The contribution of ground and space magnetometers

March 1, 2012
Boston College

Mark Moldwin (U. Michigan), Eftyhia Zesta (AFRL), Endawoke Yizengaw (BC), A. Boudouridis (SSI)
Magnetometers around the world courtesy of Peter Chi

Station Count:
Total: 250
• UCLA-built: 65
  • CPMN: 54
EEJ Estimation
Magnetometer pairs used
Longitudinal EEJ Variations

East Africa

ExB drift in East-Africa on 04 April 2010

DeltaH = AAE - ETH

West Africa

ExB drift in West-Africa on 04 April 2010

DeltaH = ILR - CMR

West America

ExB drift in America on 04 April 2010

DeltaH = JIC - PIU
Longitudinal EEJ comparison

West America

ExB drift in AMERICA on 05 April 2010

DeltaH = JIC - PIU

LT = UT - 5

West Africa

ExB drift in West-AFRICA on 05 April 2010

DeltaH = ILR - CMR

LT = UT + 1

East Africa

ExB drift in East-AFRICA on 05 April 2010

DeltaH = AA - ETH

LT = UT + 3
Comparison with other observations

More with JULIA

C/NOFS - Africa

C/NOFS - America

JULIA 150 KM
Day-to-Day Variability of EEJ

East Africa
Equatorial Electrojet over East Africa in 2010

West America
Equatorial Electrojet over West America in 2010
ULF Wave Penetration
ULF waves – High Speed Stream
Aug 9-10, 2008
ULF waves in the EEJ

East Africa : 6-15 LT
Filtered TEC on August 9, 2008 at MALI, PRN 20

UT (hr)
0420 0440 0500 0520 0540 0600 0620 0640 0700 0720

0 5 10 15 20

Frequency (mHz)

0 5 10 15 20 25

PC5-TEC (TECU)

0 5 10 15 20 25

TEC (TECU)

-10 -5 0 5 10 15 20

ExB (m/s)

Filtered drift velocities on May 2, 2010

0 5 10 15 20 25 30 35 40

Mag. Estimated ExB Drift (m/s)

0 5 10 15 20 25 30 35 40

PC5-ExB Drift (m/s)

0 1 2 3 4 5 6

Mag. Estimated ExB Drift (m/s)

0 1 2 3 4 5 6

PC5-ExB Drift (m/s)

7 8 9 10 11 12 13 14 15 16 17

LT (hr)

JULIA 150km ExB drift (m/s)

-30 -20 -10 0 10 20 30

JULIA 150km ExB drift (m/s)
Solar Wind Driver of ULF waves
Interhemispheric asymmetries
Interhemispheric asymmetries in wave power
Inter-hemispheric asymmetries at L=1.7

Figure 2
Conjugate Pc3 and Pc4–5 Power and TEC Ratios in 2003

Conjugate Pc3 power - 2003

Conjugate Pc3 power - 2005

FIT PAC

FIT PAC

Pc3 Power

Pc3 Power

FIT/PAC ratio

FIT/PAC ratio

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec

Conjugate Pc4–5

Conjugate Pc4–5

TEC (×10^6 TECU)

TEC (×10^6 TECU)

Time (Months)

Time (Months)
Inter-hemispheric asymmetries at \( L=2.3 \)

**Figure 8**

Conjugate Pc3 and Pc4–5 Power and TEC Ratios in 2006

Conjugate Pc3 and Pc4–5 Power and TEC Ratios in 2007
Contribution of Space Magnetometers and more …

- Determination of EEJ: LEO, high inclination (CHAMP, SWARM)
- Separation of magnetospheric and ionospheric current contributions: conjunctions of space and ground magnetometers
- Equatorial waves: LEO, low inclination (C/NOFS)
- Study E-field penetration during storms, correlate with plasmapause location (RBSP, DSX)
Zenith Angle Calculation for the FIT and PAC pair of stations - June Solstice

FIT will have SZA = 28° - 23° = 5°
PAC will have SZA = 53° + 23° = 76°

Power ratio calculation (FIT/PAC) = \( \cos(5°) / \cos(76°) = 0.99 / 0.242 = 4.12 \)
Zenith Angle Calculation - December Solstice

Geographic locations help explain N-S asymmetry

FIT will have SZA = 28° + 23° = 51°
PAC will have SZA = 53° - 23° = 30°

Power ratio calculation (PAC/FIT) =
\[ \frac{\cos(30)}{\cos(51)} = \frac{0.866}{0.629} = 1.38 \]
Ground magnetometer waves

East Africa - Dayside

South America - Nightside
SAMBA and McMAC chains
Radial mass density distribution using 13 pairs of stations

L = 1.59 to 3.49

pair at Northern Hemisphere

pair at Southern Hemisphere
We use the average of the PD and AR techniques as the final FLR. For this pair, FLR is reliably determined between 14 and 19 UT.

From Boudouridis and Zesta [2007]
Model calculations of FLR are done by directly solving the standing wave equations for toroidal mode waves. The mass density distribution along the field line is taken from the FLIP thermosphere-ionosphere model run for this particular day. A dipole magnetic field is used.

The agreement between observations and model is impressive. July 4, 2006 is a day with low to moderate activity and the radial mass density distributions can be well represented by the model.
Storm time: Dec 14-16, 2006
Comparisons between FLIP and Shultz inversion

Dec 14- prestorm

Dec 15- recovery

Dec 16 – late recovery

Model-Observations comparisons of FLRs: 1500 UT
Model-Observations comparisons of FLRs: 1530 UT
Model-Observations comparisons of FLRs: 1800 UT
Storm of Dec 14-16, 2006

- ESC-OHI, L=2.23
- FLIP, L=2.0
- FLIP w/ MSIS2000 + DEPL, L=2.25

More details on the FLIP response at the poster SA51D-1977 by Duffy et al.

Depletion based on Lp = 6 – 0.6*Kp
The Nov 9-12 weak storm

Radial distribution of equatorial mass density

**Nov 9**
- FLIP model
- $t=1800 \text{ UT}$
- $t=1600 \text{ UT}$

**Nov 10**
- FLIP model
- $t=1600 \text{ UT}$

**Nov 11**
- FLIP model
- $t=1600 \text{ UT}$

**Nov 12**
- FLIP model
- $t=1600 \text{ UT}$
Information from the Phase Difference

Nov 10, 2006  L = 3.02

Nov 11, 2006  L = 3.49

Illustration of the Amplitude Ratio & Phase Difference

Strong Ionospheric Loading

Plasmapause

Regions of reverse PD

$PD = P_{eq} - P_{p}$

$AR = A_{eq}/A_{p}$
Nov 9-12, 2006 storm

- Dst
- Mass Density (amu/cc)

- L=3.49
- L=3.02
- L=2.88

Model L=2.75

Universal Time (hrs)
Possible Inferred Scenario

Nov 9

Nov 10

Nov 11 and 12

![Diagram with L=3.0 and regions marked with red stars](Image)

- **Strong Ionospheric Loading**
- **Regions of reverse PD**
- **Plasmapause**

![Graph with FLR and L-axis](Image)
FLR can be used to determine $\rho_{eq}$, based on formulas by Schulz [1996] and Denton and Gallagher [2000], assuming

$$\rho = \rho_{eq} \left( LR_E / R \right)^m$$

$m$ is the power law by which the density drops off along the field line.
FLR inversion to $\rho_{eq}$ not meaningful
June 7, 2003, $L>2$

Mass density $L$ distribution is unrealistic
Radial mass density distribution using 13 pairs of stations

- Blue: pair at Northern Hemisphere
- Red: pair at Southern Hemisphere

$L = 1.59$ to $3.14$
July 4, 2006: 13 pairs of stations

<table>
<thead>
<tr>
<th>Count</th>
<th>Pair</th>
<th>L</th>
<th>Hemisphere</th>
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<td>LYFD-SATX</td>
<td>1.59</td>
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<td>2</td>
<td>SATX-RICH</td>
<td>1.77</td>
<td>North</td>
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<tr>
<td>3</td>
<td>PAC-ESC</td>
<td>1.90</td>
<td>South</td>
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<tr>
<td>4</td>
<td>RICH-PCEL</td>
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<td>6</td>
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<td>12</td>
<td>BENN-GLYN</td>
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<tr>
<td>13</td>
<td>WRTH-GLYN</td>
<td>3.14</td>
<td>North</td>
</tr>
</tbody>
</table>

Fourier FLR plots, 4 July 2006 (day 185) LYFD-SATX
July 4, 2006: FLR determination

We use the average of the PD and AR techniques as the final FLR. For this pair, FLR is reliably determined between 14 and 19 UT.

From Boudouridis and Zesta [2007]
July 4, 2006: FLR and Mass Density

FLRs, July 4, 2006: AVG of PD and AR Techniques

Equatorial Mass Density: July 4, 2006
Model calculations of FLR are done by directly solving the standing wave equations for toroidal mode waves. The mass density distribution along the field line is taken from the FLIP thermosphere-ionosphere model run for this particular day. A dipole magnetic field is used.

The agreement between observations and model is impressive. July 4, 2006 is a day with low to moderate activity and the radial mass density distributions can be well represented by the model.
Storm time: Dec 14-16, 2006
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Model-Observations comparisons of FLRs: 1530 UT
Model-Observations comparisons of FLRs: 1800 UT
Model-Observation Comparisons

Storm of Dec 14-16, 2006

- ESC-OHI, L=2.23
- FLIP, L=2.0

Mass Density (amu/cc)

DST

Universal Time (hrs)

Dec 14  Dec 15  Dec 16

00  00  00  12  12  00  12  00
FLIP model results

**L = 1.75**

- UT (hours) [101 UT = 0 UT on December 14, 2006]
- Density (au/cm$^3$)

**L = 2.00**

- UT (hours) [101 UT = 0 UT on December 14, 2006]
- Density (au/cm$^3$)

**L = 3.00**

- UT (hours) [101 UT = 0 UT on December 14, 2006]
- Density (au/cm$^3$)

**Storm onset**
CONCLUSIONS

- We were able to observationally determine the radial distribution of the equatorial mass density using multiple pairs of magnetometers from the SAMBA and McMAC magnetometer chains.

- We used the FLIP thermosphere-ionosphere model to determine the mass density distribution along the flux tube and then solved the standing wave equations along the flux tube.

- Comparisons with the FLIP model are exceptional for quiet and moderate activity. Comparisons during storm period are poor.

- Future plan: constrain FLIP with observed FLRs for better mass density distribution.
Dec 14, 2006: 13 pairs of stations

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<td>RICH-AMER</td>
<td>2.02</td>
<td>North</td>
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<tr>
<td>13</td>
<td>WRTH-GLYN</td>
<td>3.14</td>
<td>North</td>
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</table>
Dec 14, 2006: Radial Distribution of Equatorial Mass Density

- The localized density peak at $L=1.93$ is from the pair PAC-ESC in the southern hemisphere. It is similar to the localized peak seen at the Jul 4, 2006 event above, but in this case the peak is even stronger.
- The localized peak increases in magnitude during the time period plotted.
Dec 14, 2006: Comparisons of observations with FLIP model results

For details on the calculation of the model FLRs see poster 42 by McCarthy et al.

The agreement between observations and model is impressive. Dec 14, 2006 is a day with low to moderate activity, just as the previous, July 4, 2006 event. We see that for such low-to-moderate activity the radial mass density distribution can be well represented by the FLIP model.
July 31, 2006: Radial Distribution of Equatorial Mass Density

Radial distribution of equatorial mass density

Mass density (amu/cc)

L

t=1900 UT
t=1800 UT
t=1700 UT
t=1600 UT
t=1500 UT
Modeled variation of $m$ power law for $L=3.5$ and lower
By Vellante et al. [2006]

$m$ has a non-negligible variation also at $L > 2$
Model calculations of FRL are done by directly solving the standing wave equations for toroidal mode waves. The mass density distribution along the field line is taken from the FLIP thermosphere-ionosphere model run for this particular day. A dipole magnetic field is used.

The agreement between observations and model is impressive. July 4, 2006 is a day with low to moderate activity and the radial mass density distributions can be well represented by the model.
SAMBA
South American Meridional B-field Array

- 11 magnetometers (1-sec sampling) along the coast of Chile and in Antarctica
- 4 magnetometers installed April 2002
- 4 magnetometers on May 2003
- 2 magnetometers on January 2004
- 1 mag on April 2005 and the last one on Nov 2005.

- AFRL team: Eftyhia Zesta (PI), Lt Nathan Sterner, Dr Endawoke Yizengaw
  - http://samba.atmos.ucla.edu
- UCLA team: A. Boudouridis (coPI), Yong Shi, P. Chi, J. Weygand
- U. of Michigan team: Mark Moldwin (coPI)
Table 1: SAMBA (A Chilean-American magnetometer chain) and the conjugate MEASURE stations

<table>
<thead>
<tr>
<th>Station Name</th>
<th>Station Code</th>
<th>Geographic Latitude</th>
<th>Geographic Longitude</th>
<th>CGM Latitude</th>
<th>CGM Longitude</th>
<th>UT of noon MLT</th>
<th>L-value</th>
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<td>Putre</td>
<td>PUT</td>
<td>-18.33</td>
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<td>Antofagasta</td>
<td>ANT</td>
<td>-23.39</td>
<td>-70.24</td>
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<td>SER</td>
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<td>-71.13</td>
<td>-16.55</td>
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<td>1.09</td>
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<td>Los Cerrillos</td>
<td>CER</td>
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<td>-70.6</td>
<td>-19.80</td>
<td>0.75</td>
<td>16:26</td>
<td>1.13</td>
<td>May 2003</td>
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<td>Osorno</td>
<td>OSO</td>
<td>-40.34</td>
<td>-73.09</td>
<td>-26.39</td>
<td>359.73</td>
<td>16:32</td>
<td>1.25</td>
<td>Apr 2002</td>
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<td>St. Gregorio</td>
<td>ENP</td>
<td>-52.13</td>
<td>-70.9</td>
<td>-37.58</td>
<td>1.59</td>
<td>16:22</td>
<td>1.59</td>
<td>Apr 2002</td>
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<td>Magallanes</td>
<td>PAC</td>
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<td>-70.9</td>
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<td>1.63</td>
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<td>ESC</td>
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<td>-58.92</td>
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<td>15:48</td>
<td>2.18</td>
<td>Jan 2004</td>
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<td>O'Higgins</td>
<td>OHI</td>
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<td>-57.9</td>
<td>-48.8</td>
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<td>15:45</td>
<td>2.28</td>
<td>Jan 2004</td>
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<td>Palmer</td>
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<td>-64.05</td>
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<td>(Apr 2005)</td>
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<td>Vernadsky</td>
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<td>-50.19</td>
<td>9.19</td>
<td>16:00</td>
<td>2.44</td>
<td>(Ukrainian)</td>
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MEASURE CONJUGATE STATIONS

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<td>APL</td>
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<td>352.39</td>
<td>17:21</td>
<td>1.71</td>
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**Station Count:**

Total: 250

- CPMN: 54 (second)
- UCLA-built: 65 (largest)
McMAC stations and coordinates

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<tr>
<th>Station</th>
<th>Code</th>
<th>Geographic Latitude</th>
<th>Geographic Longitude</th>
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<td>Bennington</td>
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<td>41.36°</td>
<td>263.84°</td>
<td>2.58</td>
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<td>Americus</td>
<td>AMER</td>
<td>38.5°</td>
<td>263.7°</td>
<td>2.28</td>
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<td>Purcell</td>
<td>PCEL</td>
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<td>263.25°</td>
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<td>SATX</td>
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<td>261.39°</td>
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<td>LYFD</td>
<td>26.4°</td>
<td>262.2°</td>
<td>1.53</td>
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</tbody>
</table>
ULF or Alfven Waves

- $V_A = B/\left(\mu_0\rho\right)^{1/2}$
- PC 3/4 waves (7 - 100 mHz or 10-150 s)
- Frequency is function of field line length, field strength, and mass density of plasma
- Field-line standing wave period
  - $T = (2/n) \int ds/V_A$ [Dungey, 1954]
We determine the local FLR from the northern and southern pairs of stations from $L=1.59$ to $L=3.14$ during the dayside period of selected days, using the amplitude ratio and cross-phase technique [Baranksy et al., 1985].

The frequency of the local resonance can be used to determine the equatorial mass density of the resonating flux tube. We use the formulas defined by Schulz et al. [1996] and Denton and Gallagher [2000]. The assumption is that of a dipole magnetic field and that the mass density, $\rho$, varies along the magnetic field line as

$$\rho = \rho_{eq} \left( LR_E/R \right)^m$$

where $m$ is the power law by which the density drops off along the field line.
FLRs and equatorial mass densities for power law of m=2,3,4,5 (along the field lines)

The green, orange, and light blue lines are the predicted mass densities at L=1.74 based on the observed mass densities at L=1.6 for a radial density drop-off as \( \frac{1}{R^2} \), \( 10^{-0.67L+5.1} \) [Berube et al., 2005], and as \( \frac{1}{R^4} \)

The radial power law \( a=2 \) is close to the radial drop-off according to the H⁺ scale height
FLR inversion to get equatorial mass density
July 11, 2003 event. Only 2 pairs of stations

JULY 11, 2003

CONJUGATE FLRs

Equatorial Mass Density for m=3

Figure 5: FLR and equatorial mass density determinations for July 11, 2003. \( m \) is the density power law along the field line, while \( a \) is the radial density power law.
FLR inversion to get equatorial mass density
July 4, 2006 event
We observe lower FLR at L=1.9 than at L=2.14 implying a higher mass density at L=1.90, which is surprising.
Dec 14, 2006: FLR and Mass Density

FLRs, Dec 14, 2006: AVG of PD and AR Techniques

Equatorial Mass Density: Dec 14, 2006
Jul 31, 2006: 9 pairs of stations

<table>
<thead>
<tr>
<th>Count</th>
<th>Pair</th>
<th>L</th>
<th>Hemisphere</th>
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<tr>
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<td>LYFD-SATX</td>
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<tr>
<td>2</td>
<td>SATX-RICH</td>
<td>1.77</td>
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<tr>
<td>3</td>
<td>PAC-ESC</td>
<td>1.90</td>
<td>South</td>
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<td>4</td>
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<td>BENN-GLYN</td>
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<tr>
<td>9</td>
<td>WRTH-GLYN</td>
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</table>

Fourier FLR plots, 31 July 2006 (day 212) AMER-BENN

[Graph showing frequency and phase difference over universal time]
July 31, 2006: FLR determinations

Fourier FLR plots, 31 July 2006 (day 212)

**PAC-ESC**

- Frequency (mHz)
- Phase Difference PAC-ESC
- Amplitude Ratio PAC-ESC

**WRTH-GLYN**

- Frequency (mHz)
- Phase Difference WRTH-GLYN
- Amplitude Ratio WRTH-GLYN
July 31, 2006: FLRs and Mass Density

FLRs, July 31, 2006: AVG of PD and AR Techniques

Equatorial Mass Density: July 31, 2006

LYFD-SATX
SATX-RICH
PAC-ESC
RICH-AMER
AMER-BENN
AMER-WRTH
BENN-WRTH
BENN-GLYN
WRTH-GLYN