A New Method To Investigate Arc Electrodynamics

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Abstract

The simplest representation of an auroral arc consists of a homogeneous block of increased conductance, infinitely extended in longitudinal direction; field-aligned current (FAC) sheets that flow in and out of the ionosphere at the boundaries of the arc are connected through Pedersen current across the arc, while the electrojet (EJ) that flows along the arc as Hall current is divergence free. To evaluate the deviation of the real arcs from this ideal configuration we developed a new method, based on a parametric model of the arc, that allows the derivation of the parameters by numerical fit to the experimental data. The method is illustrated with a wide, stable evening arc, for which both FAST measurements, at ∼4000km altitude, and ground optical data are available. We find that in order to obtain consistent results one has to take into account, as a minimum, the ionospheric polarization, the contribution of the Hall current to the meridional closure of the FAC, and the coupling between the FAC and the EJ.

1. Preamble

To get the electrodynamic description of the ionosphere one needs:

- $\mathbf{E}$ – the ionospheric electric field (IEF)
- Σ_P, Σ_H – the Pedersen and Hall conductances
- $\mathbf{J}_\perp$ – the ionospheric height-integrated current

With satellite measurements Σ_P and Σ_H can be derived from particle data. If the satellite does not cross the Auroral Acceleration Region (AAR) $\mathbf{E}$ may be obtained, in principle, by mapping along the filed line, and then $\mathbf{J}_\perp$ can be found from Ohm's law. However:

- The DC E_{E-W} is not measured on FAST
- Occasionally FAST crosses the AAR and the mapping does not work

Task:

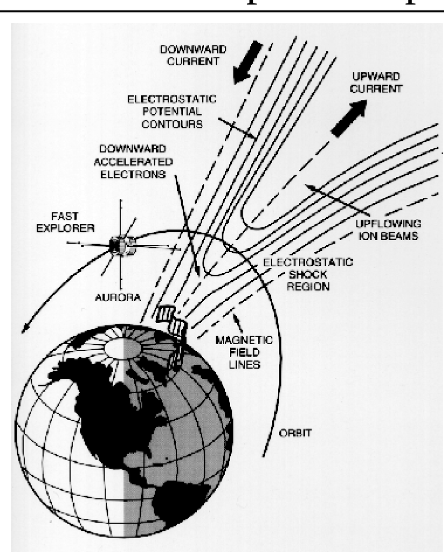
- Method to find the IEF from FAST data (this poster)
- Investigation of the ionospheric current flow pattern (oral session)

2. Auroral IEF: Earlier Work

- Boström (1964) suggested two topologies for the coupling between the FACs and the auroral EJs.
- The polarization of the auroral EJ under intensified auroral precipitation was studied theoretically by Coroniti and Kennel (1972).
- In many cases the IEF in the vicinity of auroral arcs was found to be either correlated or anti-correlated with the electron precipitation. Evans et al. (1977) (rocket data) interpreted this feature in terms of field-aligned currents, while de la Beaujardière et al. (1977) (radar data) in terms of ionospheric polarization.
- Marklund (1984) reviewed a large amount of published data and identified polarization, Birkeland, and combination arcs, according to the mechanism that provides the current continuity.
- By using DE-2 data Sugiura (1984) showed that the ionospheric closure of the FAC is often achieved through Pedersen current, while the Hall current is essentially divergence free, as predicted by Boström (1964).
- Several methods based on ground magnetometer and radar data were developed (see, e.g. Glassmeier, 1987; Untiedt and Baumjohann, 1993). Their main advantage is the 2D coverage. A drawback is the relatively poor spatial resolution.

3. Experimental Setup

Fast Auroral SnaphoT Explorer



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

- Second **SM**all **EX**plorer NASA satellite (Carlson et al., 1998);
- PI Institution: Space Sciences Lab., University of California at Berkeley;
- Launch date: August 21, 1996
- Orbit: 351 × 4175 km, 83°;
- Reversed cartwheel motion, **spin axis perpendicular to the orbit plane**
- Plasma analyzers: IESA, EESA, SESA – high time resolution, **uninterrupted 360° coverage**
- Mass spectrometry: TEAMS – 3D H+ and O+ in 1/2 spin, He+ in 1 spin
- Electric field: 3 orthogonal boom pairs, equipped with spherical probes
- Magnetic field: DC fluxgate and AC search coil magnetometers

Ground Optics

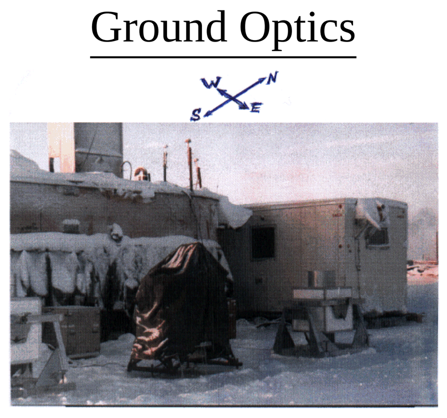
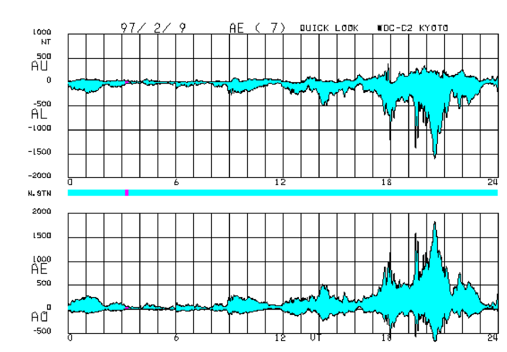


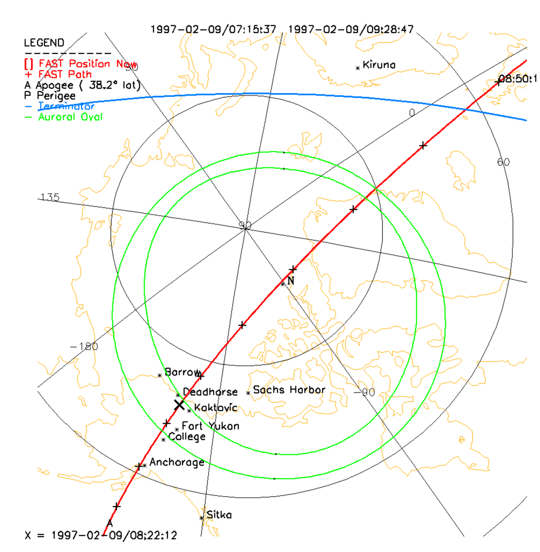
Photo courtesy W. Lieb

- Low-light CCD cameras developed by the Max-Planck-Institut für extraterrestrische Physik, Garching (Frey et al., 1996)
- Wide-angle optics, $86^\circ \times 64^\circ$
- Pass band filter, $\geq 650nm$
- Exposure time 40ms multiplied with / divided through powers of 2
- Location: Deadhorse, Alaska, 70.22°LAT, 211.61°LON
- Time: February 9, 1997, ∼8:22UT

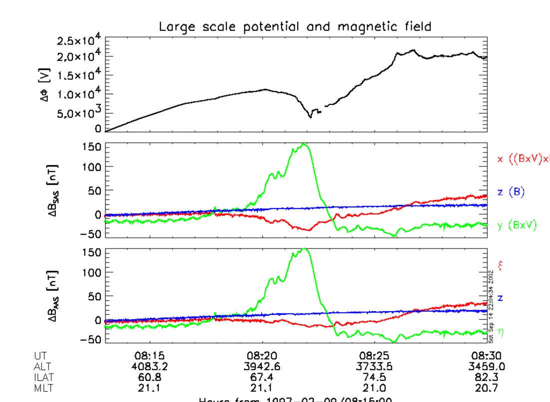
4. Data



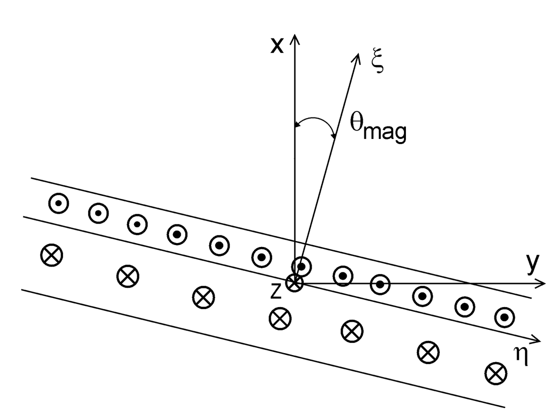
AE Index. From World Data Center for Geomagnetism, Kyoto, http://swdcdb.kugi.kyoto-u.ac.jp



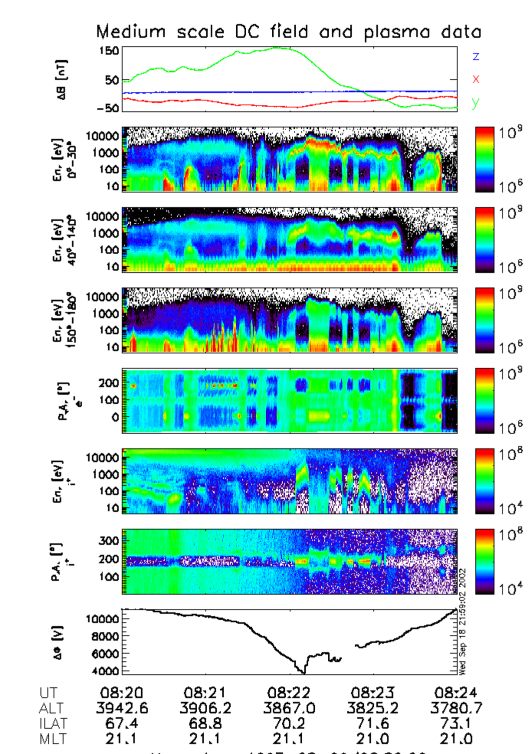
FAST trajectory. Magnetic noon at the top, "N"=magnetic pole, "X"=arc position



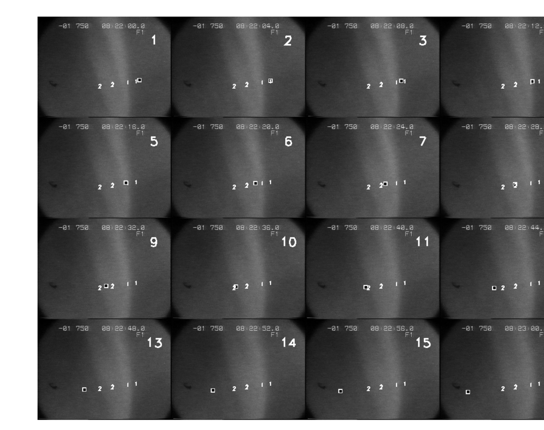
Top: High-alt. Potential. *Middle:* Magnetic field in the Satellite Associated System (SAS). *Bottom:* Magnetic field in the Arc Associated System (AAS).



SAS (x, y, z) vs. AAS (ξ, η, z).



Panel 1: Magnetic field. *Panels 2–4:* Electron energy spectrograms. *Panel 5:* Electron pitch-angle spectrogram. *Panels 6/7:* Ion energy/pitch-angle spectrograms. *Panel 8:* Electric potential. **The arc is north of the convection reversal.**



Mapping of FAST in the image plane courtesy Dr. J. Vogt

Selection of Images 4 sec apart from 8:22 to 8:23. FAST footprint is shown as a square. '11' and '22' are the boundaries of the first two ion beams. **The arc is stable and drifts southward with ∼200m/s, equivalent to ∼10mV/m westward IEF if one assumes the arc has no proper motion.**

5. Theory

By writing the current continuity equation at ionospheric level and assuming the electric field to be electrostatic and constant along the arc one can obtain the fit equation (Marghitu, submitted):

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

The quantities on the r.h.s. can be calculated from the measured satellite data: H_y from magnetic, Σ_P from particle, and E_{0_X} from electric field data. In particular, E_{0_x} represents the average IEF, which can be derived from high-altitude data even for time intervals including AAR crossings.
The unknown parameters on the l.h.s. of Eq. 1 are:

- a_i – polarization coefficients:

$$E_x = E_{0_x} + \delta E_x = -\Delta\Phi/L + \sum_{i=1}^{i=n_x} a_i G_i, \qquad \int_{s_1}^{s_2} \delta E_x \, ds = 0 \; \forall \, n_x \quad (2)$$

G_i are Legendre polynomials and n_x is associated with the *polarization scale*;

- b_0 – Hall coefficient: the component of the IEF along the arc;
- c_0 – current supply from/to the polar cap;
- c_1 – FAC–EJ coupling coefficient: $c_1 = \tilde{c_1}\cos\theta$ and $\tilde{c_1}$ can be associated with the length scale of the electrojet, $L_\eta \simeq |J_\eta/\tilde{c_1}|$;
- $\tan\theta$ may be added to the list, in which case the fit equation becomes non-linear, or derived from the magnetic data;
- n_x depends on the precipitation pattern and can be tuned to the data.

Some of the parameters can be set to 0 and $\tan\theta$ can be considered or not as fit parameter. Depending on the choice one obtains a hierarchy of arc models, as follows:

No FAC–EJ coupling, $c_1 = 0$	FAC–EJ coupling, $c_1 \neq 0$
NPNH(L)	NPNHX(L)
NPYH(L)	NPYHX(L)
YPNH(L)	YPNHX(L)
YPYH(L)	YPYHX(L)

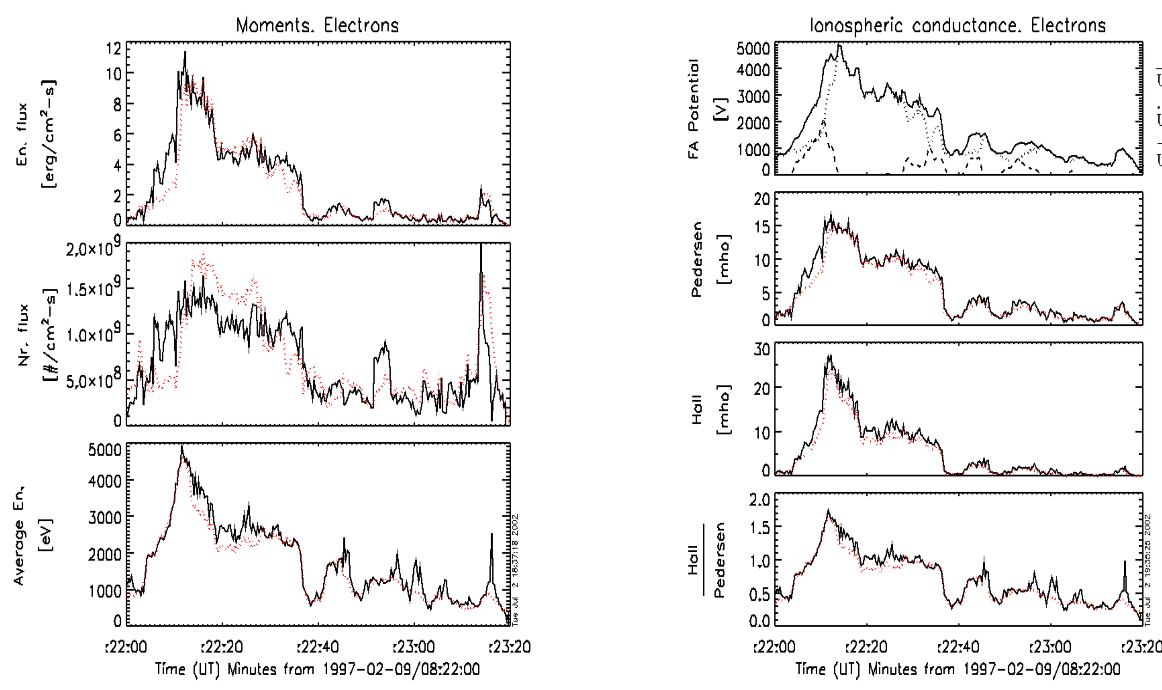
NP=**N**o **P**olarization, $a_i = 0$
NH=**N**o **H**all, $b_0 = 0$
L=**L**inear, $\tan\theta$ from magnetic data

6. Ionospheric conductance

For the arc under investigation the solar induced conductance does not make a significant contribution (winter nightside auroral oval). The conductance is mainly induced by particle precipitation. By fitting experimental results Robinson et al. (1987) and Galand et al. (2001) found approximate formulas for Σ_P, Σ_H, induced by electrons and protons respectively. During the inverted-V event the conductance is induced by electron precipitation:

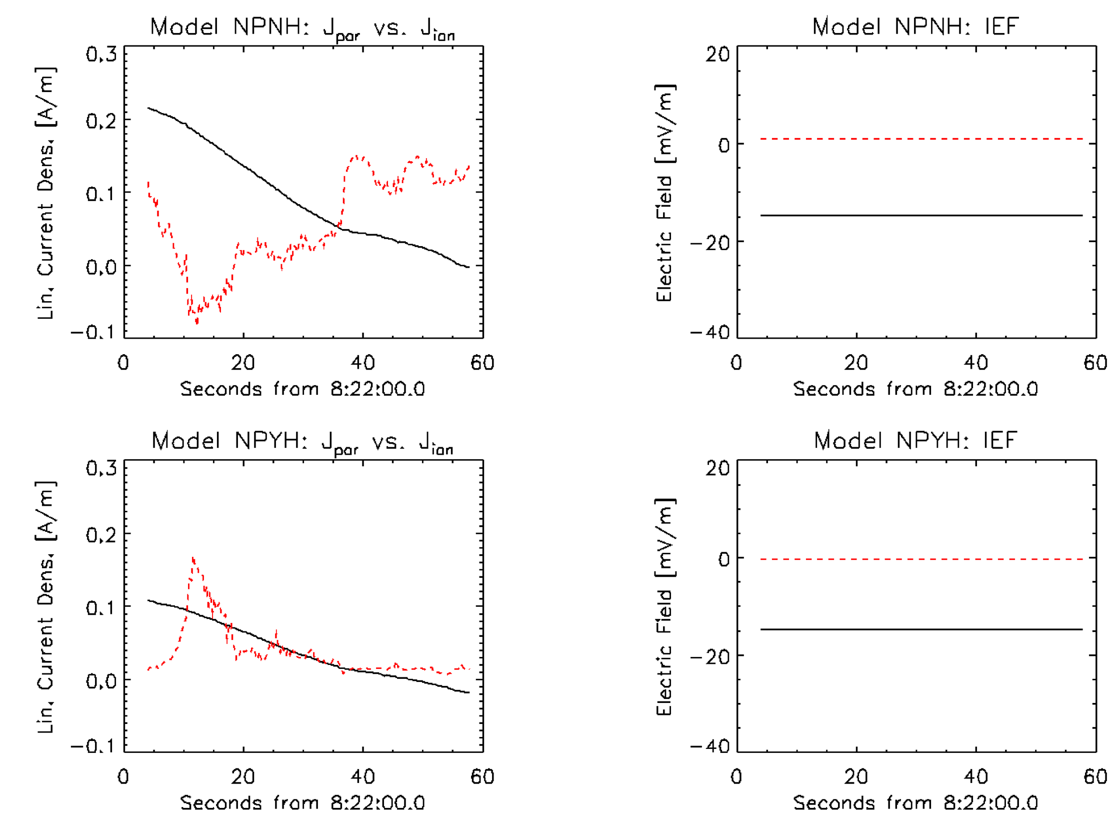
$$\Sigma_P = \frac{40\overline{E}}{16+\overline{E}^2} J_E^{1/2}$$
$$\frac{\Sigma_H}{\Sigma_P} = 0.45\overline{E}^{0.85}$$

where J_E is the energy flux, in erg/cm^2·s, and $\overline{E}$ is the average energy, in keV, calculated as ratio of energy to number flux.

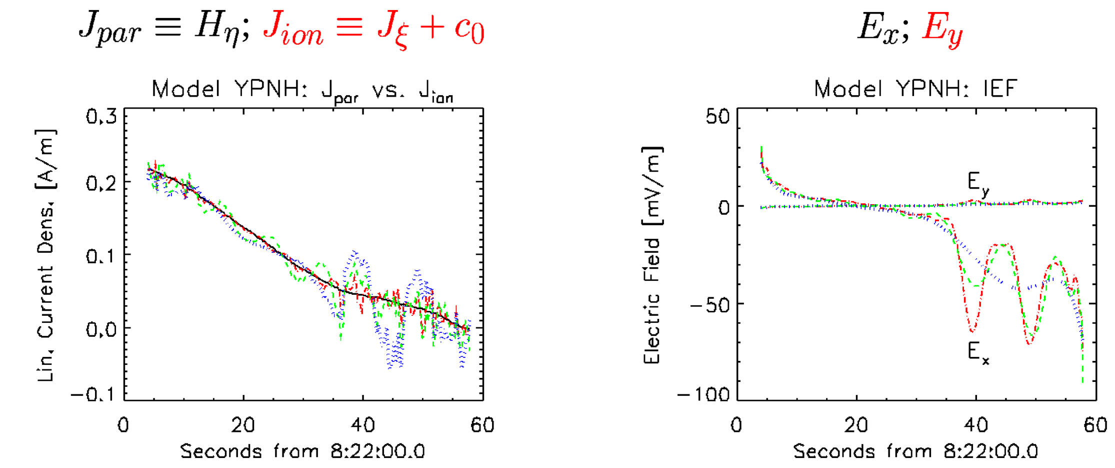


Integration over full velocity space
Integration over the loss-cone

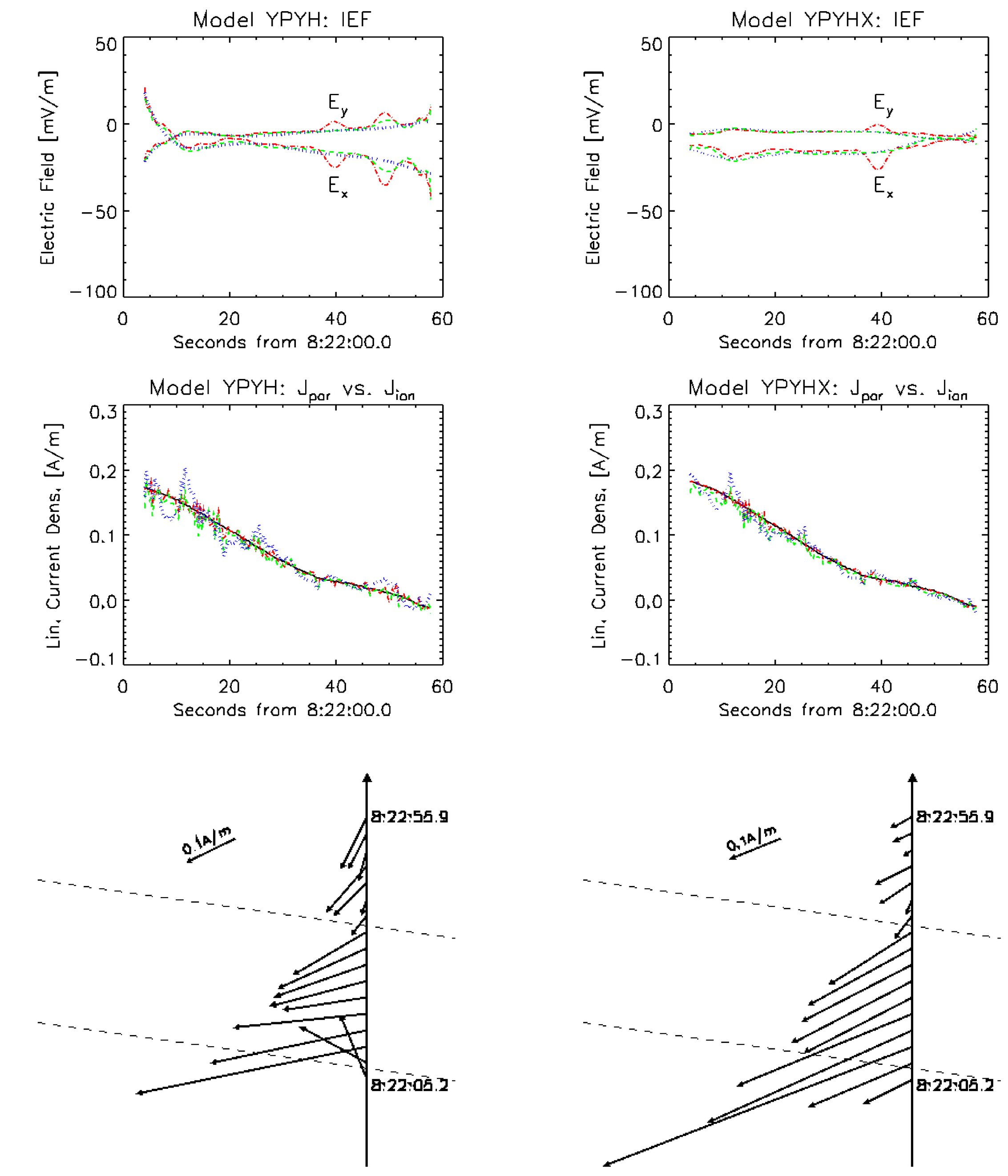
7.1 Models NPNH, NPYH, and YPNH: Fit Results



$J_{par} \equiv H_\eta$; $J_{ion} \equiv J_\xi + c_0$ E_x; E_y

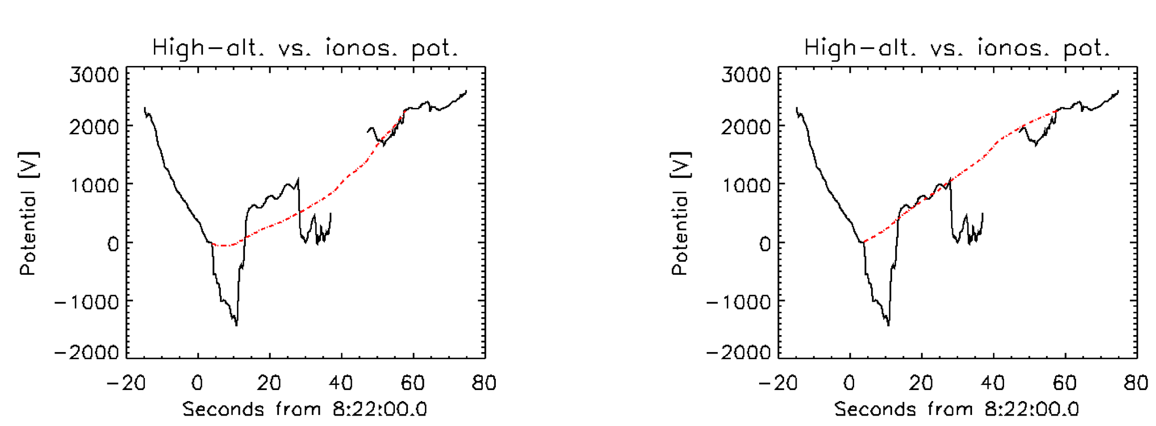


7.2 Models YPYH and YPYHX: Fit Results

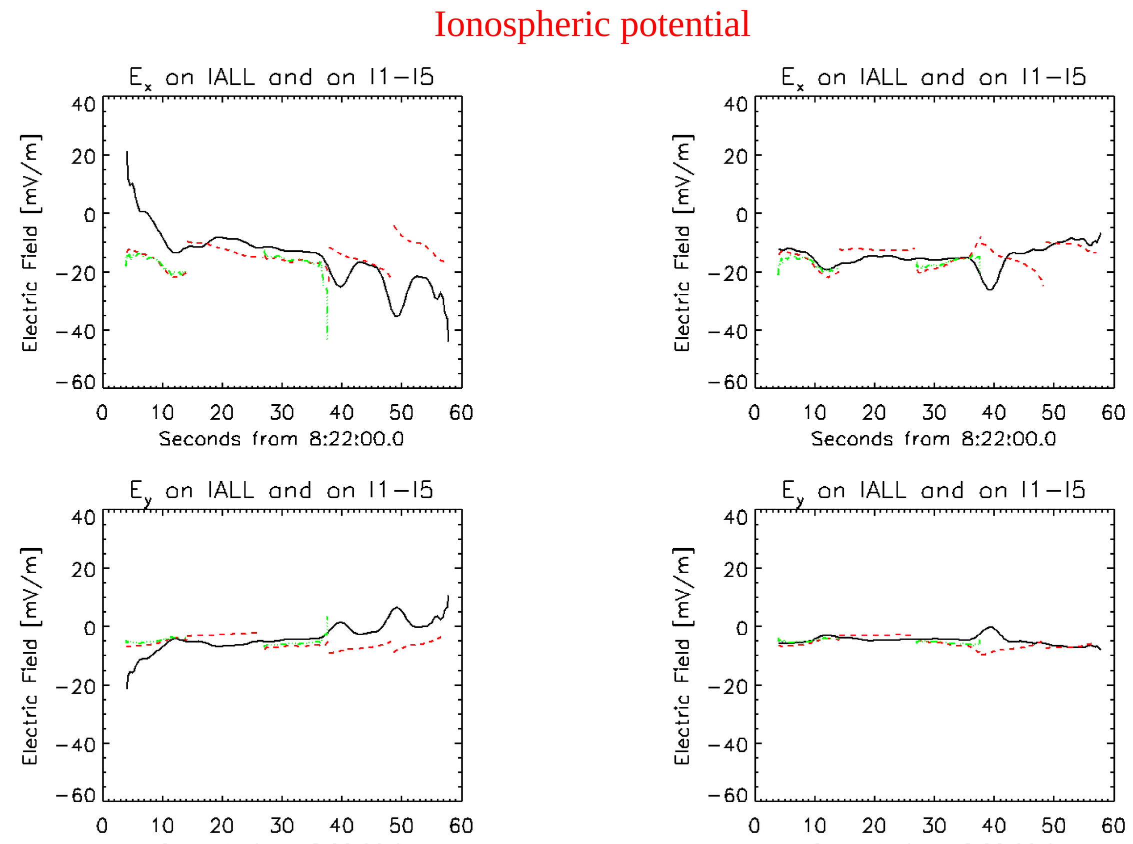


$n_x = 7$; $n_x = 18$; $n_x = 36$

7.3 Models YPYH and YPYHX: Internal Consistency



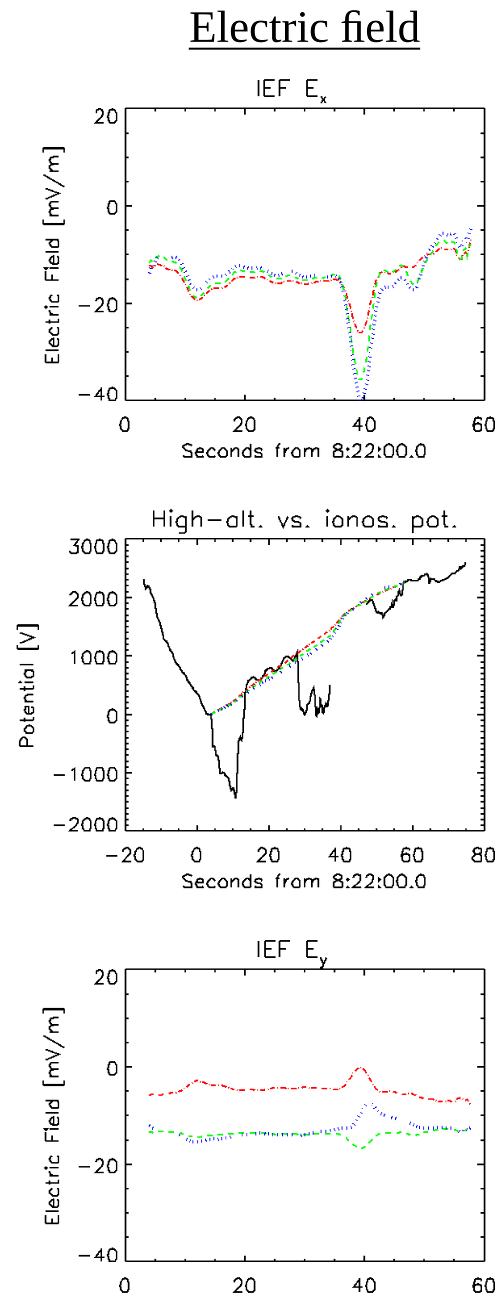
High-altitude potential
Ionospheric potential



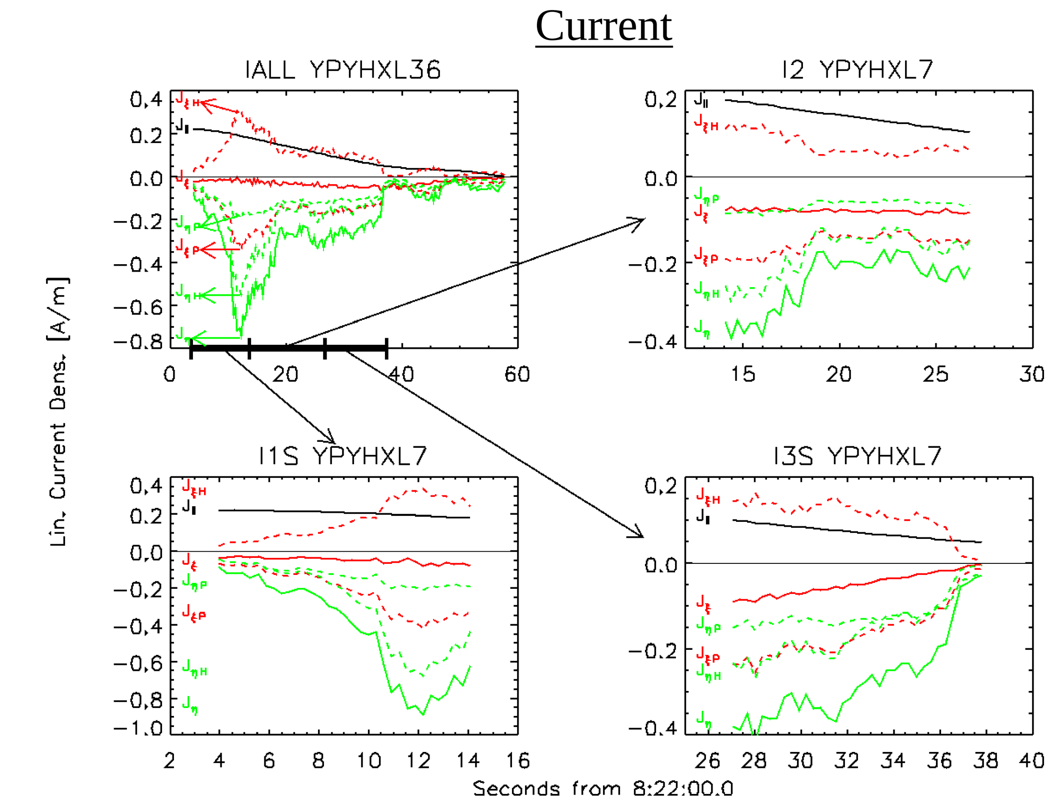
Fit on the whole interval, IALL; Fit on sub-intervals, I1–I5; Fit using burst data, available during I1 and I3. IALL=8:22:03.8–8:22:57.5, the ion beam period. I1,…,I5=intervals of ∼10sec, determined by the sequence of ion beams.

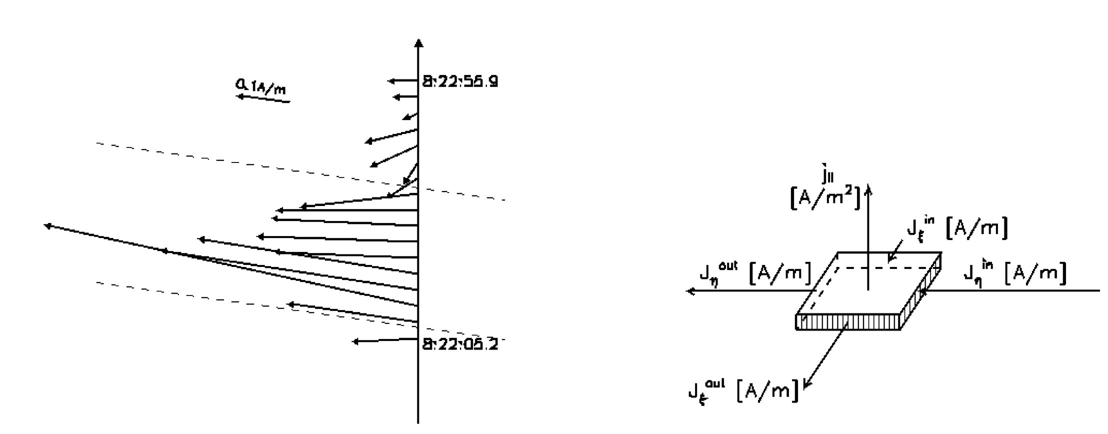
7.4 Model YPYHXL

Electric field



Current





Electric field:Model YPYHX; Model YPYHXL, variance analysis over IALL; Model YPYHXL, variance analysis over a 10sec sliding window. The E_y results are in slight disagreement with $E_y = -10$mV/m, inferred from optical data, suggesting proper motion of the arc initiated at AAR level (Haerendel, 1989, and references therein). Current: J_ξ practically vanishes at the beginning of IALL, and remains small over the whole interval, because the Pedersen and the Hall components compensate each other. J_ξ **cannot provide the ionospheric connection between the downward and upward FAC, which implies an uncommon current topology, to be discussed in more detail in the oral session**. The current continuity is provided through the variation of J_η, as sketched in the cartoon.

8. Summary

- High-resolution satellite data — particle, electric field, and magnetic field — are incorporated in a new method developed to determine the IEF in the vicinity of the arc.
- The results were checked for internal consistency. In addition, an external check was possible, due to the ground optical data.
- The minimum set of parameters necessary to model the arc includes **the polarization, the longitudinal electric field, and the FAC–EJ coupling**, even if the arc is reasonably quiet and homogeneous.
- The FAC–EJ coupling coefficient allows the quantitative evaluation of the 2D current flow in the vicinity of the arc.

9. Prospects

- Extending the method to determine the IEF in summer time conditions, by adding the solar induced conductance.
- Extending the method to the downward current region, by including the proton induced conductance. This might prove to be difficult, because of the lower conductance values, affected by higher uncertainties.
- Improving the fit procedure by working in orthogonal curvilinear coordinates. This would be more natural both for arcs and for other auuroral forms.
- A different procedure to estimate the ionospheric potential drop is required for non-stationary cases, i.e. when the auroral structure has a significant variation during the satellite crossing.
- The present method might be transformed into a reliable routine tool for the remote sensing of the high-latitude ionosphere.
- Investigation of conjunction events, when ground data is available. The 1D high-resolution satellite data are complementary to the 2D lower-resolution ground data.

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