

The inversion of the FLRs is based on the solution of the MHD wave equation for the toroidal shear Alfvén mode in a stationary, cold plasma in a given geomagnetic field model supposing some kind of plasma distribution along the field line. At low latitudes (L<4), the dipole magnetic model can be sufficient, whereas at high latitudes a more realistic, semiempirical magnetic field model (e.g. Tsyganenko) has to be taken into account. The MHD wave equations in an arbitrary magnetic topology was given by Singer et al.[1981], that can be solved using a numerical, successive algorithm. The analytical or numerical solutions of the problem under different conditions are given in the literature [e.g. Cumming et al., 1969, Schulz 1996, Denton and Gallagher, 2000], and can be coded directly. These achievements have stimulated the realization of new extended magnetometer arrays (e.g., SAMBA, McMAC in South and North America, MAGDAS in the Japanese-Austral sector) whose primary objective is the remote sensing of the magnetospheric plasma mass density. In the frame of the present project we will combine the already existing European magnetometer arrays IMAGE (http://www.space.fmi.fi/image/index.html), MM100 (http://www.elgi.hu/newwww/index.php?akt_menu=564) and SEGMA (http://sole-terra.aquila.infn.it/staz_segma.asp?lang=en) to retrieve equatorial plasma mass densities in the L-shell range 1.6 - 6.7. The unified EMMA array should be extended by filling some gaps at middle latitudes (Hungary, Slovakia, Poland, Latvia). The plasma monitoring will be accomplished through the use of the combined PGM-AGM applied to ULF measurements from a number of pairs of stations. We will also make use of the existing South African stations maintained by HMO along the same meridian. With the use of southern hemisphere observations we can check the assumptions on north-south symmetries, and those observations will give an independent estimate on the accuracy of the method. During years close to the sunspot maximum, because of the seasonal variation of ULF activity, HMO data will help to increase the plasma mass density data coverage in general. All these recent improvements yield us the possibility to fulfill the objective: the retrieval of equatorial plasma mass densities and density profiles automatically both in the plasmasphere and in the plasmatrough.

Because of the scarce ionospheric wave reflection at night-time, the ULF method is applicable mainly at daytime. The opposite occurs for the VLF method for retrieving the electron density. Therefore the two techniques complement each others in local time coverage. However, the two time windows are partially overlapped and therefore when measurements from both arrays will be simultaneously available, evaluations on the relative abundances of heavy ions could be provided.

The calibration can be performed in either a relative or absolute sense. In the former case the results from the two methods (whistlers and FLRs) will be calibrated with respect to each other, while in the latter case these measurements will be calibrated to an absolute reference such as in situ satellite measurements of plasmaspheric density.

The relative calibration would be carried out on a event-by-event basis, where a cross-correlation procedure would identify periods of time where both whistler and FLR data are available. Although whistler data are available from a range of local times, this procedure would most appropriately be applied to measurements which pertain to the SEGMA and MM100 meridians. Whistler data for comparison will be obtained from Tihany in the northern hemisphere and Marion Island in the southern hemisphere. An additional source of reference data might be VLF-Doppler measurements, which are available from Marion Island.

1.2.3 Objective 3:

The use of data assimilation in space physics is still in its infancy. Data assimilation methods are used in ionospheric modeling [Bust et al., 2004, Bust and Crowley, 2007] and are beginning to be used in radiation belt modeling as well [Koller and Friedel, 2005, Koller et al., 2007, Kondrashov et al., 2007, Fuller-Rowell et al., 2006], and one example exists of using it to constrain a ring current model using global ENA images [Nakano et

al., 2008]. The relatively slow adoption of data assimilation for magnetospheric physics may be connected to the relative sparsity of observations. However, this problem will be addressed through the work in WP1 and WP2.
A variety of plasmasphere models are used as drivers to existing ring current and radiation belt models to compute the loss processes [e.g. Fok et al., 1991, 2001, Friedel et al., 2002]. Even the radiation belt models and ring current models that have been run under a data assimilation scheme do not include data assimilation on the plasmasphere but simply run it using for example an electric field parametrized by geomagnetic activity index such as K_P.
The first advance we will make is to apply the feedback loop in which the model parameters are adjusted to make the model consistent with the data taking into account the various data sources. The model parameters include the time-dependent electric field as well as flux tube refilling and loss rates.
The second advance we will make is to use a particle filter. The particle filter has several significant advantages over some other data assimilation approaches in that it includes future data in its estimation. To say it differently, the particle filter allows for the modification of model parameters in the past to improve the agreement between observation and model at the current time. This is particularly important when dealing with spare observations or large time-gaps in the data stream. By contrast, the Kalman filter only allows for the modification of the current model parameters based on the most recent observations, which can lead to problems when data gaps occur.

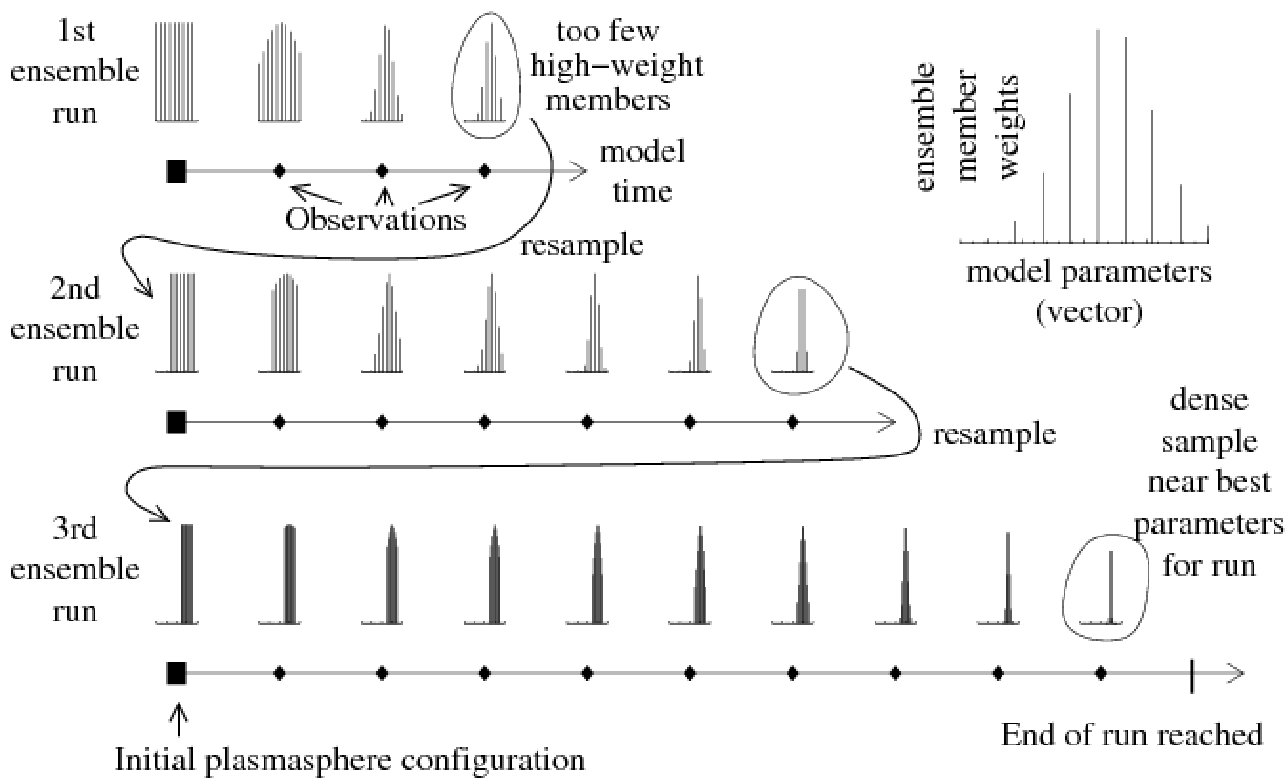


Figure 3. Example of running a particle filter with resampling, for an ensemble of 10 models. Model time runs from left to right, and the model (bar graphs) are updated each time data are available (marked by diamonds). Once the ensemble has been resampled enough around the optimal set of parameters for the assimilation to run to the end, the assimilation problem has been solved and we can produce a map of the plasmasphere for every time in the interval.

All data assimilation schemes work by using observations to adjust free parameters of a physics-based model. In the case of the plasmasphere these free parameters include timeseries of the parameters of a global electric field model. The details of how we implement this electric field model are given later.
The particle filter works by representing a point in parameter space by a multidimensional vector. A search algorithm then find the point in parameter space which evolves the plasmasphere in a way which best agrees with the observations. In practice a large number (100-500) of candidates are generated at the start of the run

each with equal weights. The model is run forward in time and at each observation the probability of each model is evaluated and the weights updated. At the end of the run the model with the largest weight is assumed the best fit [e.g. Nakano et al., 2008]. In practice this approach must be modified because the parameter space can be very large and the number of models limited. Most of the models are quickly eliminated with only few data such that the candidates must be resampled over a smaller range. This process is illustrated in Figure 3. For a very long run the length of the input time-series can be very large. In that case it is often advantageous to divide the long run into multiple shorter runs, where the output of one run is used as the initial input to the next run.This also works because the plasmasphere does not have inifinite time history: the importance of inputs in the past decrease the further back in time we go. We can then perform runs inside a sliding window stretching back in time. As the window is moved forward the assimilation left behind becomes definitive, whereas more recent assimilations are still subject to change by data. This process if illustrated in Figure 4.

The third advance we will make is to use a sophisticated electric field model. The electric field is the most important driver of the plasmasphere. We will use the output of the Assimilative Mapping of Ionospheric Electrodynamics (AMIE) [e.g Emergy et al., 1996]. AMIE derived electric fields, which are themselves derived through a data assimilation approach. By making the assumption that AMIE electric fields mapped to the magnetosphere are a good approximation for magnetospheric electric fields the assimilation will compute timedependent perturbations to the AMIE fields. We expect this approach will produce a better estimate of the electric field with fewer adjustable parameters. As a side benefit, using this approach it should be possible to estimate the relationship between ionospheric and magnetospheric electric fields, as a function of geomagnetic activity [Boonsiriseth et al., 2001].

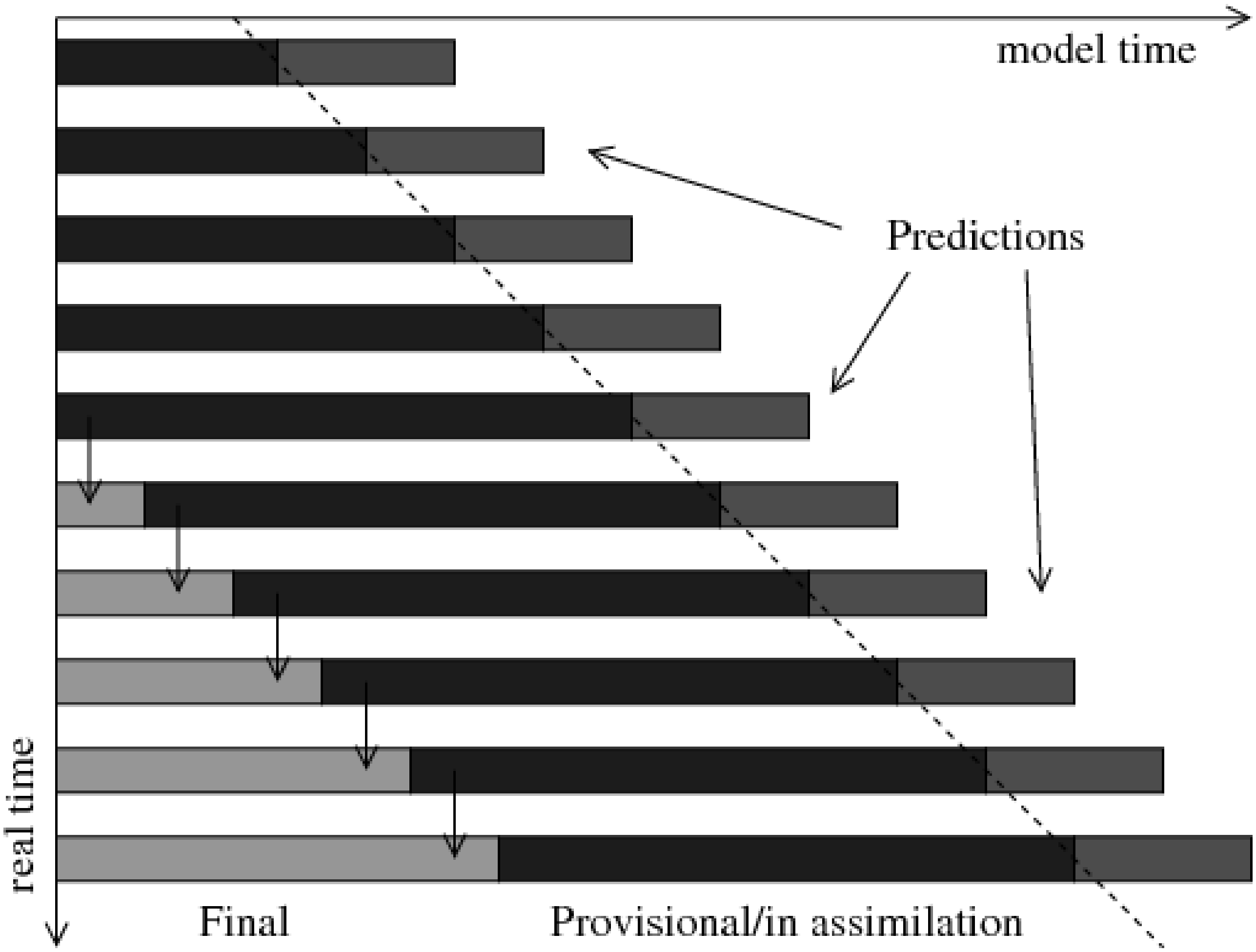


Figure 4. For long runs, the assimilation takes place over a sliding window stretching back in time from the present. Plasmasphere maps in the assimilation window (black) are provisional pending more future data. As the

sliding window moves forward, the early times dropped become final maps (light gray), and initial configuration for the assimilation. Predictions (gray) can also be performed based on an assumed ensemble of future drivers.

1.2.4 Objective 4:

In the more than four decades since the discovery of the Earth's Van Allen radiation belts, it has proved difficult to confirm the principal source and loss mechanisms that control radiation belt particles. During a geomagnetic storm the length of time during which space assets are in danger is determined by the efficiency of the loss mechanisms. A key loss mechanism is precipitation into the atmosphere. One of the more intense and deeply penetrating precipitation types is relativistic electron precipitation (REP) which represents the high energy electron population of the radiation belts.. REP can be driven by several processes that are linked to structures in the plasmasphere. EMIC waves, plasmaspheric hiss, and chorus have all been linked to electron precipitation processes that are focused on, inside, and outside the plasmapause. In this work package we will expand the AARDDVARK network to produce a series of quasi constant *L*-paths monitoring through which we will monitor the occurrence and properties of REP. Riometers and AARDDVARK data will be used to characterize the precipitation flux from the separate regions of the plasmasphere (plus some information on the energy spectrum provided by POES satellite observations) through the use of the density and structure information provided by the plasmasphere model under development in workpackage 3. Significant modeling efforts are required to "back out" precipitation fluxes from the AARDDVARK network observations. Our recent studies have shown we have the necessary approaches to do this [e.g., Rodger et al., 2007; 2008] and with pre-modelling preparation activities, to be lead from the University of Otago, we will be in a position to determine the properties of the REP events associated with the different regimes of the plasmasphere.

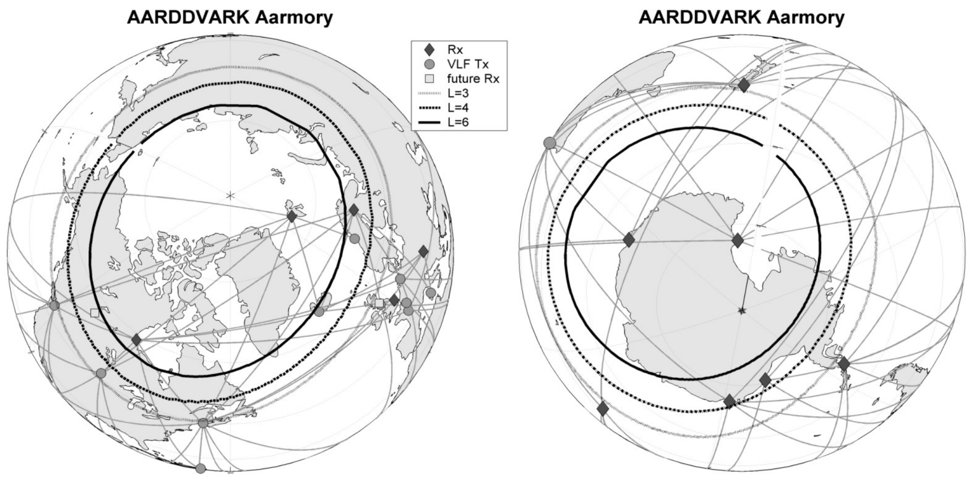
The AARDDVARK network [Clilverd et al., 2009a] has recently been used to specifically investigate the efficiency of the individual loss processes associated with plasmaspheric hiss and EMIC waves, using the network's sensitivity to REP as a critical element in the analysis of geomagnetic storm-induced precipitation [Rodger et al., 2007; Clilverd et al., 2007; Rodger et al., 2008, Clilverd et al., 2009b]. In the next few paragraphs we discuss the investigation of plasmaspheric hiss, EMIC, and REP in detail to highlight the effectiveness of the AARDDVARK network in this type of investigation.

Rodger et al. [2008] used an AARDDVARK transmitter-receiver path that crossed the north Atlantic Ocean at a quasi constant L~3 to study the impact of a geomagnetic storm on electron losses induced by processes taking place inside the plasmapause. Analysis of the AARDDVARK data showed that electron precipitation occurred for ~10 days after the onset of the geomagnetic storm, lasting well after geomagnetic activity levels had returned to quiet values. The study also showed that the daytime precipitation fluxes were significantly higher than the nighttime fluxes, which is consistent with the MLT distribution of plasmaspheric hiss wave power, identifying hiss as the most likely source of the wave-particle interaction loss process. Rodger et al. also showed proof of concept for techniques to determine the flux of REP from AARDDVARK data.

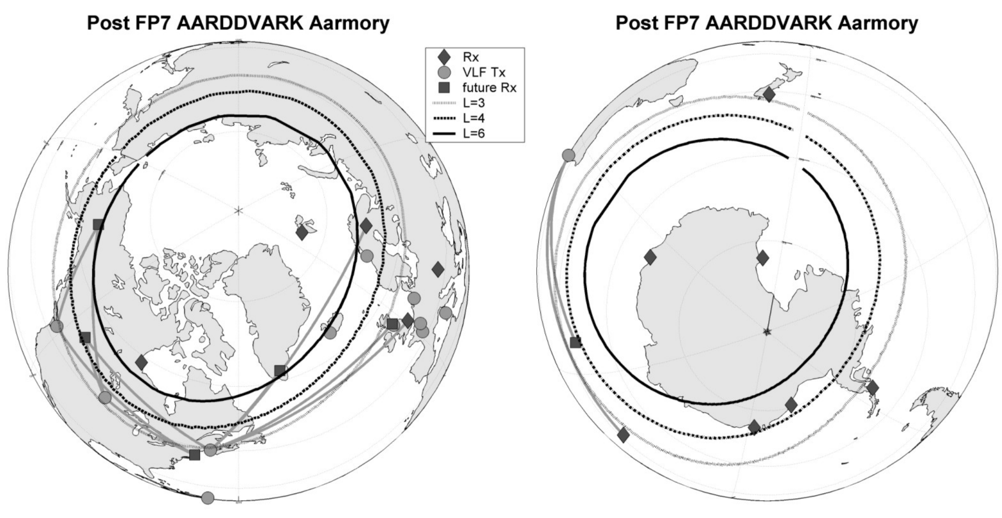
To the best of the authors' knowledge, it is only very recently that experimental evidence has been presented that demonstrates the link between EMIC activity and REP. AARDDVARK measurements made during a large geomagnetic storm on 21 January 2005 detected a 50 min precipitation event which peaked at the same time as a Pc-1 EMIC wave detected at *L*=3.4, probably associated with the location of the eroded plasmapause [Clilverd et al., 2007]. Further evidence comes from POES satellite observations during a moderate geomagnetic storm in which regions of 30-80 keV proton precipitation were found to be co-located with those of relativistic electrons (>1.5 MeV) [Sandanger et al., 2007], consistent with EMIC-driven precipitation of both low-energy protons and highly energetic electrons.

Relativistic precipitation events lasting minutes to hours have been previously observed from the MAXIS balloon. They occured at about *L*=4-7, were observed in the late afternoon/dusk sector, and could be produced by EMIC waves [Millan et al., 2002]. The mechanism that was proposed suggested that relativistic electrons would be rapidly driven into the bounce loss cone through interaction with electromagnetic ion cyclotron (EMIC) waves, which can resonant with relativistic electrons for some plasmasphere conditions [Summers and Thorne, 2003]. Loss rates suggest that these minute-hour events are the primary loss mechanism for outer zone relativistic electrons. EMIC waves occur in the Pc1-Pc2 frequency range (0.1-5 Hz) and are generated near the magnetic equator by unstable distributions of ring current ions. The waves can propagate away from the generation region roughly along the geomagnetic field lines and can also be observed on the ground [Erlandson

et al., 1996]. For at least 3 decades multiple theoretical studies have demonstrated that EMIC waves should be an effective mechanism for loss of >1 MeV electrons from the radiation belts in regions of increased magnetospheric particle density [Engebretson et al., 2008, and references therein].
Further confirmation of REP generated by EMIC waves has come from more recent subionospheric VLF observations from the AARDDVARK network. A series of case studies have been presented from the Finnish sector combining multiple ground-based observations linking EMIC to relativistic precipitation [Rodger et al., 2008].



Existing AARDDVARK network



Extended AARDDVARK network (showing only the appropriate quasi-constant L paths associated with inside and outside the typical plasmapause location *L*~4), with the extensions to occur through this FP7 project

Events showing EMIC waves, observed by ground-based pulsation magnetometers, were shown to be linked to strong responses in the subionospheric precipitation monitor. This instrument response reported in the Rodger et al. [2008] study was consistent with precipitation occurring near the plasmapause, where EMIC waves may resonate with relativistic electrons [Meredith et al., 2003]. During these events there were only small responses in the Finnish riometer chain measurements, consistent with relativistic precipitation causing peak ionization enhancements well below the altitudes where riometers are most sensitive. Modelling presented in this study

showed that the instruments response was consistent with an ionospheric modification is caused by the precipitation of 2 MeV monoenergetic electrons with flux 500 el. $cm^{-2}s^{-1}str^{-1}keV^{-1}$ [Rodger et al., 2008], that is a >10 dB amplitude decrease in the AARDDVARK data, accompanied by only a <0.2 dB increase in riometer absorption.
These studies show that EMIC, and plasmaspheric hiss, (and in future other VLF waves) can be strongly linked to intense relativistic electron precipitation, as expected by previously reported theoretical modelling, and also highlight the potential of the AARDDVARK data. Using the AARDDVARK data as described in this project will allow us to bring together the plasmasphere product of work packages 1, 2, and 3 with an electron precipitation monitoring network. This synergy will provide qualitative measurements, and near real-time monitoring, of the impact of plasmaspheric structures on radiation belt electron loss processes.

Impact

1 Expected impacts listed in the work programme

Research towards operational Space Weather Models is currently a global effort underway in many parts of the world, most notably in the USA, Japan and Europe. The outstanding problem for any operational system is the provision of global, useful and on-going data sources for space physics models. "Global", by the simple nature of our system where any ground-based station samples one local time, requires data contributions from many local time sectors at the same time - requiring participation not only across Europe but across the world. Most of the current development of operational space weather systems is undertaken in Europe and the USA, with radiation belt models currently most advanced in the USA. The modeling work in this project represents an areas currently not being undertaken elsewhere, opening the possibility of a leadership role in this work for European researchers. As *security of space assets from space weather events* is a global challenge and thus difficult to confine any activity into the EU, therefore – completely conforming to the *call -,* we will involve partners from other space-faring nations (USA, New Zealand, and South Africa) as well as IPCP partner (South Africa). Without their specific expertize or the utilization of their special geographic (geomagnetic) location(s), the project objectives cannot be achieved.

As a result of S/T efforts in the project, we will establish a complex chain of data services and models that are capable of prediction and forecasting specific space weather events. But all three layers (see Section 1.3.1) will provide autonomous output alone, that can be integrated into various existing or planned space weather models or services: the data provide by layer 1 can be directly used for modeling wave-particle interactions in many space weather related investigations; the plasmasphere model extends the spatial and temporal limits of these investigations to the whole plasmasphere and beyond, while layer 3 provide new information on REP characteristic not achievable by other means. All these data, models and information will significantly contribute to European capacity to estimate and prevent damage of space assets from space weather events as well as to improving forecasting and predicting of disruptive space weather events.

The main target addressed in the corresponding section of the work programme (Area 9.2.3: Research into reducing the vulnerability of space assets; SPA.2010.2.3-01 Security of space assets from space weather events) was **space storms** (particle, plasma and electromagnetic) and the expected impact was the development of a more accurate prediction, assessment and early warning capability. Results are expected in the following areas:

1. early warning and forecasting methods to allow for a mitigation of space weather effects on humans in aerospace vehicles and on vulnerable technologies in space (in particular satellites, communication and navigation systems) and on the ground (communication and power nets).

2. countermeasures to avoid or mitigate possible harmful space weather effects on humans and technological systems (including life science experimentation).
3. space weather models to improve specification and prediction capabilities, with emphasis on the linkage of the different physical processes that occur simultaneously or sequentially in many domains

Our project will be able to significantly contribute to all the three areas listed above:

Ad 1.: modeling REP losses (a major hazard for space electronics) combined with prediction capability of our plasmasphere model is able to forecast space weather events and this forecast can be used in mitigation plans.

Ad 2.: our results will contribute to plan countermeasures to avoid or mitigate possible harmful space weather effects on the way described above

Ad 3: the data-assimilative plasmasphere model that will be developed in the project has highly improved specification and prediction capabilities for the plasmasphere and inner magnetosphere linking the overlapping regions: the 'cold' plasmasphere, the 'warm' ring current and the 'hot' radiation belts, allowing better modeling of the physical processes interconnecting these domains

No such or even similar service or method exists in ESA member states, no complex service or method is currently in the list of space weather-related assets of ESA compiled for the ESA SSA programme. Thus the project will provide a significant added value to both EU and ESA efforts and is complementary to them in all senses.

The data, models and forecasting capabilities will be available for European and international actors in the field.

2 Dissemination and/or exploitation of project results, and management of intellectual property

2.1 Dissemination of project results.

We are planning **five** ways to disseminate the results of the project:

1. the activity planned in the project is in a transition phase from pure research to applications, but the major emphasis is still on research, therefore the most important way to disseminate the results is to communicate them on scientific journals. We will publish the results synchronized with the projects schedule in major journals in upper atmospheric physics, space weather and space research, such as Journal of Geophysical Research, Geophysical Research Letter, Space Weather, Journal of Atmospheric and Solar-Terrestrial Physics and Advances in Space Research. We foresee 10 publications in these journals connected to the project, 5 during the project term, 5 after the end of the project (this is partly because the publication procedure usually takes months or even years)
2. because the publication in scientific journals are slow, the best way for prompt dissemination is to communicate them on scientific conferences. We are planning to attend on such conferences and workshops and present the results obtained in the project, both on large meeting such as URSI, IAGA, EGU, AGU and on topical meetings such as VERSIM and HEPPA. We foresee at least 30 presentations at conferences.
3. beside general scientific meetings, we will organize a workshop *dedicated* to the project results on the second half of the project term open to the scientific community, we plan to organize this workshop as an additional day at the VERSIM workshop or IAGA SA or organize a workshop through ISSI and make use of their facilities.
4. we consider very important to disseminate the results not only in the scientific community, but for the general public as well. Therefore we will publish popular papers in the local media of participating countries, we foresee 10-12 such a publication and we will also present our results to general audience

on various events and will incorporate them to lectures at university courses.

5. finally we will setup a web page for the project, it will contain general information about the project and the summary of the results obtained in different phases of the project. The web page will serve for internal communication and data sharing during the project. At the end of the project, selected data will also published for the scientific community.

2.2 Exploitation of project results

The exploitation of the results can be complex and diverse. The first exploitation will be immediately inside the project, the data provided as an output of WP1 and WP2 will be used by the models in WP3 and WP4, the plasmasphere model itself, developed in WP3 will also be used as an input for understanding the drivers and occurrence of the losses of the radiation belts as described in WP4. The results in science will be utilized by the whole scientific community (the various methods developed to obtain plasmaspheric densities) as well as the data themselves, they will be used in forthcoming studies related to plasmasphere, magnetosphere, radiation belts, upper atmosphere and space weather. The models developed during the project will be used for investigation space weather events, in prediction and forecasting space weather. Beside the expected bold impact on science and the exploitation followed by related to project, the major area of exploitation is expected to be the incorporation of the results and data into the space security programs, first of all, the European ESA SSA program, that could be the first beneficiary of an operational service built on the results of the project.

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