Cluster EFW Electric Field Measurements in the Polar Wind

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Preliminary report summarizing the work, thought and data of a lot of Cluster people, including (alphabetically)

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1 Introduction

The Cluster spacecraft are equipped with two instruments directly aiming at measuring the electric field: the Electric Fields and Waves (EFW) instrument, using spherical electrostatic probes on wire booms in the spin plane, and the Electron Drift Instrument (EDI), determining $\mathbf{E}$ from the drift of keV electrons emitted by the instrument. In addition, the electric field can also be determined from the drift velocity observed by CIS, provided the density is sufficiently high. All the techniques have their strengths and weaknesses, so the availability of several is a major advantage in that it allows verification of the data. When the instruments agrees, we can trust the data; when they disagree, at least one of them do not provide a useful estimate the unperturbed local E-field in the plasma. In most plasmas, the agreement is either very good or the disagreement is as expected from previous knowledge of the techniques. We here report on a disagreement in a region where problems were not anticipated but have been discovered when EDI and EFW data have been available for comparison: the polar cap.

2 Data

2.1 Polar cap density holes

The first hints of a problem started to appear in the spring of 2001 when the first EFW-EDI comparisons were made. EFW and EDI were found to generally agree very well, except in certains regions of increased spacecraft potential. Figure 1 shows an example of such an event, at first called "PPP" events for "post-perigee problem", as the first observations all were discovered after perigee, i.e. over the northern hemisphere. The characteristics of such an event are as follows (not all data shown here):

1. The spacecraft potential $V_{\rm s}$ (estimated as the negative of the EFW probe-to-spacecraft potential $V_{\rm ps}$) suddenly jumps from typically 10 V to 20 – 40 V.
2. Comparisons to WHISPER show that the reason for the $V_{\rm s}$ increase is a real drop in plasma density, to below 1 cm^{-3}.
3. Inside the density depletion, the electric field strength estimated by EFW increases to typically 3 – 10 mV/m. EDI sees no such increase.
4. The magnitude of the electric field estimated from EFW inside the density depletion varies with the spacecraft potential.
5. The electric field estimated from EFW inside the density depletion is aligned with the projection of the magnetic field in the spin plane. The direction is always radially outward from the Earth, i.e. parallel to B in the southern hemisphere and antiparallel in the northern.
6. CIS shows essentially no ions at all. The plasma density indicated by EFW and WHISPER thus must be due to cold plasma (energy below the spacecraft potential) only. As essentially no ions are seen, CIS data cannot provide a useful E-field in these cases.
7. PEACE also shows no or few plasma electrons above $eV_{\rm s}$. The cold plasma electrons are hard to discern, as they are largely swamped by photoelectrons emitted by the EFW probes.
8. The invariant latitude is always above $75°$, so we are over the polar cap.

When two instruments disagree, one must decide which one (if any) is to be trusted. In these cases, the EDI data quality generally is very good, and there are no indications of EDI problems. On the other hand, observations 4 and 5 from the list above suggests that the electric field detected by EFW is not the unperturbed local field in the plas,a. Observation 5 indicates strong parallel electric fields, always a caution sign. Observation 4 also deviates from usual behaviour of EFW: EFW usually has no problem with measuring E for wide variations in $V_{\rm s}$. Considering that the EFW probe potential, and thus the electric field measurement, will always depend on the plasma environment of the spacecraft, observation 4 is consistent with an error source dependent on $V_{\rm s}$.

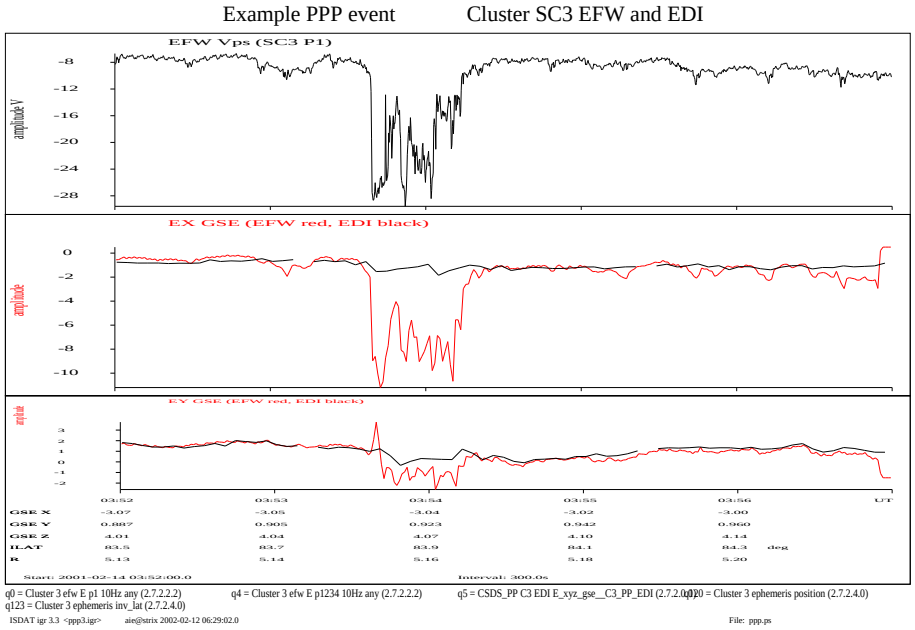

Figure 1: EFW and EDI data showing disagreement in a density hole over the polar cap. From top to bottom: EFW V_{ps}, EX (GSE) and EY (GSE). EDI E-field (black) are from CSDS PP, EFW E-field (red) are high resolution data despun to GSE and averaged to 1 s time resolution, with a constant $\mathbf{v} \times \mathbf{B}$ removed.

Our interpretation of the EDI-EFW discrepancy in these cases thus is that EFW measures a spurious potential, violating the assumption that the measured probe voltage difference gives the local unperturbed electric field in the plasma. We refer to this signal as a spurious electric field. One should note that a spurious electric field in EFW data of 10 mV/m corresponds to a potential difference between the two involved probes of only 0.88 V, so the perturbation to the local plasma environment need not be very large.

2.2 Widespread regions over the polar cap

While the initial thought thus was that this kind of EFW problem was confined to small and easily identifiable density holes, the huge increase in available EDI data during autumn 2001 now have made it obvious that the problem may persist over large parts of the polar cap, not just in narrow density holes. Figure 2 shows an example of this, with CIS data in Figure 3. The characteristics is about the same as outlined above, with some distinctions:

1. The spacecraft potential V_s does not have to show a sudden jump to high values – problems can appear at values as low as 10 V.

2. Comparisons to WHISPER data show that any variations in V_s still are due to plasma density variations, and that densities are around or below 1 cm^{-3}.

3. The electric field strength estimated by EFW typically is 2 – 10 mV/m, without any corresponding field seen by EDI.

4. The magnitude of the electric field estimated from EFW inside the density depletion shows some signs of covariation with the spacecraft potential, though the correlation now is much less clear and not always present.

5. The electric field estimated from EFW still has the same direction (i.e. parallel/antiparallel to the projection of B onto the spin plane).

6. CIS still sees no ions.

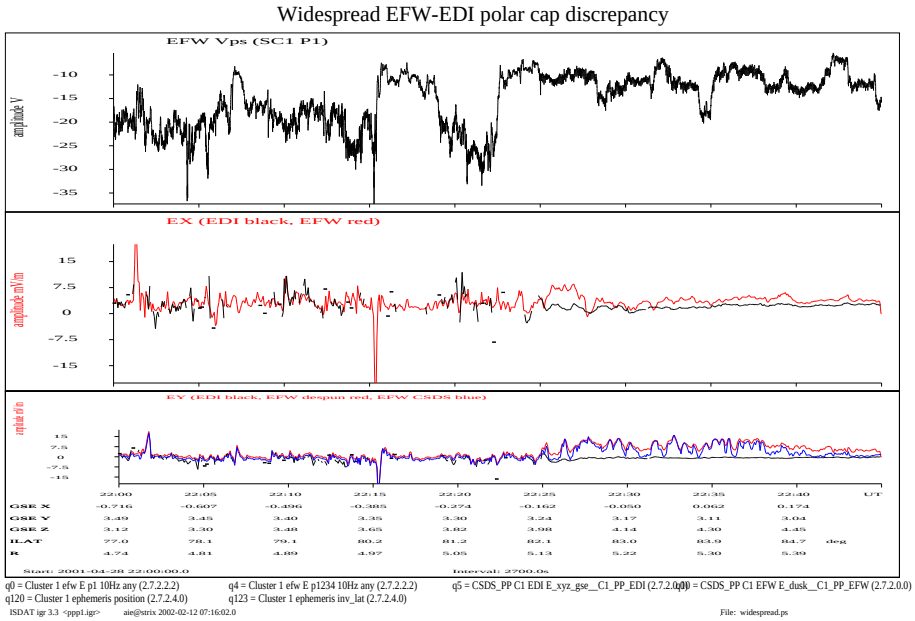

Figure 2: Disagreement between EFW and EDI over a wide region over the polar cap, not directly correlated to any density depletion or high V_s value. Before 22:15, EFW and EDI generally agree well when data from both are available. After 22:25, EFW observes a spurious electric field, mainly in the GSE Y direction. Panels from top to bottom: 1. EFW V_{ps}, essentialy the negative of V_s. 2. GSE EX (black = EDI PP, red = EFW despun and averaged high-res data). 3. GSE EY (red and black as in panel 2, blue = EFW CSDS PP). The red curves are not corrected for $\mathbf{v}_{sat} \times \mathbf{B}$.

7. PEACE indicates essentially all plasma electrons are cold here as well.

8. The extended problem regions also are found over the polar cap, at invariant latitudes above $75°$.

These recent observations extend the problem from being an unusual event in confined and easily identifiable (by their spacecraft potential signature) density holes to a commonly occurring phenomenon persisting during long periods of time (hours).

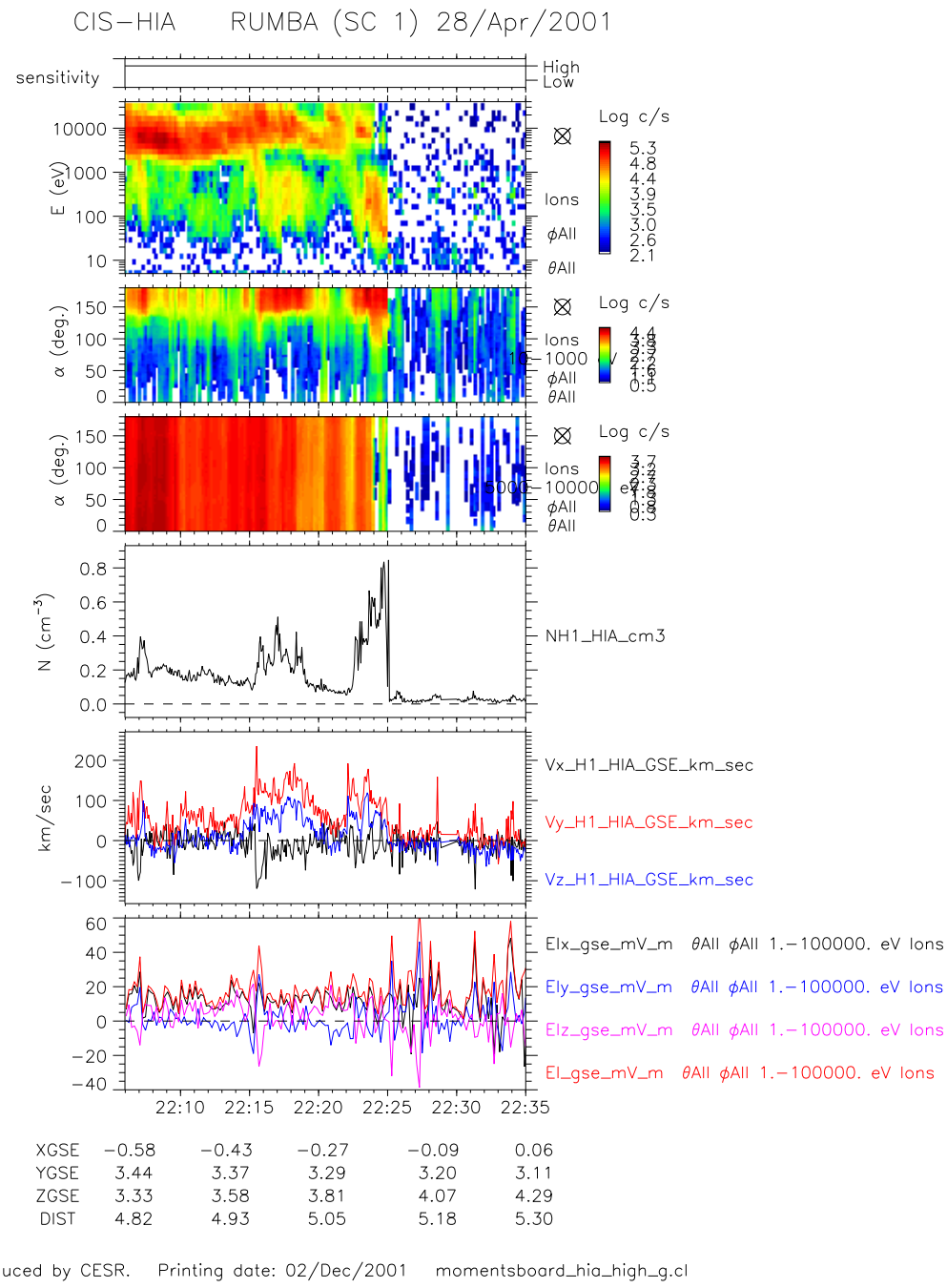

Figure 3: CIS data for the event in Figure 2. After 22:25, CIS observes almost no plasma, though the EFW data in Figure 2 does not suggest any density decrease (consistent with WHISPER data, not shown). The implication is that the existing plasma must be cold: the polar wind.

3 Understanding the data

3.1 The polar wind plasma

One feature of the polar cap field lines is the upwelling cold plasma known as the polar wind. Observations from POLAR [Moore et al., 1997, Su et al., 1998] (Moore et al, 1997) indicates that we may expect to see densities between 0.1 and 1 cm^{-3}, of which about 90 % are protons. The typical parallel velocity would be about 20 – 80 km/s, corresponding to ram energies of 2 – 30 eV, and thermal proton energies of 1 – 10 eV. Electron thermal energy is of the same order.

3.2 Hypothesis: The spacecraft electrostatic wake model

Adding the facts that (1) the spurious electric field is directed along the geomagnetic field lines and outward as seen from the Earth, and (2) that the spurious field is seen only in a region of a known cold plasma outflow, i.e. the polar wind, a wake effect almost suggests itself. A negatively charged wake would give the desired sense of the electric field.

Wake theory normally considers the case of a negatively charged spacecraft, as appropriate for ionospheric conditions. In that case, the edge of the wake is the edge of the spacecraft, and the volume of the wake is thus directly controlled by the geometric dimensions of the spacecraft. Such a wake would give a very small effect on the Cluster probes.

However, for a spacecraft at a potential of say 10 V in a plasma where the ion energy is about 2 eV, the situation is drastically different. The obstacle seen by the upflowing ions now is not just the spacecraft itself, but the volume defined by the 2 V equipotential surface around the spacecraft. The situation is illustrated in Figure 4 for a spacecraft with only one wire boom pair. A wake region with linear dimensions on the order of the boom length and 2 V equipotential distance from the boom appears behind the spacecraft. Model calculations indicate that this lies some 5 m from the wire booms in the case indicated. The wake is depleted of ions and thus negatively charged, as the much faster electrons still will reach into the wake. Assuming that the electrons are freely flowing and Boltzmann distributed, the highest potentials in the wake will be of order KT_e/e. For a large wake, the potential perturbation seen by the probes will be of this order, as they are close to the charge cloud: however, it is clear that they will see different potentials, with the lower potential appearing at the probe farthest from the Earth, thus giving the desired field. It seems that the hypothesis should be able to explain probe potential differences of up to perhaps 1 V, which corresponds to the observed spurious fields of up to 10 mV/m.

Magnetization effects may possibly change the electron flow, so that the wake is filled by s/c photoelectrons rather than by ambient plasma electrons, in which case the relevant T_e value should pertain to the photoelectrons.

Some predictions of this model can immediately be seen:

1. The wake size follows the spacecraft potential: thus the magnitude of the spurious electric field should depend on V_s.

2. The spurious field should scale roughly as the cosine of the elevation angle of the magnetic field over the spin plane.

3. The effect is expected in the regime

$$KT_\mathrm{i} < \frac{1}{2} m_\mathrm{i} v_\mathrm{ram}^2 < eV_\mathrm{s}$$

   where v_ram is the ion bulk flow speed relative to the spacecraft.

4. As the problem scales with V_s, ASPOC should have a positive effect on EFW in these regions.

In the density holes, the relation of the spurious E to V_s is as suggested by the first prediction. The second prediction needs statistical analysis of a large set of data to be tested. The third prediction is directly observed in the data: we only see this effect in the polar wind. In the solar wind and magnetosheath, ion ram energies are so high that the ions do not care about the spacecraft potential. In the plasmasphere, some effects may be revealed by very careful analysis, but as the spacecraft speed is roughly along $\mathbf{B}$ here, the

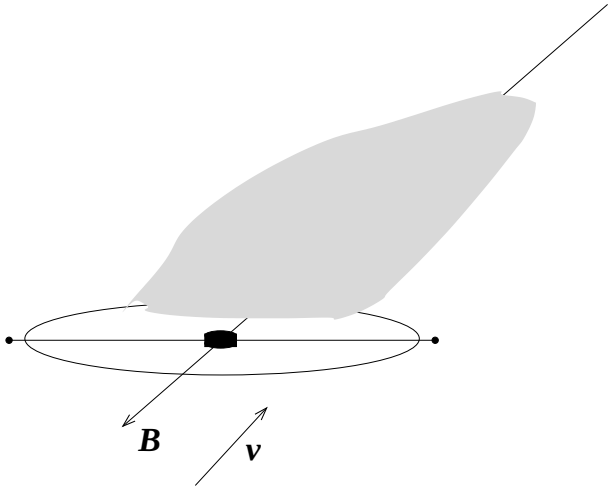

Figure 4: Sketch of the electrostatic wake around a positively charged spacecraft with one boom pair. The solid ellipse indicates the 2 V equipotential due to the unperturbed spacecraft potential, defining the size of the wake in a plasma with ion energy of that order. The shaded region indicates the negative space charge in the wake: it is clear that the probes will see different potentials from this charge cloud. Note that the probes are biased to close to plasma potential, and thus protrudes outside the equipotential surface.

effect should be small anyway. In all other regions encountered by Cluster, ion thermal energies are much above eV_s, so no effect is seen. This is something only seen in the polar wind. The fourth prediction is the subject of Section 4.1.

One should note that this is not an effect that should be particular to Cluster, but be seen on all double probe electric field instruments flown in this region. When thinking about this, members of the EFW team realizes they may have indeed seen things like this on previous spacecraft, though there has never before been any other instrument to compare to – as ion data cannot be used for comparison, the Cluster EDI instrument gives the first opportunity to observe the effect by direct comparison.

3.3 Regions of spurious fields

According to the electrostatic wake hypothesis, one should expect this kind of spurious field to affect the E-field estimates from electrostatic probe instruments in cases where the ion drift energy in the spacecraft frame is below eV_s. In Table **??** we tabulate some parameters of plasma envrionments encluntered by Cluster.

4 Artificial control of the spacecraft potential

4.1 Effects of ASPOC in the polar cap

Figure 5 shows SC3 WHISPER, EFW and EDI data from a polar cap passage. EDI and EFW agrees well before entering the polar cap at 04:20, except for a few excursions. Between 04:20 and 04:23, EFW shows a large spurious field, directed mainly in the GSE X. At 04:23 ASPOC is turned on, and the spurious field dissappears. Comparing to similar data from SC1 in Figure 6, we find that on this spacecraft, where ASPOC is not operative, EFW sees a large spurious electric field for the rest of the plot (40 min).

It is quite clear that ASPOC is beneficial for the spin resolution electric field data produced by EFW in this case. We have examined more cases, finding several like this.

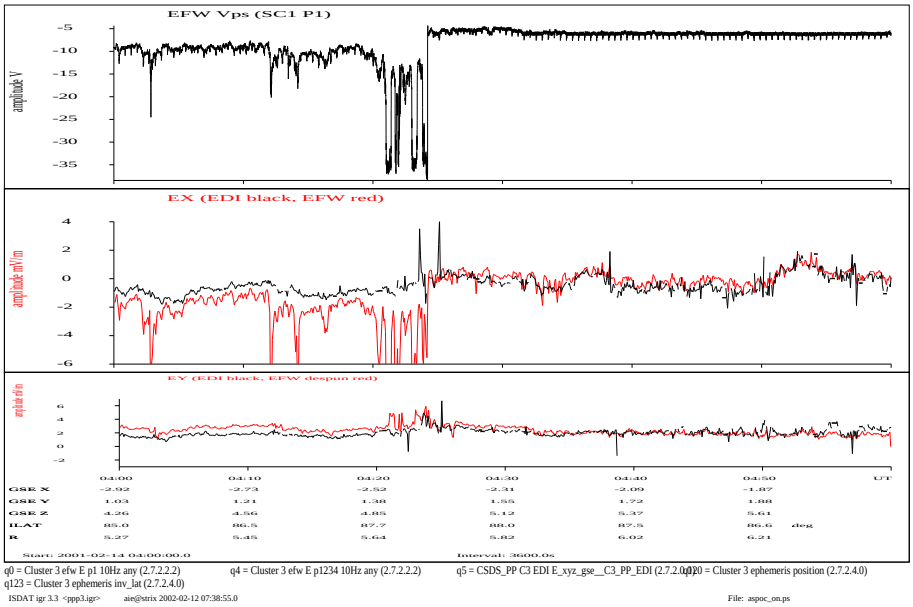

Figure 5: EFW and EDI data from SC3 at an ASPOC turn-on. Format as in Figure 2.

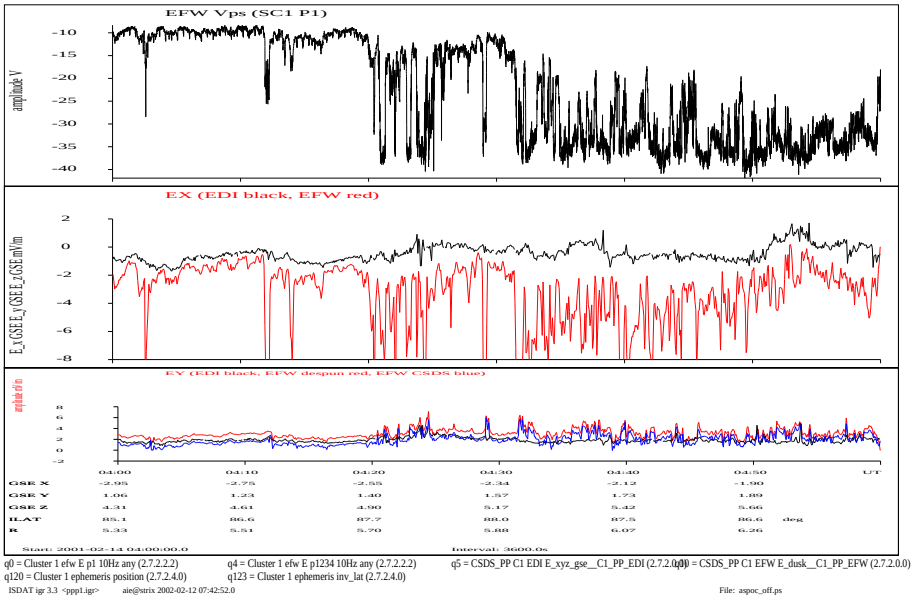

Figure 6: As Figure 5, but for SC1, with no APSOC.

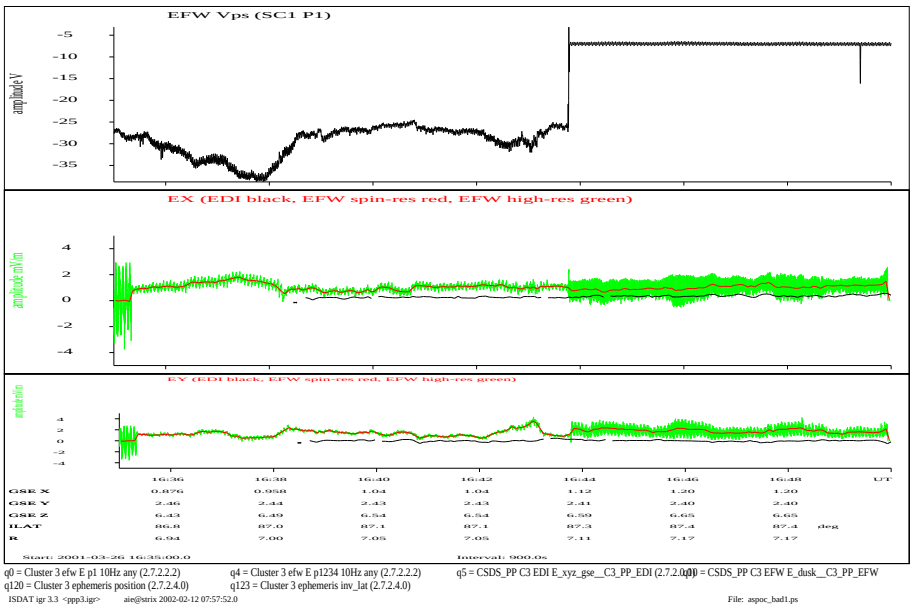

Figure 7: EFW data at an ASPOC turn-on. 1. EFW $V_{\rm ps}$, essentialy the negative of $V_{\rm s}$. 2. GSE EX (black = EDI PP, red = EFW spin resolution, green = EFW high-res data). 3. GSE EY. EFW data are not corrected for $\mathbf{v}_{\rm sat} \times \mathbf{B}$.

4.2 ASPOC effects on EFW in general

We still have a lot to investigate, using the new tool of EDI comparison, before we can give any general statements to the effect that ASPOC definitely is bad or good for EFW. While the examples above indicated that ASPOC at least sometimes has positive effects on spin averaged EFW electric field measurments, and we have found others where ASPOC appears to have no effect at all, Figures 7–8 show that ASPOC has undesirable effects as well. At the ASPOC turn-on at 16:43:45, the changes to the deviation of EFW spin averages (red) from EDI (black) may not be so dramatic, but it is clear that EFW data at higher resolution (blue) may be quite perturbed by ASPOC. Before turn-on, the despun E-field has a slight spin frequency remnant, on the order of 10 % of the total field. When ASPOC turns on, a strong signal at the fourth harmonic of the spin frequency (1 Hz) suddenly appears. This signal is as strong as the spin averaged field. The effect on EFWs ability to directly observe phenomena in the spin frequency range is clearly seen in the spectrum (Figure 9).

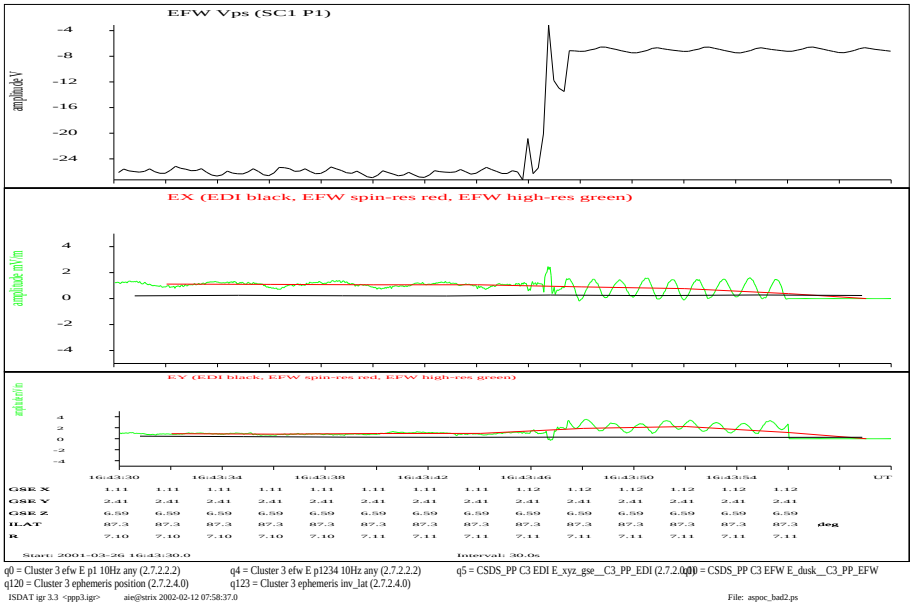

Figure 8: Zooming in on the ASPOC turn-on in Figure 7.

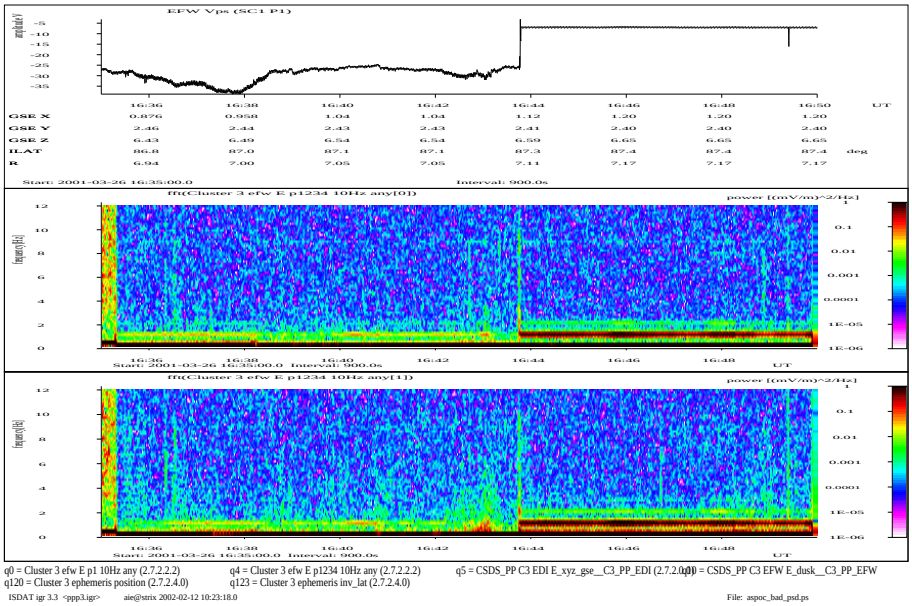

Figure 9: EFW spectrogram at ASPOC turn-on. Panels from top to bottom: 1. EFW V_{ps}. 2. GSE EX spectrogram. 3. GSE EY spectrogram. Power spectra based on 128 point FFTs, shifted by 32 points.

5 Conclusions

To summarize the data shown and discussed in this report:

1. Over the polar cap, EFW measurements of the DC electric field should be treated with care as large spurious electric field signals, radially directed out from the Earth, often are present.
2. The spurious fields occurs in regions of low ion density and temperature, so that the electric field cannot be established from CIS data.
3. The ambient magnetic field is sufficiently strong in this region for EDI to produce good DC electric field estimates.
4. For time variations faster than the spin frequency, where EDI data are less useful, EFW data are still accurate. Hypothetically, there may exist exceptions to this rule in small-scale polar wind stuctures, though we have not seen any as yet.
5. An explanation qualitatively agreeing with the observations is the electrostatic wake model.
6. From this qualitative model, we can conclude that the spurious field should appear in cold plasmas of low plasma density, so that the ion energy is below eV_{s}.
7. As expected from the qualitative model, ASPOC operations seem to diminish or sometimes even remove the spurious field.
8. There are also examples of undesirable effects of ASPOC on EFW.

It is indeed very fortunate that the only region where EFW observes this spurious field is where the geomagnetic field is sufficiently strong for EDI measurements to be reasonably unproblematic. If it had occurred in regions of weak magnetic field, where EDI cannot be used, we may have lost DC electric field data altogether: thanks to Cluster having two DC electric field instruments, we can get reliable electric field measurements in all regions traversed by the spacecraft.

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