Auroral Electrodynamics on Arc and Oval Scales: Insights from a New Technique

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Abstract

Basic features of the auroral oval, on the large scale, and of the auroral arc, on medium to small scales, can be understood with a highly idealized model, where the oval or arc is assumed to be a stripe of uniformly enhanced conductance, associated with a specific system of currents. Field-aligned currents (FACs) in and out of the ionosphere are connected across the oval/arc through Pedersen current, while a divergence free electrojet flows in azimuthal direction as Hall current. Most of the time, however, the experimental data show a complicated interplay between the ionospheric conductance, electric field, and current, which points to the need for more realistic models. In order to take full advantage of the measured data we developed the ALADYN method, originally designed for the higher conductance regions close to and within the arc. Here we present the extension of this technique to downward current regions, both on large and smaller scales. The application of ALADYN to synthetic data enables the investigation of key oval features, like the relative location of the electric field (and plasma convection) reversal with respect to the FAC boundaries. By using ALADYN with arc related satellite data, we are able to examine the consistency of the results and evaluate the deviation of the real arc from the idealized model.

Outline

A. The ALADYN method

B. Arc electrodynamics – measured data

- Experimental setup
- Event 1: FAST Orbit 1859
- Event 2: FAST Orbit 1902

C. Oval electrodynamics – synthetic data

- Test configurations
- Convection versus FAC reversal

D. Summary

ALADYN Method

- The ALADYN (AuroraL Arc electroDYNamics) method enables a realistic description of an auroral arc (Marghitu, 2003; Marghitu et al., 2004). The method is based on a parametric arc model, that allows the derivation of the parameters by numerical fit to the experimental data. In order to obtain consistent results one can take into account the ionospheric polarization, the contribution of the Hall current to the meridional closure of the field-aligned current (FAC), and the coupling between the FAC and the electrojet (EJ) flowing along the arc.
- The processing of the current continuity equation at ionospheric level yields the fit equation:

$$\begin{gathered} H_x \tan\vartheta + \Sigma_P E_{0x} \tan^2\theta + \Sigma_P (1+\tan^2\theta) \sum_{i=1}^{n_x} a_i G_i + \\ (-\Sigma_H + \Sigma_P \tan\theta) b_0 \sqrt{1+\tan^2\theta} + (c_0 + c_1 x)\sqrt{1+\tan^2\theta} = H_y - \Sigma_P E_{0x} \end{gathered} \qquad (1)$$

where $a_1, \ldots, a_n$ are polarization coefficients, b_0 the Hall coefficient, c_0 a constant current to / from the polar cap, and c_1 the FAC–EJ coupling coefficient. $\tan\theta$ can be determined by fit or from magnetic field data, while n_x depends on the precipitation profile.

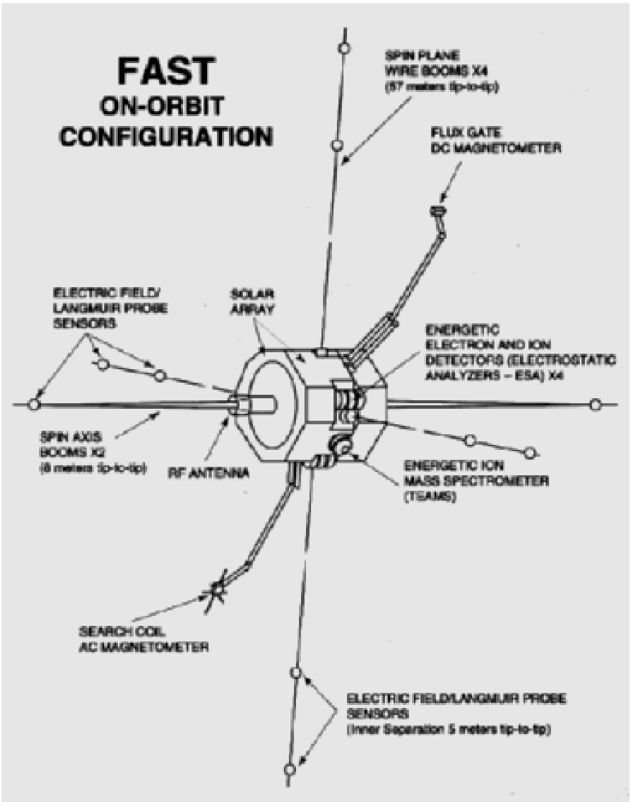
- Some of the parameters can be set to 0. Depending on this choice one obtains a hierarchy of models:

  No FAC–EJ coupling, $c_1 = 0$: NPNH(L), NPYH(L), YPNH(L), YPYH(L)

  FAC–EJ coupling, $c_1 \neq 0$: NPNHX(L), NPYHX(L), YPNHX(L), YPYHX(L)

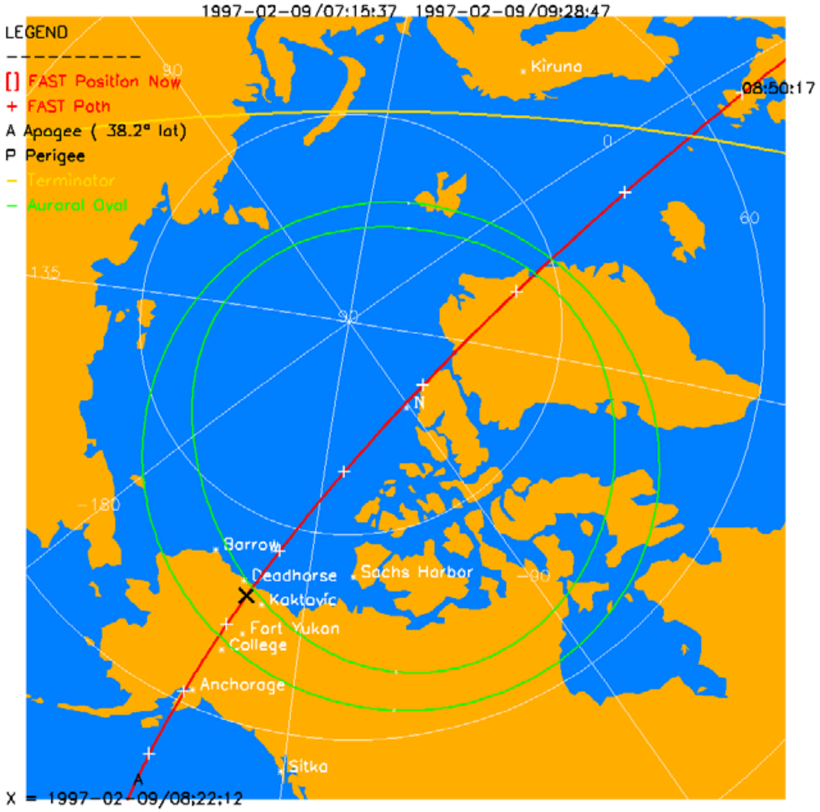
where: NP = No Polarization, $a_i = 0$; NH = No Hall, $b_0 = 0$; L = Linear, $\tan\theta$ from magnetic data

Arc Electrodynamics: Setup



http://www-ssc.igpp.ucla.edu/fast

- 2nd NASA SMEX Mission
- Launch: August 21, 1996, still operational
- Orbit: 351 x 4175km, 83^o
- Full set of plasma and field sensors



Magnetic noon at top; N=Magnetic pole

X=Arc Event 1: Deadhorse, AK, 70.22^o x 211.61^o

Time: Feb. 9, 1997, 8:22UT

FAST; Aur. Oval ; Terminator at 110km

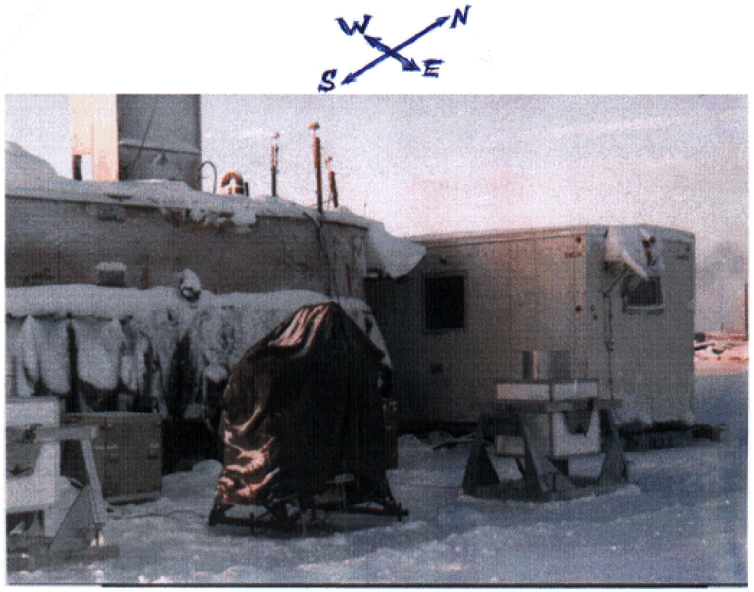
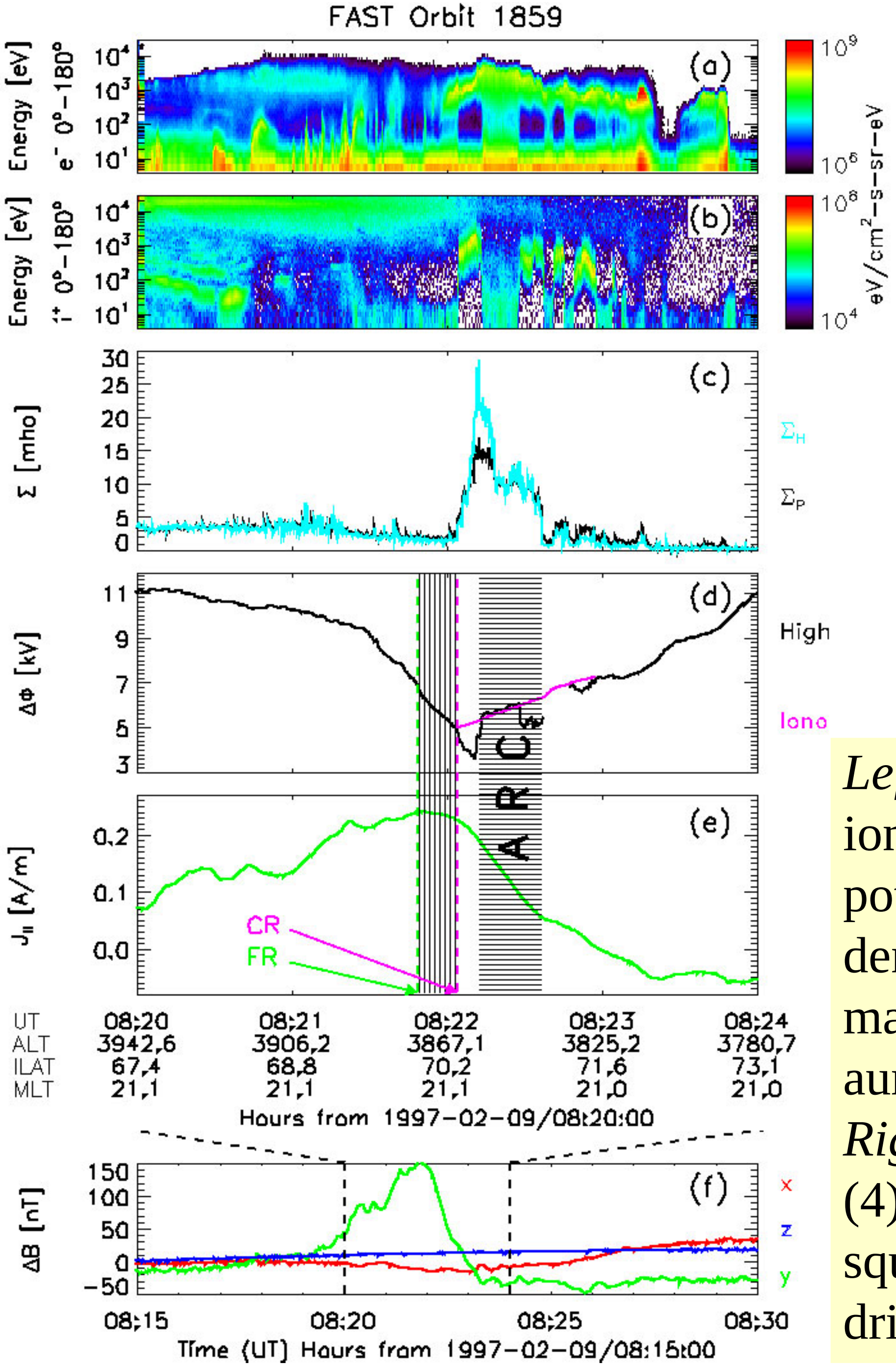
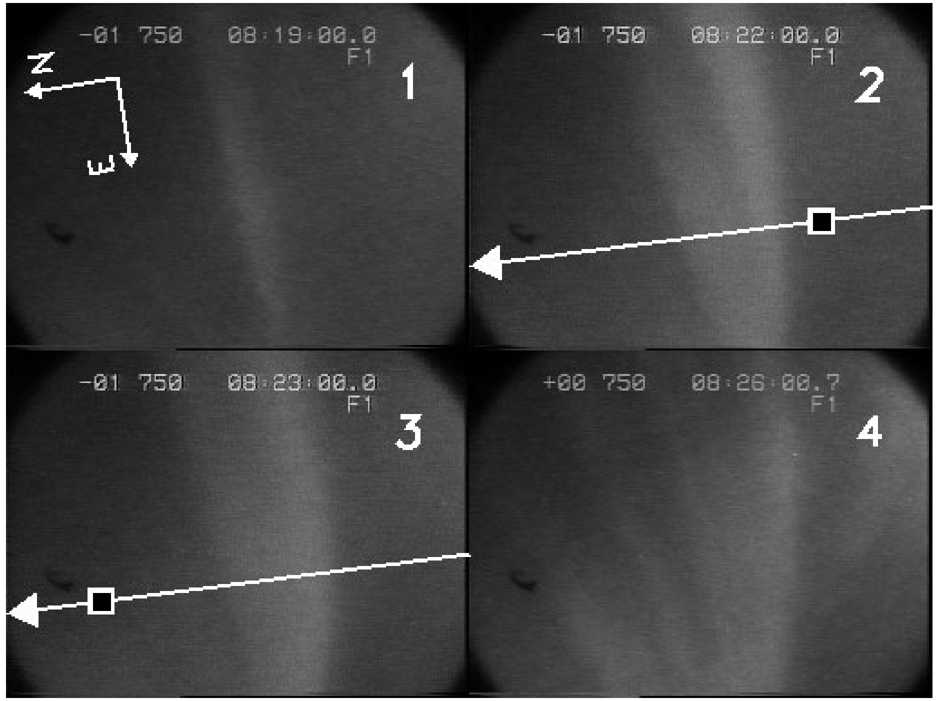


Photo: courtesy W. Lieb, MPE

- Low-light CCD cameras developed at MPE
- Wide-angle optics (86^{o}x64^o)
- Pass band filter, 650nm
- Exposure time 20ms
- Digitized images, 768x576x8

Arc Electrodynamics: Event 1 Data

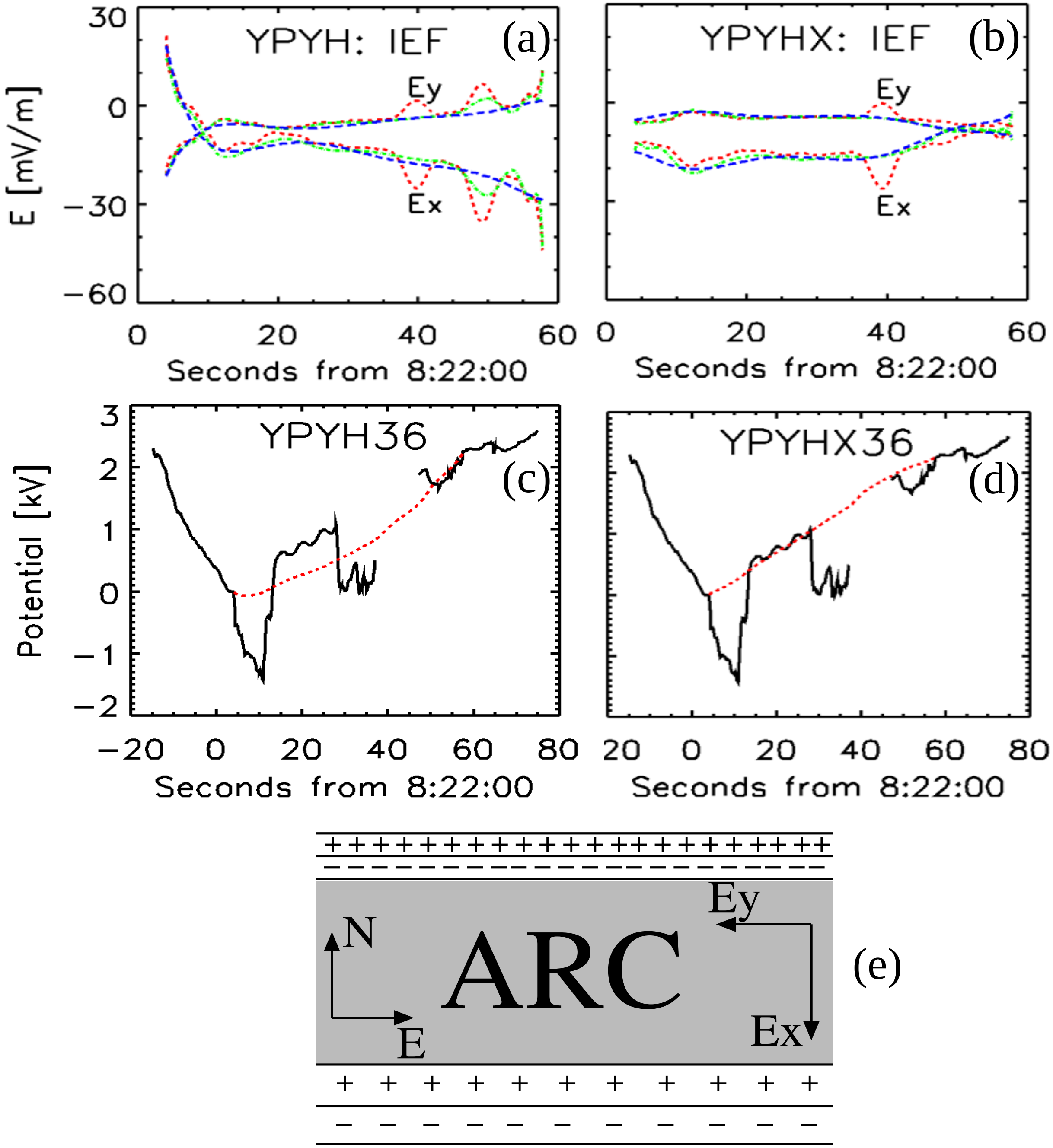




Left: FAST data. Electron (a) and ion (b) energy spectrograms; ionospheric conductance (c); high altitude and ionospheric potential drop along the satellite track (d); FAC linear current density mapped to ionosphere (e); large scale perturbation magnetic field (f). The convection reversal, FAC reversal, and auroral arc are indicated in the panels (d) and (e).

Right: Ground optical data before (1), during (2, 3), and after (4) FAST overpass. The satellite footprint is indicated with a square in the frames 2 and 3. Except for a ~200m/s southward drift, the auroral arc is stable during the 2min conjunction.

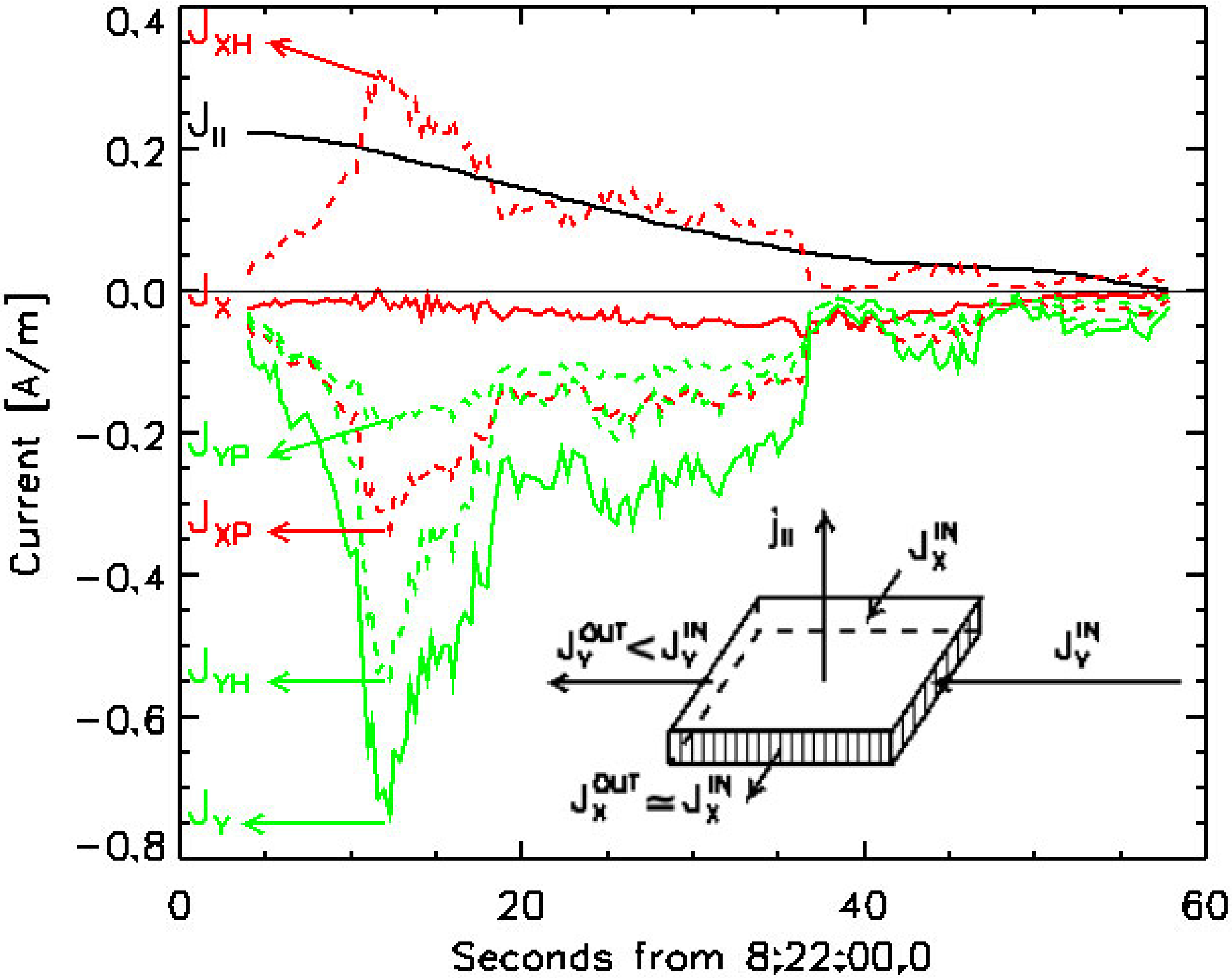
ℬ Arc Electrodynamics: Event 1 Results ℬ



The ionospheric electric field (IEF; a, b) and potential (c, d), as obtained by ALADYN, for the arc models YPYH (only the polarization and Hall terms are considered), and YPYHX (the FAC–EJ coupling is added). The IEF is shown for polarization length scales of 4 km (red), 8 km (green), and 20 km (blue).

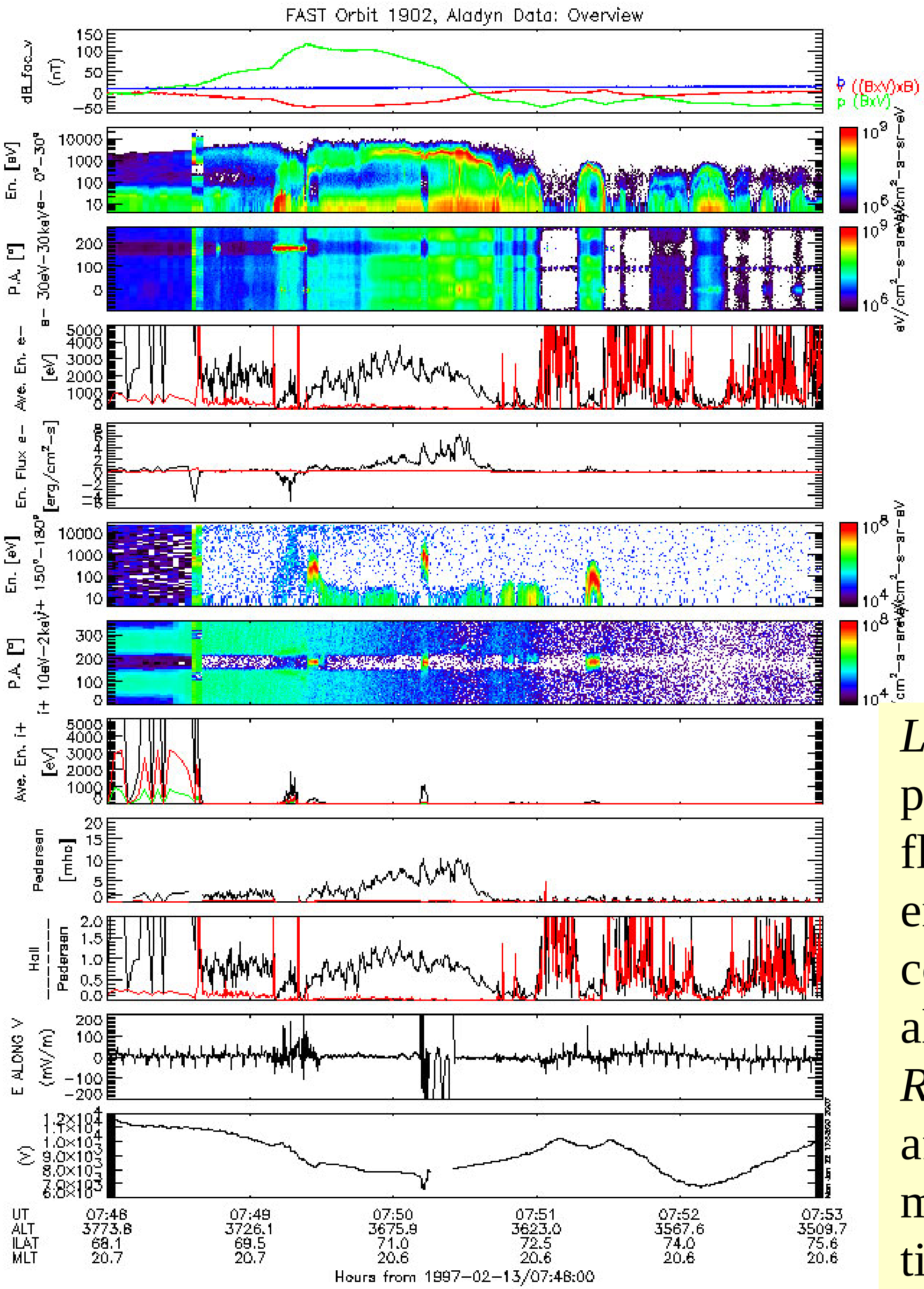
Outside of the ion beams the potential drops at FAST (black) and ionospheric level (red) match each other (as expected, because the magnetic field line is equipotential) for model YPYHX (d), but not for model YPYH (c). This is a key feature, pointing to the importance of the variations along the arc. The negative excursions of Ex at the arc boundaries indicate polarization charge double layers, as sketched in panel (e).

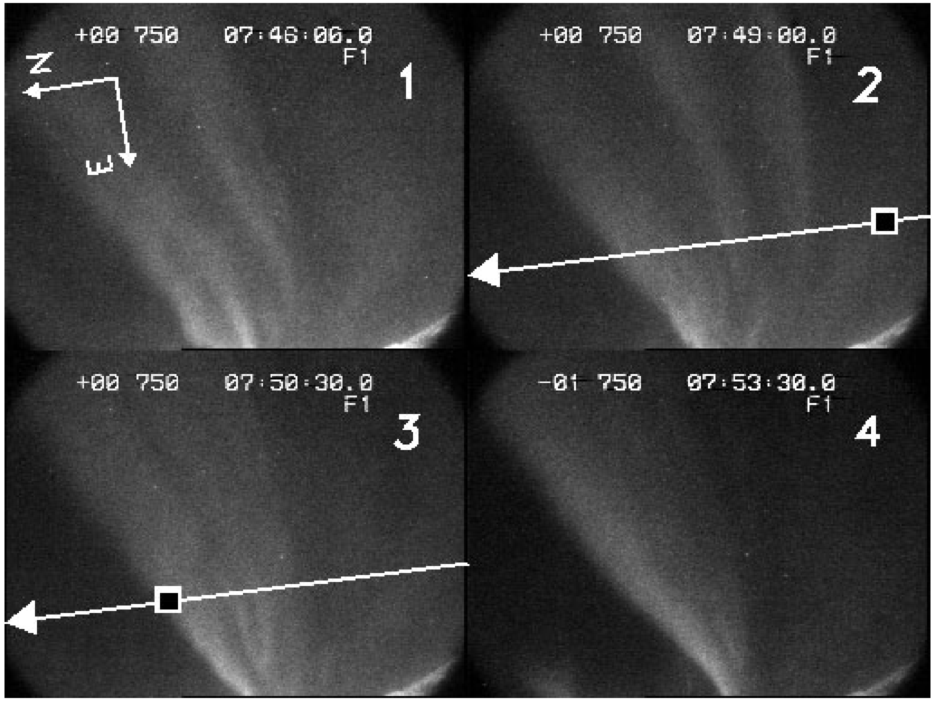
Arc Electrodynamics: Event 1 Results



Field-aligned and ionospheric sheet currents obtained by applying ALADYN between 8:22:04 and 8:22:58. The Pedersen and Hall components of the northward (red) and eastward (green) ionospheric current are shown with dashed lines. J_X almost vanishes near the CR, at the beginning of the interval, indicating quasi no ionospheric current transfer between the downward and upward FAC sheets.
The cartoon illustrates the current continuity, with the westward EJ feeding the upward FAC.

Arc Electrodynamics: Event 2 Data

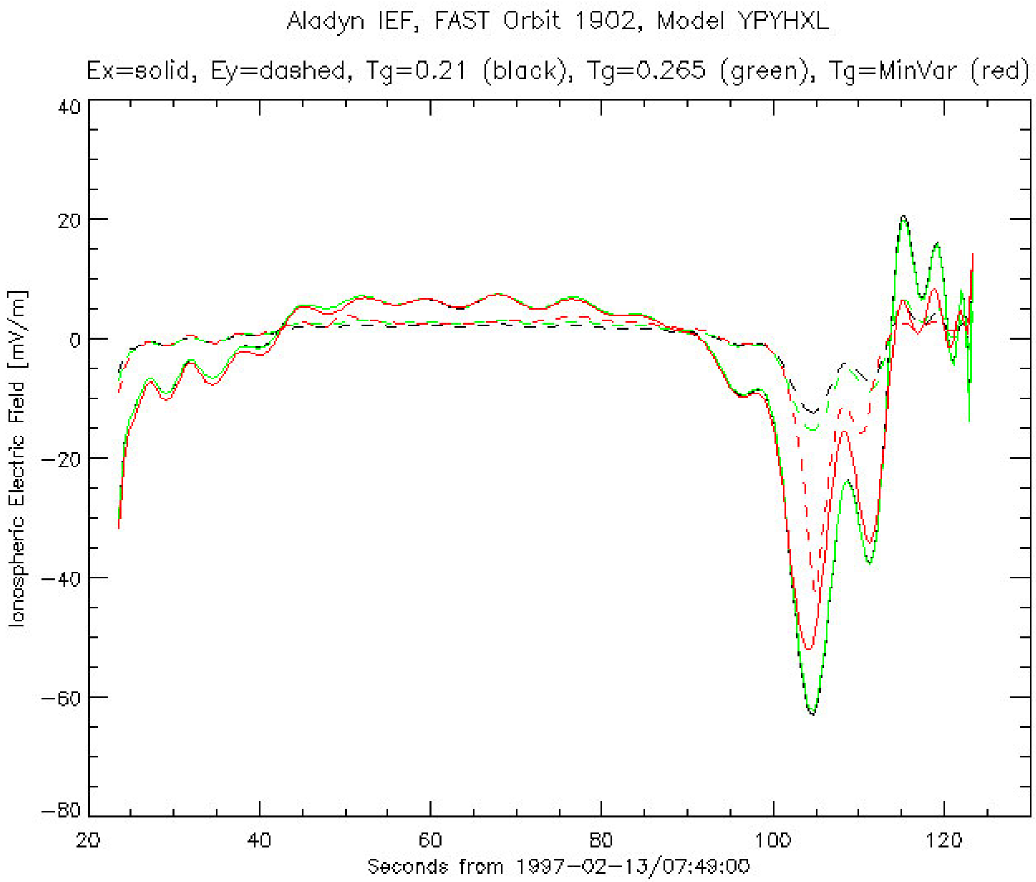


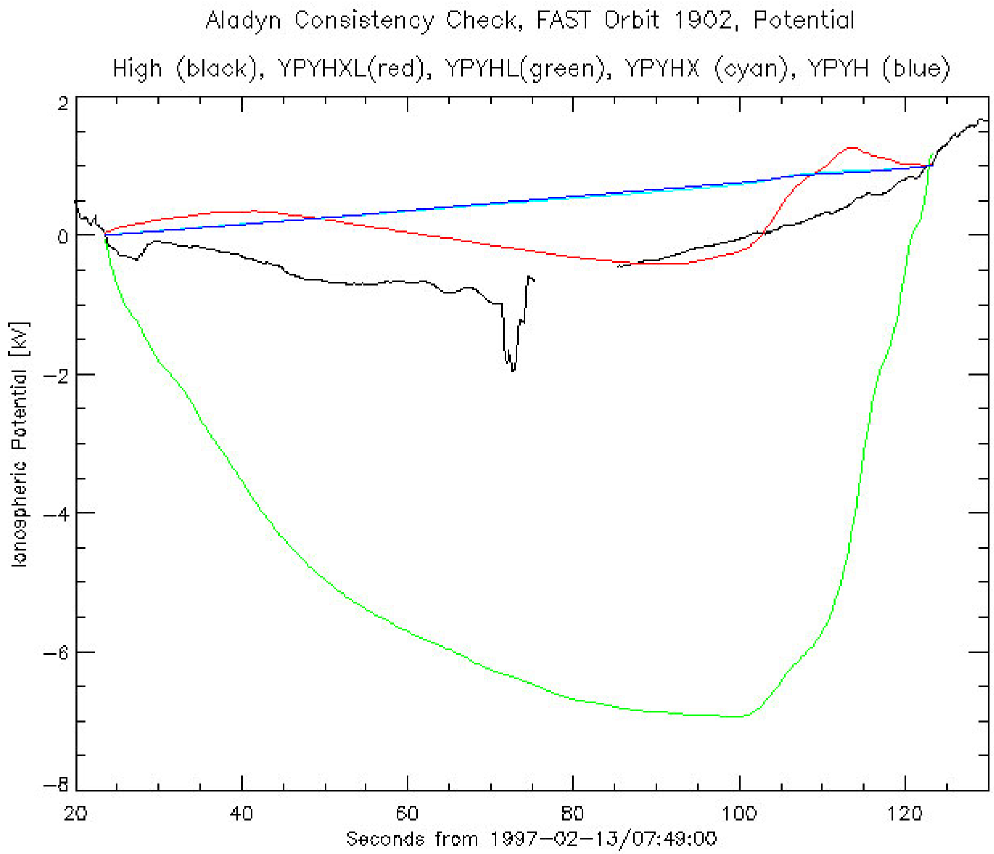


Left: FAST data: magnetic perturbation, electron energy / pitch-angle spectrograms, average energy, and energy flux; ion energy / pitch-angle spectrograms and average energy; Pedersen conductance and Hall to Pedersen conductance ratio; meridional electric field and high-altitude potential drop.

Right: Ground optical data before (1), during (2, 3), and after (4) FAST overpass. Compared to Event 1, the arc is more dynamic, but still reasonably stable on a minute time scale.

Arc Electrodynamics: Event 2 Results





Electric field (left) and potential (right) obtained by ALADYN for FAST Orbit 1902. The best results (even if not perfect) are provided by model YPYHXL. If the FAC–EJ coupling is neglected, the mismatch between the ionospheric and high-altitude potential is very large. Additional work is needed for a better tuning of the model YPYHXL, e.g. by dropping the very low conductance boundaries of the interval. The relation of the FAC and convection reversal is not as clear as for Event 1, but similar to Event 1 the arc is located in a region of southward IEF.

Oval Electrodynamics: Background

- The ALADYN method has been developed for arc intervals, where the conductance is high enough and the errors in conductance relatively low. In order to extend the method to oval scale, including downward FAC and low conductance regions, it is convenient to start with synthetic data, which offer full control of the conductance.
- Since the cross-check of the ionospheric and high altitude potential drop is not possible with synthetic data, we neglect, for the time being, the FAC–EJ coupling. By taking into account only the polarization and the Hall terms, and assuming $\tan\theta = 0$, the fit equation (1) reduces to (model YPYHL):

$$\Sigma_P \sum_{i=1}^{n_x} a_i G_i - \Sigma_H b_0 + c_0 = H_y - \Sigma_P E_{0_x} \qquad (2)$$

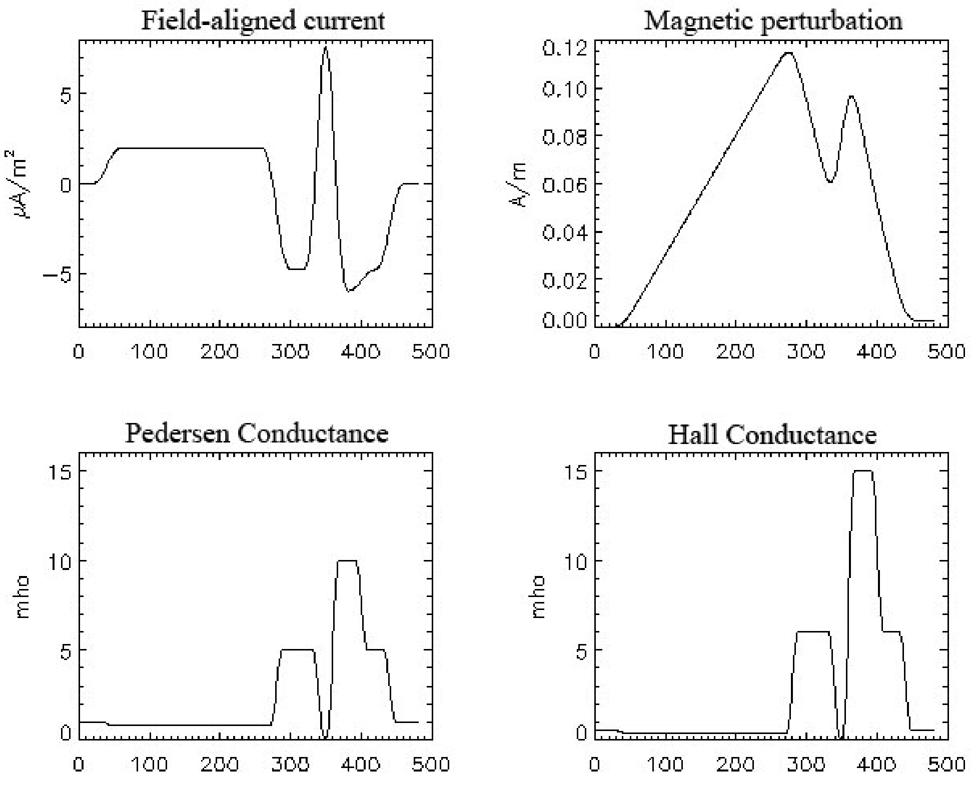
- The reduced fit equation is the integrated form of the first order differential equation satisfied by E_x, when the oval is assumed homogeneous in the East–West, y direction:

$$\Sigma_P \frac{dE_x}{dx} + \frac{d\Sigma_P}{dx} E_x = \frac{d\Sigma_H}{dx} E_y + j_z, \quad \text{with } E_y \equiv b_0 \qquad (3)$$

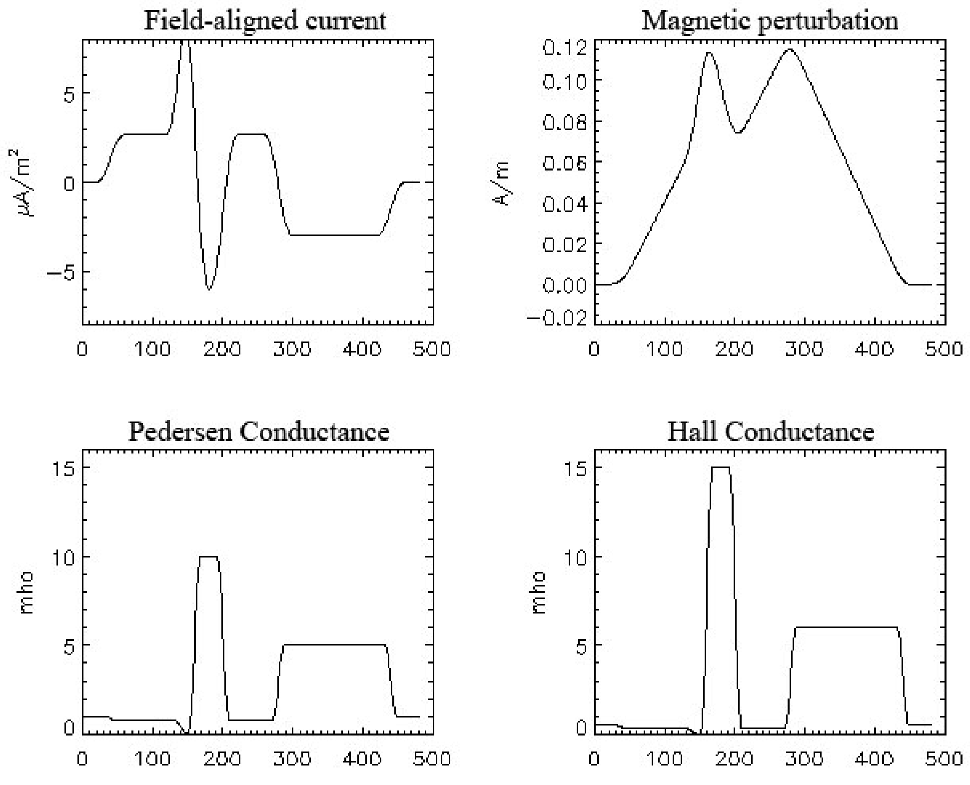
As emphasized by Karlsson (2001), if Σ_P, Σ_H, and j_z are known, and b_0 is fixed, one needs just another constant in order to uniquely determine E_x. This constant can be the value of E_x at a certain point, or the more robust average E_x in ALADYN applications.

- By using ALADYN with synthetic data it is possible to check the influence of various parameters on the relative position of the FAC and convection reversal. Starting from Eq. (2) ALADYN allows the evaluation of two models: YPNHb0, which keeps b0 constant, and YPYH. We apply ALADYN on two test configurations, consisting of balanced large-scale FACs (winter conditions), and balanced small-scale FACs, embedded once in the upward and once in the downward branch of the large-scale FAC.

C Oval Electrodynamics: Test Configurations C



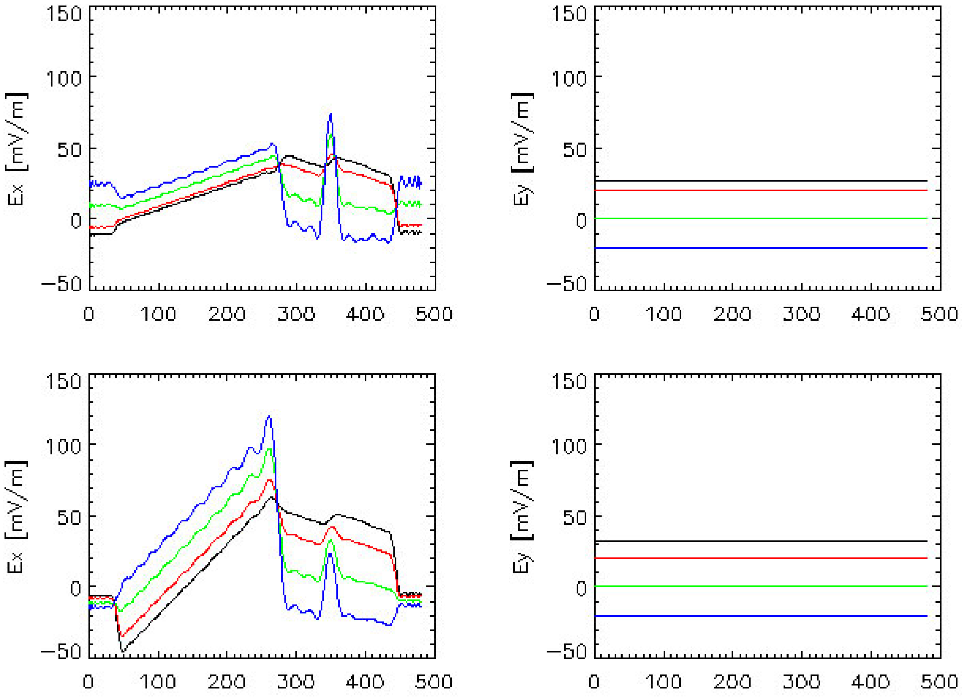
Data Set 1



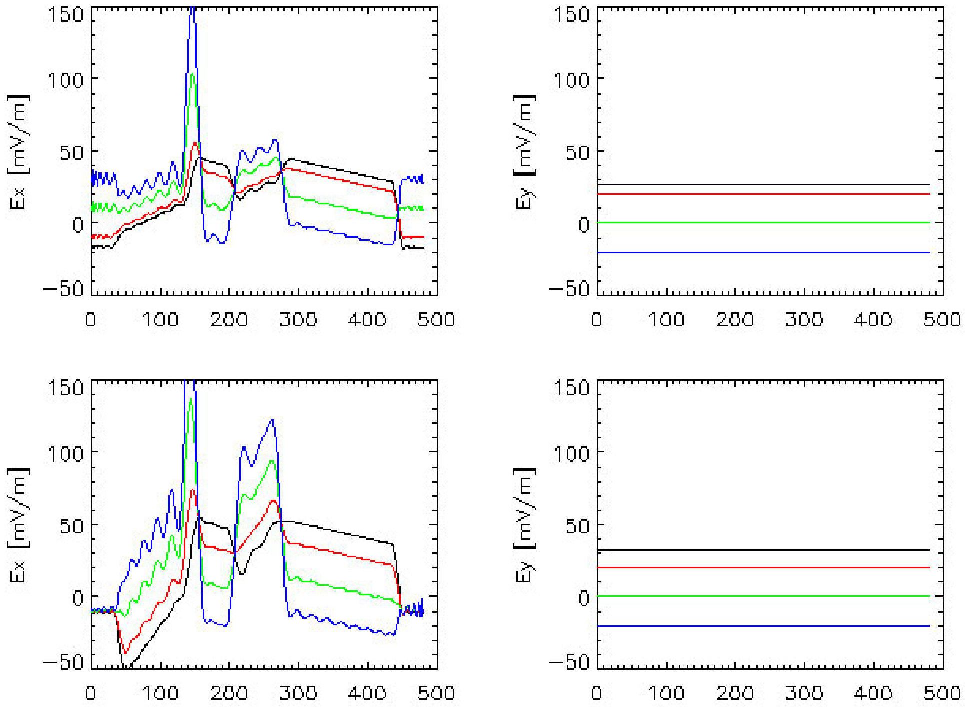
Data Set 2

Input parameters for two test configurations. For each configuration we show the field-aligned current, the magnetic perturbation, and the Pedersen / Hall conductance. The field-aligned current, the magnetic perturbation, and the width of the various regions – which are usually known pretty well from the data – are kept unchanged during the tests. The electric field profile across the oval is checked with respect to the model, conductance, and average electric field in North–South, *x* direction.

Oval Electrodynamics: Dependence on Model



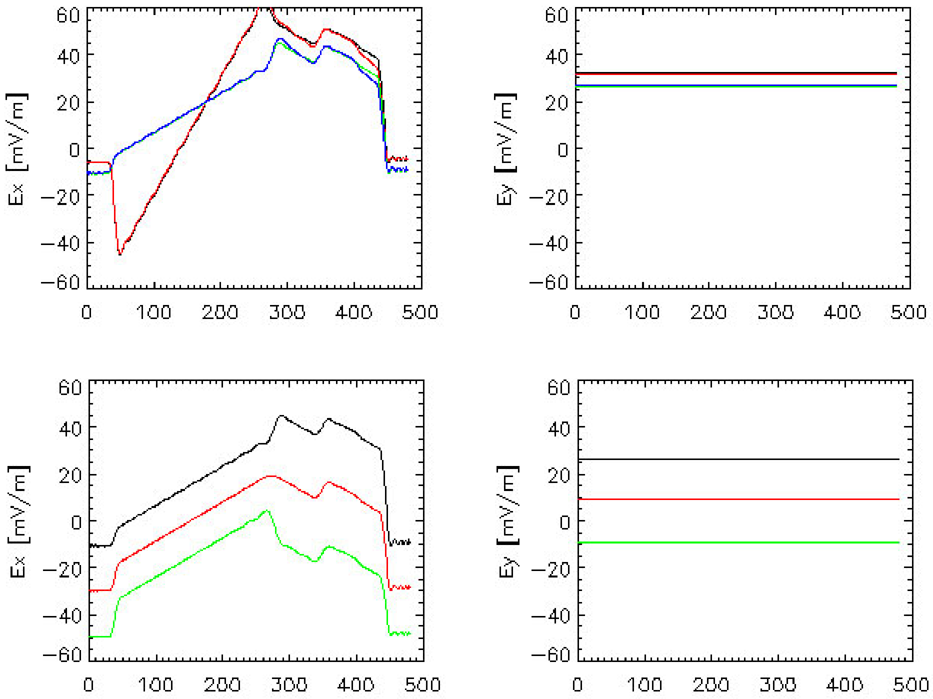
Data Set 1



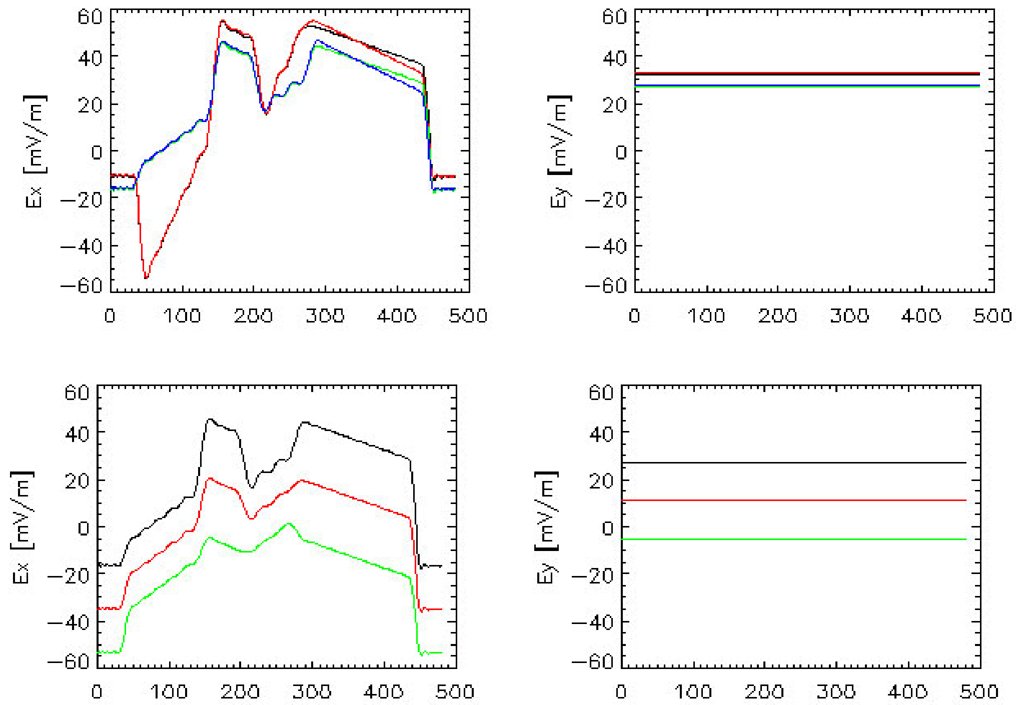
Data Set 2

- Dependence of E_x and E_y on the model, with an average electric field E_{0x} = 20 mV/m. The Pedersen conductance for the background / downward FAC / upward FAC region is 2 / 3 / 7 mho in the top panels, and 2 / 1 / 7 mho in the bottom panels. Each panel shows results for the model YPYH (black) and YPNHb0 with b_0 = 20 mV/m (red), 0 (green), and –20 mV/m (blue).
- In the top panels the convection reversal takes place at the oval boundaries, but in the bottom panel the reversals move towards the interior of the oval. When b_0 is fixed, the poleward convection reversal is close to the FAC reversal if b_0 is negative enough, a configuration resembling the Event 1 data.
- When the small-scale structure is hosted by the downward FAC, the induced perturbation is substantial, because of the large relative variation in the conductance.

Oval Electrodynamics: Dependence on Cond. and E_{0x}



Data Set 1



Data Set 2

- Dependence of E_x and E_y, model YPYH, on conductance (top) and average electric field (bottom). The dependence on conductance has been tested for Σ_P in the downward / upward current region of 1 / 7 mho (black), 1 / 5 mho (red), 3 / 7 mho (green), and 3 / 5 mho (blue). The dependence on E_{0x} has been tested with Σ_P = 3 / 5 mho, for E_{0x} = 20 mV/m (black), E_{0x} = 0 (red), and E_{0x} = –20 mV/m (green).
- A change of 2 mho in Σ_P results in a substantial change of E_x and b_0, when associated with the downward FAC.
- The variation of E_{0x} leads to an overall shift of the electric field, which changes the location of the convection reversals.

Oval Electrodynamics: Conclusions

- ALADYN is able to reproduce correctly the large scale structure of the electric field E_x, in particular the convection reversals at the auroral oval boundaries.
- The location of the convection reversals can be shifted towards the interior of the oval by:
  - adjusting the value of the constant E_y electric field;
  - modifying the conductance associated with the downward FAC;
  - changing the average E_x electric field.
- As expected, the small-scale structures generate essentially local effects. These effects, however, can be quite substantial for structures embedded in the large scale downward FAC, because of the large relative variation in the conductance.

Summary

- ALADYN allows realistic arc models, which take into account the polarization, the longitudinal electric field, and the FAC–EJ coupling. The best fit to the measured data for two arc events was obtained by taking all these parameters into account.
- For one of these events the current configuration close to the arc was checked in detail. Although the magnetic field data show the standard pattern, suggesting ionospheric Pedersen coupling between the downward and upward FACs, the current sheets appear to be decoupled in the ionosphere.
- The atypical current topology is related to the close proximity of the convection and FAC reversals.
- By applying ALADYN to synthetic data it is possible to check the relative position of the convection and FAC reversals, as well as their locations with respect to the boundaries of the auroral oval.

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References:

- Karlsson, T.: Auroral electric fields from satellite observations and numerical modelling, Ph.D. thesis, Alfvén Laboratory, Royal Institute of Technology, Stockholm, 2001.
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- Marghitu, O., Klecker, B., Haerendel, G., and McFadden, J.: ALADYN: A method to investigate auroral arc electrodynamics from satellite data, J. Geophys. Res., 109, A11 305, doi:10.1029/2004JA010 474, 2004.