Optimising Models of HF Absorption in the Polar Cap Ionosphere

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Outline

1. Project objectives
2. Modelling Polar Cap Absorption
3. Comparison of model with riometer measurements at Kilpisjärvi, Finland, for 94 Solar Proton Events, 1996-2006
4. Modifying the absorption map by assimilating multiple riometer measurements
Project Objectives

• Predict HF comm outages at high latitudes due to space weather
  – useful for airlines on polar routes
• Produce a real-time/forecast map of 30 MHz absorption
  – forecast up to 12 hours ahead
• Combine maps with HF ray-tracing tools* to provide a planning tool for HF comm.
  – * University of Leicester

Trans-polar flight paths [Neal et al. 2013]
Measurements - HF sounders and DF receivers

- See presentation by Alan Stocker et al. tomorrow at 10:09 am (Space Weather Impacts on Aviation session)
Measurements - Global Riometer Array (GloRiA)
Measurements - Riometers

- RIOMETER = Relative Ionospheric Opacity Meter
- Measures ionospheric absorption of (stable) cosmic noise background at ~ 30 MHz
- Measured relative to a Quiet Day Curve (a 24-hour noise profile)

![IRIS imaging riometer in Kilpisjärvi, Finland](image)

Example of riometer noise power (blue) and QDC (red) [Marple, 2012]
CANOPUS / NORSTAR Riometers  (University of Calgary)

- pina  Pinawa, Canada     (50.2° N, 96.0°W)
- isll  Island lake, Canada (53.9° N, 94.7° W)
- mcmu  Fort McMurray, Canada (56.7° N, 111.2° W)
- fchu  Fort Churchill, Canada (58.8° N, 94.1° W)
- eski  Eskimo Point, Canada (61.1° N, 94.1° W)
- fsim  Fort Simpson, Canada (61.8° N, 121.2° W)
- fsmi  Fort Smith, Canada (60.0° N, 111.9° W)
- rank  Rankin Inlet, Canada (62.8° N, 92.1° W)
- daws  Dawson, Canada (64.1° N, 139.1° W)
- cont  Contwoyto Lake, Canada (65.8° N, 111.3° W)
- talo  Taloyoak, Canada (69.5° N, 93.6° W)
- gill  Gillam, Canada (56.4° N, 94.6° W)
- rabb  Rabbit Lake, Canada (58.2° N, 103.7° W)

CANOPUS/NORSTAR riometers [http://aurora.phys.ucalgary.ca]
Sodankyla Geophysical Observatory (SGO) Riometers

- ABI Abisko, Sweden (68.4°N, 18.8°E)
- IVA Ivalo, Finland (68.5°N, 27.3°E)
- JYV Jyväskylä, Finland (62.4°N, 25.3°E)
- ROV Rovaniemi, Finland (66.8°N, 25.9°E)
- SOD Sodankyla, Finland (67.4°N, 26.4°E)
- KIL Kilpisjärvi, Finland (69.05° N, 20.79° E)

Finnish riometer chain [www.sgo.fi]
Modelling Polar Cap Absorption

• D-Region Absorption Prediction model (DRAP)
  – NOAA Space Weather Prediction Center model

• Inputs
  – X-ray flux (1-8 Å band)
  – Integrated proton flux
  – Geomagnetic indices, $K_p$ and $D_{st}$
  – Solar-zenith angles

• Outputs
  – absorption (30 MHz CNA)
MAJOR SOLAR FLARE
A major X-Class solar flare peaking at X1.7 was observed around new Sunspot 1882 this morning at 08:01 UTC. The event was associated with Type II and Type IV sweep frequency events, along with a 10cm Radio Burst (TenFlare) lasting 24 minutes and measuring 610 solar flux units (SFU). A bright coronal mass ejection (CME) is now visible in the latest LASCO imagery. Because of the location near the limb, a majority of the plasma cloud will be directed away from Earth. More updates to follow regarding a possible Earth directed component.

\[
HAF = \{10 \log(F(\text{W} m^{-2})+65)(\cos \chi)^{0.75} \text{ (MHz)}
\]

\[
A_{xray} (30 \text{ MHz}) = \frac{1}{2} \left( \frac{HAF}{30} \right)^{1.5} \text{ (dB)}
\]

DRAP predictions of a shortwave fadeout due to X-ray ionisation (25 Oct. 2013)
The NOAA / DRAP model

- **Daytime absorption**
  \[ A_d = 0.115 [J(E > 5.2 \text{ MeV})]^{1/2} \text{dB} \]

- **Night-time absorption**
  \[ A_n = 0.020 [J(E > 2.2 \text{ MeV})]^{1/2} \text{dB} \]
  - (From a study of four SPEs/PCAs at the Thule 30 MHz Riometer [Sellers, 1977])

- **Proton energy must also exceed a rigidity cut-off energy, \( E_c \)
Example 1: The Bastille Day Event

Absorption

GOES integral proton fluxes

Rigidity cut-off energy

$K_p$

Solar zenith angle

![Graphs showing solar zenith angle, $K_p$, GOES integral proton fluxes, and absorption over time.](image)

**SPE Start time = 14-Jul-2000 10:45:00**

- IRIS Kilpisjärvi Riometer
- DRAP

**E (MeV)**

- Blue: 1
- Green: 5
- Red: 10
- Pink: 30
- Purple: 50
- Yellow: 60
- Grey: 100
Periods of “negative absorption” are spurious.

In daytime these may be due to solar radio emissions.
Spikes in >1 MeV protons correlate with large (~2dB) spikes in absorption.

DRAP only considers protons > cut-off energy and excludes the effect of lower-energy, magnetospherically trapped protons (and electrons).
CNA vs. $\sqrt{\text{Proton Flux}}$ at IRIS Kilpisjärvi

- Find least-squared error fit for the scaling factor $m$ in
\[ A_r = m J_p (> E_t)^{1/2} \]
\[ m = \begin{cases} \frac{m_d}{\text{day}} \\ \frac{m_n}{\text{night}} \end{cases} \]

- Select times of Solar Proton Events (1996-2006)
  - 94 periods for which $J_p (> 10 \text{ MeV}) > 10 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$

- GOES 8 satellite (or GOES 11 after 17 June 2003)

- Remove periods of
  - Solar Radio Emissions
    - Times when $A_r < 0.1 \text{dB}$ (and, on dayside, within +/-15 minutes)
  - Sudden Impulses / Storm Sudden Commencements
    - 15mins before to 6 hours afterwards

- Subtract DRAP estimates of X-ray-induced absorption

- Use $f^{-1.5}$ frequency scaling
CNA vs. $\sqrt{\text{Proton Flux}}$ at IRIS Kilpisjärvi

Daytime ($\chi < 80^\circ$)
CNA vs. $\sqrt{\text{Proton Flux}}$ at IRIS Kilpisjärvi

Daytime ($\chi < 80^\circ$): Restricting to “Inside Polar Cap” only ($E_c < 5.2$ MeV)
CNA vs. Proton Flux at IRIS Kilpisjärvi

Night-time ($\chi > 100^\circ$)
CNA vs. √Proton Flux at IRIS Kilpisjärvi

Night-time (χ > 100°): Restricting to “Inside Polar Cap” only (E_c < 2.2 MeV)
Can also vary the scaling factors $m_n$ and $m_d$ to minimise other error statistics.

Note: optimal values for $m_n$ and $m_d$ are higher for minimising signed errors.
CNA vs. √Proton Flux at IRIS Kilpisjärvi

- The above analysis discards periods for which $80^\circ < \chi < 100^\circ$ – (approx. half of the data)
- For twilight region DRAP uses a linear transition based on zenith angle, $\chi$

$$A = A_d Z_d + A_n Z_n$$

Zenith angle weighting functions
Real-time optimisation of DRAP scaling factors

- Find a least-squared error solution for \((m_d, m_n)\)

\[
\begin{pmatrix}
A_r(1) \\
A_r(2) \\
A_r(3) \\
\vdots \\
A_r(n)
\end{pmatrix} =
\begin{pmatrix}
J^{1/2} \left( > E_{t,d}(1) \right) Z_d(\chi(1)) \\
J^{1/2} \left( > E_{t,d}(2) \right) Z_d(\chi(2)) \\
J^{1/2} \left( > E_{t,d}(3) \right) Z_d(\chi(3)) \\
\vdots \\
J^{1/2} \left( > E_{t,d}(n) \right) Z_d(\chi(n))
\end{pmatrix} m_d
\begin{pmatrix}

\end{pmatrix}

\begin{pmatrix}
J^{1/2} \left( > E_{t,n}(1) \right) Z_n(\chi(1)) \\
J^{1/2} \left( > E_{t,n}(2) \right) Z_n(\chi(2)) \\
J^{1/2} \left( > E_{t,n}(3) \right) Z_n(\chi(3)) \\
\vdots \\
J^{1/2} \left( > E_{t,n}(n) \right) Z_n(\chi(n))
\end{pmatrix} m_n
\]

\[
\bar{A} = Jm \\
J^T \bar{A} = J^T Jm \\
(J^T J)^{-1} J^T \bar{A} = m
\]

- Applying to full IRIS Kilpisjärvi data set (for SPE times) gives
  \[m_d = 0.103 \text{ and } m_n = 0.023\]
  (cf. \(m_d = 0.115 \text{ and } m_n = 0.020\) in DRAP)
Real-time optimisation of DRAP scaling factors

- Try this technique on the Bastille Day event (multiple riometers)
- Fit $m_n$ and $m_d$ to all riometer measurements over a 30-minute period
- Night measurements (for $m_n$) not always available so revert to standard model values at these times

![Graph showing real-time optimisation of DRAP scaling factors](image)
$m_d = 0.103, \ m_n = 0.020$

$00:00 \ 15 \ July \ 2000$

$00:00 \ 15 \ July \ 2000$
Optimised DRAP

$m_d = 0.100, \ m_n = 0.020$

DRAP

$m_d = 0.115, \ m_n = 0.020$

02:00  15 July 2000
Optimised DRAP

$m_d = 0.073$, $m_n = 0.320$

Extreme value of $m_n$ used on nightside (from least-squares fit)

04:00 15 July 2000

DRAP

$m_d = 0.115$, $m_n = 0.020$
Optimised DRAP

\[ m_d = 0.065, \ m_n = 0.024 \]

DRAP

\[ m_d = 0.115, \ m_n = 0.020 \]

06:00  15 July 2000
$m_d = 0.073, \ m_n = 0.027$

$\ m_d = 0.115, \ m_n = 0.020$
**Optimised DRAP**

\[ m_d = 0.074, \quad m_n = 0.020 \]

**DRAP**

\[ m_d = 0.115, \quad m_n = 0.020 \]

10:00   15 July 2000
Optimised DRAP

$m_d = 0.065, \ m_n = 0.020$

DRAP

$m_d = 0.115, \ m_n = 0.020$

12:00   15 July 2000
Optimised DRAP

\[ m_d = 0.065, \ m_n = 0.020 \]

DRAP

\[ m_d = 0.115, \ m_n = 0.020 \]

14:00  15 July 2000
$m_d = 0.071, \ m_n = 0.020$

$15$ July $2000$

$16:00$

$Riometer$

$Absorption (dB)$

$Absorption (dB)$

$Absorption (dB)$

$m_d = 0.115, \ m_n = 0.020$
Optimised DRAP

$m_d = 0.076, m_n = 0.020$

DRAP

$m_d = 0.115, m_n = 0.020$

18:00  15 July 2000
Optimised DRAP

$m_d = 0.126, m_n = 0.020$

DRAP

$m_d = 0.115, m_n = 0.020$

20:00 15 July 2000
Optimised DRAP

\[ m_d = 0.114, \ m_n = 0.020 \]

\[ m_d = 0.115, \ m_n = 0.020 \]

22:00 15 July 2000
Optimised DRAP

\[ m_d = 0.128, \quad m_n = 0.020 \]

DRAP

\[ m_d = 0.115, \quad m_n = 0.020 \]

00:00  16 July 2000
An Alternative Data Assimilation Method for Mapping PCA

- Combine riometer measurements (at multiple sites) with DRAP predictions
- Fit a spherical harmonic function to all points

\[ \Phi(\theta, \phi) = \sum_{l=0}^{L_{\text{max}}} \sum_{m=-l}^{l} A_{lm} P_l^m(\cos \theta) e^{im\phi} \]

- Scale the colatitude, \( \theta \), from 180° to a maximum of (say) 60°

Spherical harmonic components (up to \( l = 4 \))
[from Grocott et al., 2012]
An Alternative Data Assimilation Method for Mapping PCA

- Then find vector of all coefficients, $A_{lm}$, by regression to a vector of measurements, $\mathbf{f}$

\[
\begin{pmatrix}
  f_1(\theta_1, \varphi_1) \\
  f_2(\theta_1, \varphi_1) \\
  \vdots \\
  f_n(\theta_n, \varphi_n)
\end{pmatrix} = 
\begin{pmatrix}
  [Y_0^0(\theta_1, \varphi_1), Y_1^0(\theta_1, \varphi_1), \ldots, Y_l^m(\theta_1, \varphi_1), \ldots] \\
  [Y_0^0(\theta_2, \varphi_2), Y_1^0(\theta_2, \varphi_2), \ldots, Y_l^m(\theta_2, \varphi_2), \ldots] \\
  \vdots \\
  [Y_0^0(\theta_n, \varphi_n), Y_1^0(\theta_n, \varphi_n), \ldots, Y_l^m(\theta_n, \varphi_n), \ldots]
\end{pmatrix} 
\begin{pmatrix}
  A_0^0 \\
  A_1^0 \\
  \vdots \\
  A_l^m
\end{pmatrix}
\]

$\mathbf{f} = \mathbf{Y} \mathbf{A}$

- A weighted linear regression is used, weighting the riometers more highly than the model, thus

\[
\mathbf{A} = (\mathbf{Y}^T \mathbf{W} \mathbf{Y})^{-1} \mathbf{Y}^T \mathbf{W} \mathbf{f}
\]
An Alternative Data Assimilation Method for Mapping PCA

CNA (30 MHz): Spherical harmonic fit \( (L_{\text{max}}=4, M_{\text{max}}=4) \). 14-Jul-2000 10:00:00

Absorption (dB)
Combined Optimisation and Fitting

Original DRAP model (from NOAA)

Fit spherical harmonics

Optimise linear model parameters

Combined methods

$m_d = 0.115, \ m_n = 0.020$

$m_d = 0.070, \ m_n = 0.024$
Conclusions

• A comparison of linear scaling factors in DRAP model with IRIS Kilpisjärvi measurements (1996-2006) suggests:
  – *Daytime*: $m_d$ is 10-20% too high (over-predicting absorption)
  – *Night-time*: $m_n$ is 0-15% too low (under-predicting absorption)

• Riometer measurements may be used to adapt the model parameters in real-time and so produce a map of polar cap absorption

• Alternatively we can fit a spherical harmonic function to the riometer data, with extra points provided by a model