Data assimilation with plasmaspheric density measurements from VLF whistlers: preliminary results

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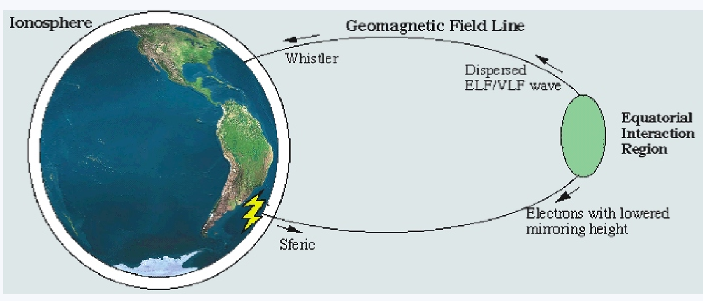
Abstract AWDANet is a global network for monitoring the plasmasphere. It consists of 15 ground stations automatically detecting VLF whistlers and performing automatic inversion on GPUs. The algorithm yields real-time plasmaspheric electron densities. Another source of data used here is ground based measurements of magnetic field line resonances (FLR), obtained from magnetometer arrays, such as the European quasi-Meridional Magnetometer Array. These data are fed into a data assimilation process which combines models and observations, to arrive at the most probable model of the plasmasphere. This poster presents an event study of a specific storm event from 2012.

Electron Densities from Whistlers

- Whistlers are VLF (3-30 kHz) impulses generated by lightning, traveling along magnetic field lines, observable on the ground and/or in space.
- Through propagation in the plasma content of the magnetosphere, they acquire a frequency-time signal with a characteristic shape
- The time delay depends on the plasma density along the propagation path (it is also frequency dependent, causing their typical curved shape, see fig 1.)
- Therefore, whistler measurements can tell us about the plasma density in the plasmasphere



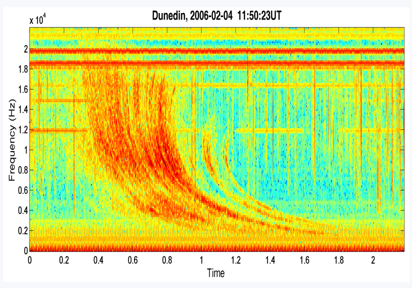


Fig. 1 Spectrogram of a typical whistler group

Whistlers have been regarded as cheap and effective tools for plasmasphere diagnostics since the early years of whistler research, but have never been routinely used, since the extraction of equatorial densities was very labour intensive. Recently (between 2002 and 2014) an Automatic Whistler Detector and Analyzer Network (AWDANet) was developed which is capable of automatically detecting and analysing whistlers [1].

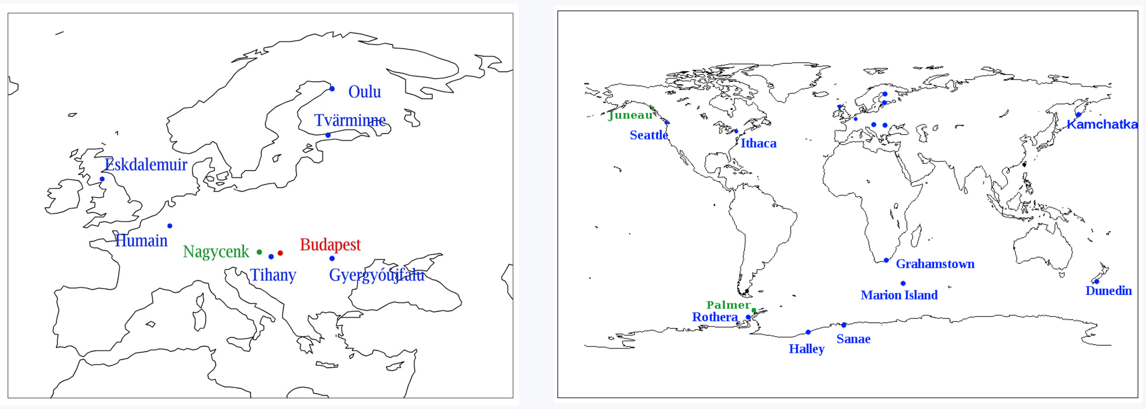


Fig. 2 Distribution of existing and planned (green) Automatic Whistler Detector and Analyzer Network (AWDANet) stations in Europe and around the world.

Data for 2012 July storm event

We identified a storm event with relatively good data coverage (see fig. 7) from all sources currently used by our data assimilation model. The investigated period is 12-21 July 2012.

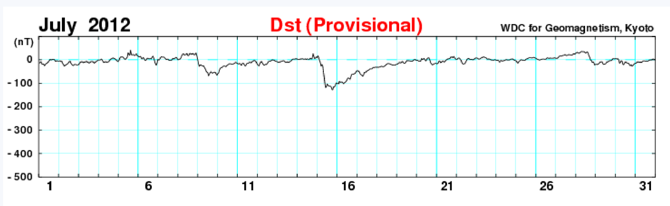


Fig. 3 Dst indices for the investigated period

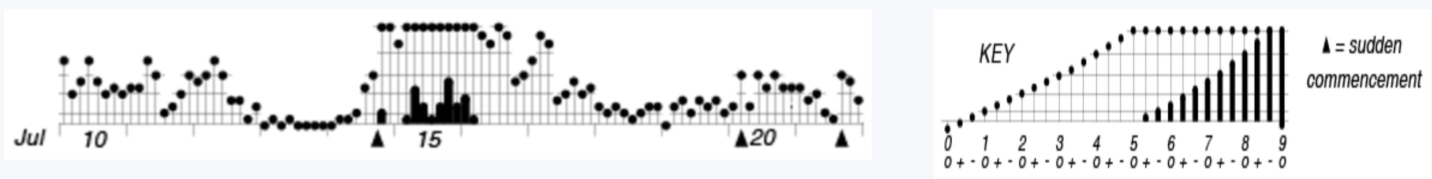


Fig. 4 Kp indices for the investigated period

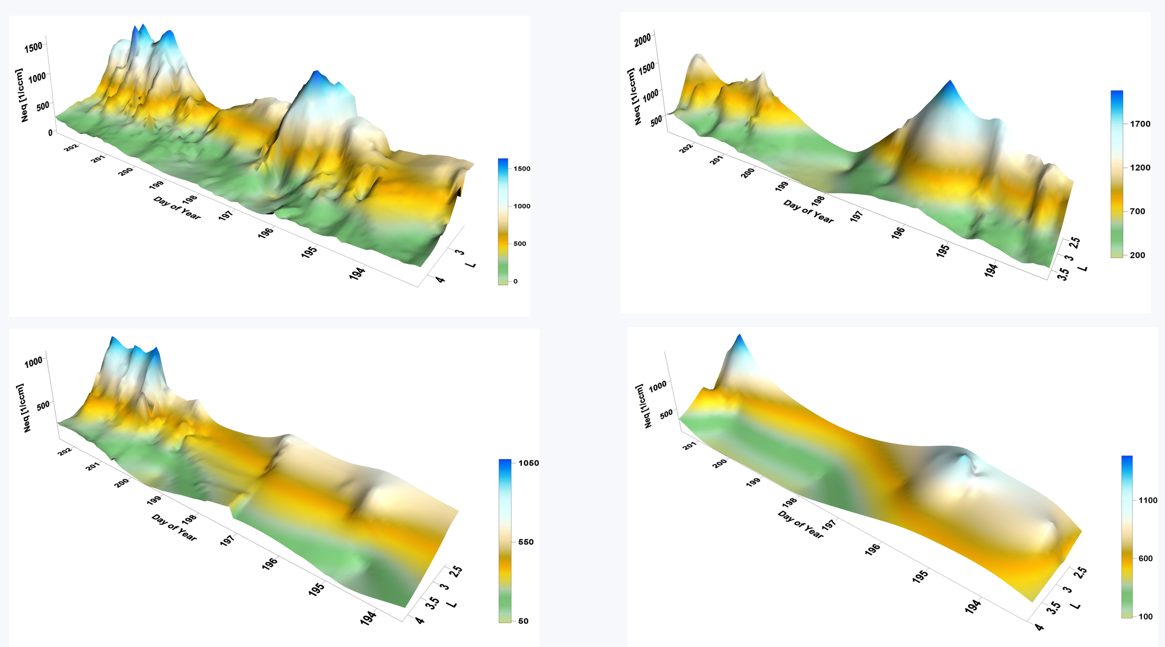
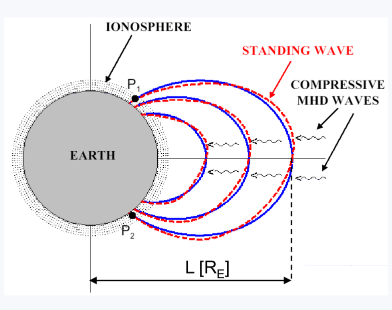


Fig. 5 Data obtained by whistler inversion from 4 AWDANet stations: equatorial radial density profiles corresponding to 4 different longitudes, as a function of time (day of year, increasing right to left, DOY 196 is July 15).

Mass Densities from Magnetometer Arrays

Field line resonances (FLR) are transversal standing waves of the magnetic field lines fixed into the ionosphere at their ends, caused by compressive MHD waves. From the detected resonance frequency the equatorial plasma mass densities can be inferred.



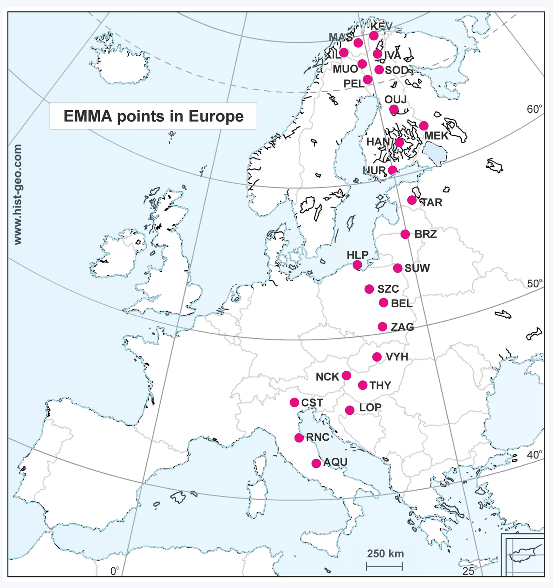
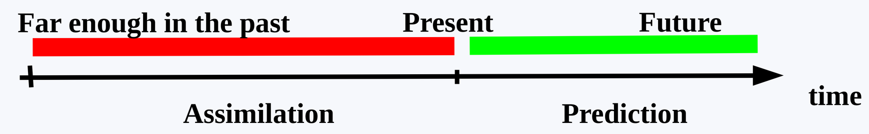


Fig. 6 The European quasi-Meridional Magnetometer Array (EMMA) network.

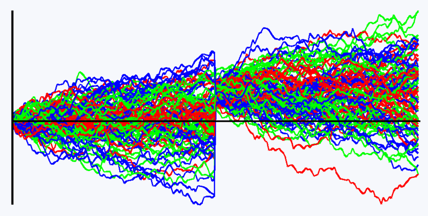
The European quasi-Meridional Magnetometer Array (EMMA) was established in 2012 with the main goal of monitoring plasmaspheric mass densities based on the detection of geomagnetic FLRs. FLRs are detected by applying the phase gradient technique [2] to data recorded at two closely spaced (100–300 km) stations. The PLASMON inversion code solves the MHD wave equations in a realistic magnetic field (Tsyganenko model) topology. Having a meridional chain of magnetometers the whole dayside plasmasphere as well as the plasma trough can be monitored. Also, dayside FLR data complements the data obtained from whistlers, which predominantly occur on the nightside.

Assimilative Model of the Plasmasphere

- Data assimilation combines models and observations to arrive at the best specification of a state.
- Data assimilation is the de-facto standard approach to conditioning weather models for weather prediction, e.g.



- Data assimilation does not forecast, but it can be used to constrain the state from which a prediction is run with known (or more often guessed) model drivers.
- Data assimilation is expressed in Bayesian way: a sprobability distribution evolvesthrough time, determined by
  - (1) The range of possible evolution, taking into account the probability distribution of unknown physics and drivers which are not measured.
  - (2) Measurements which partially constrain the model and thus eliminate some possible evolutionary paths
- Example:
  - A plasmasphere model might implement quiet and storm time behavior, and without other knowledge (e.g. solar wind or observations in the plasmasphere) all scenarios are included in the probability distribution
  - A satellite at L=5 observes it is not in the plasmasphere, so all evolution which places the plasmasphere at or beyond L=5 can be eliminated.
- Useful data assimilation narrows the probability distribution.



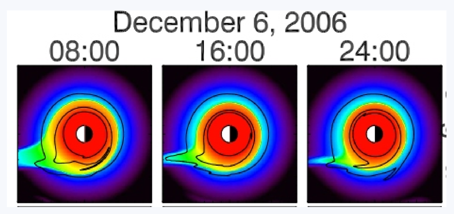
- Bayesian calculations are computationally intensive so in practice we choose simplifications
  - Kalman Filter – when the model is linear and noise is Gaussian
  - Ensemble Kalman Filter – Monte Carlo approximation to KF (used in this study)
  - Particle Filter – Monte Carlo approximation to Bayesian
  - Etc.....

Dynamic Global Core Plasma Model

- 2D single species model of the plasmasphere (e.g. Ober et al. [3])

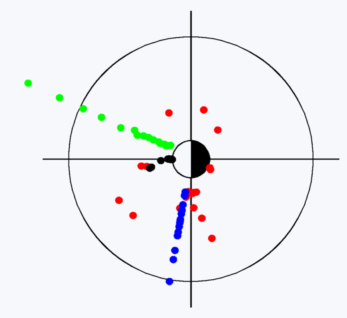
$$\vec{B}\,(\vec{r}) \qquad \vec{E}\,(\vec{r})$$

$$F_n = -\frac{NB_i}{\tau} \qquad F_d = \frac{n_{\text{sat}} - n}{n_{\text{sat}}} F_{\max} \qquad \frac{D_\perp N}{Dt} = \frac{F_N + F_S}{B_i}$$



Assimilative Run for 2012 July Event

Data sources used so far



- EMMA magnetometer array (Central Europe)
- SAMBA magnetometer array (South America west coast)
- McMac magnetometer array (North America central)
- AWDANet VLF stations

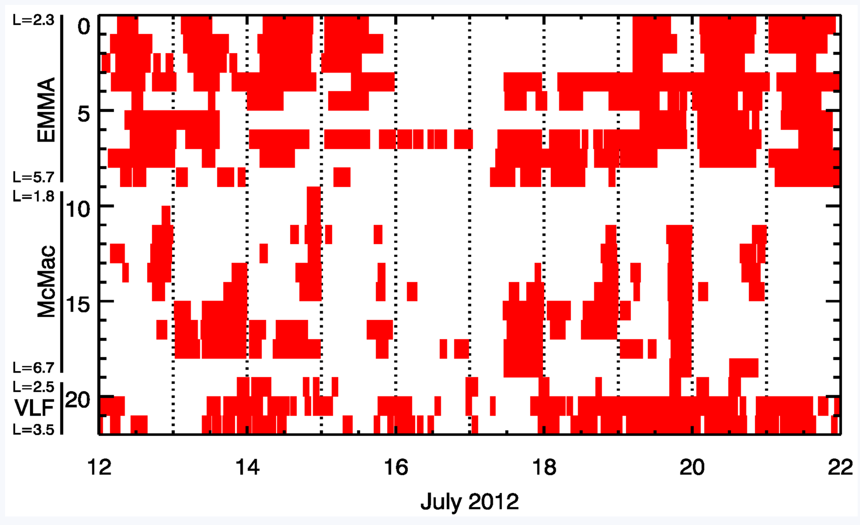


Fig. 7 Data coverage for the analyzed event

Data sources used in this study:

9 EMMA pairs
10 McMac pairs
~~3~~ 5 VLF stations

Large gaps, very little coverage at outer L-shells

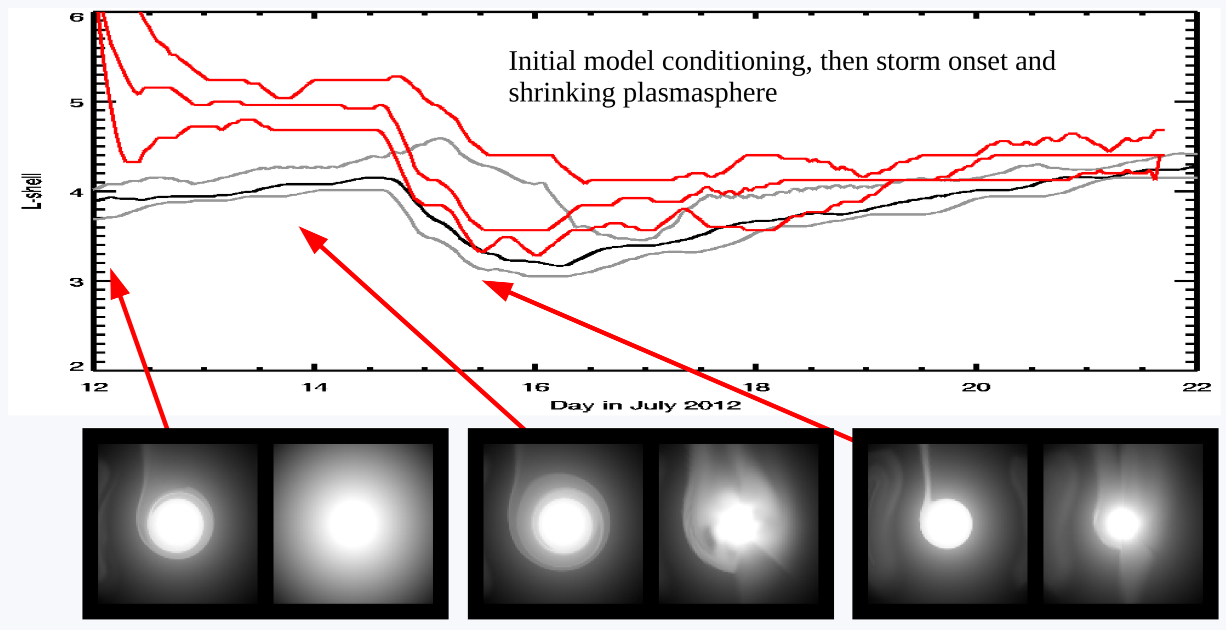
Result of the model runs

Figs. 8-9

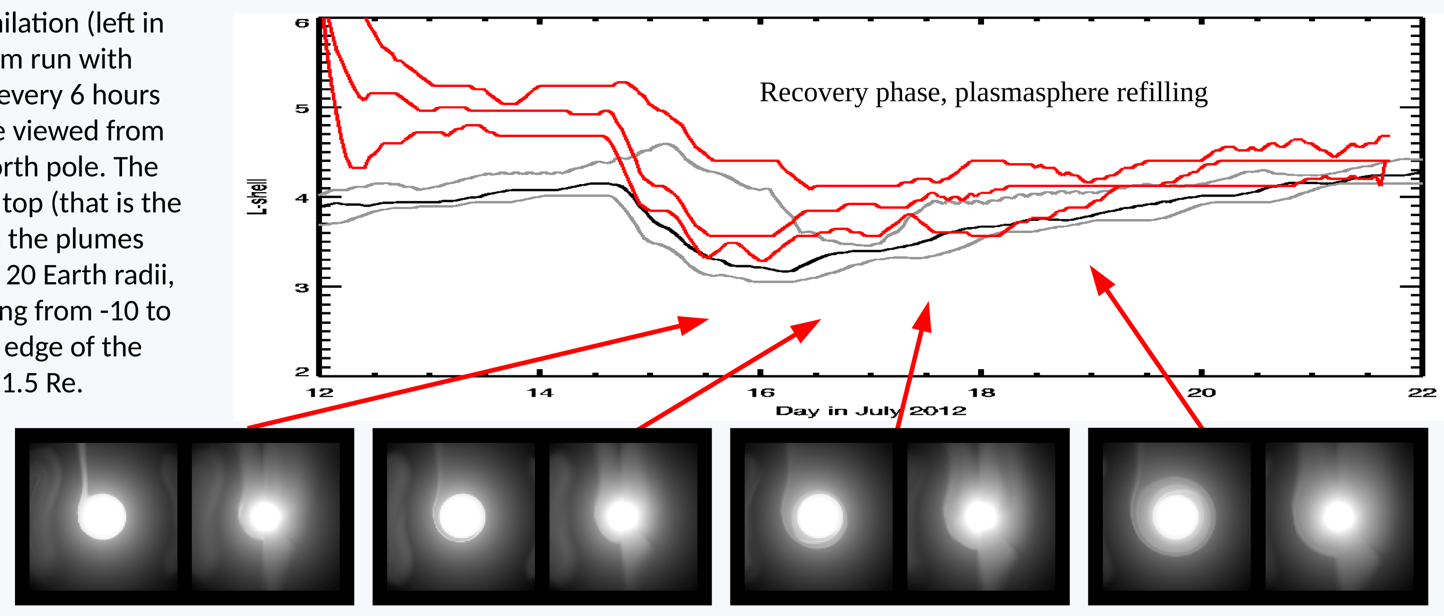
Graphs indicate plasmapause locations during the event.

Black/grey: median and range over MLT of plasmapause locations from non-assimilative model run.

Red: median and range over MLT of plasmapause locations from data assimilation run with ground-based observations.



Images are equatorial density maps, obtained from reference run without assimilation (left in each pair) and from run with data assimilation every 6 hours (right). Images are viewed from high above the north pole. The Sun is toward the top (that is the direction in which the plumes flow). Each side is 20 Earth radii, coordinates running from -10 to +10 Re. The inner edge of the model space is at 1.5 Re.



Conclusions

- Data assimilation is the correct approach to obtaining the plasmasphere state from limited observations. By definition, combining all available information gives best results. It is a way to combine direct observations of plasma density, boundaries, images, empirical and statistical models, etc. Difficulties: bad data or calibration can bias the results, model uncertainty and data uncertainty must be well-understood, model must be sufficiently flexible to represent real plasmasphere evolution. Practical problems to be addressed before improving models and assimilation procedures: inter-calibration and weighting of different data types, studying and adjust saturation and inflow/outflow. Also, event studies involving larger data sets.

References

[1] J. Lichtenberger, C. Ferencz, D. Hamar, P. Steinbach, C. J. Rodger, M. A. Clilverd, and A. B. Collier. Automatic Whistler Detector and Analyzer system: Implementation of the analyzer algorithm. Journal of Geophysical Research, 115:A12214, Dec. 2010. doi: 10.1029/2010JA015931.

[2] L. Waters, F. W. Menk, and B. J. Fraser. The resonance structure of low latitude Pc3 geomagnetic pulsations. Geophysical Research Letters, 18(12):2293–2296, 1991. doi: 10.1029/91GL02550.

[3] Daniel M. Ober, J. L. Horwitz, D. L. Gallagher. Formation of density troughs embedded in the outer plasmasphere by subauroral ion drift events. Journal of Geophysical Research, 102, p. 14595, Jan. 1997. doi: 10.1029/97JA01046

Acknowledgements

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