Optimising Models of HF Absorption in the Polar Cap Ionosphere

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In collaboration with the University of Leicester, Natural Resources Canada and SolarMetrics.com.

Ionospheric Effects Topical Working Group,
European Space Weather Week 10, Antwerp, Belgium.
19 November 2013

Outline

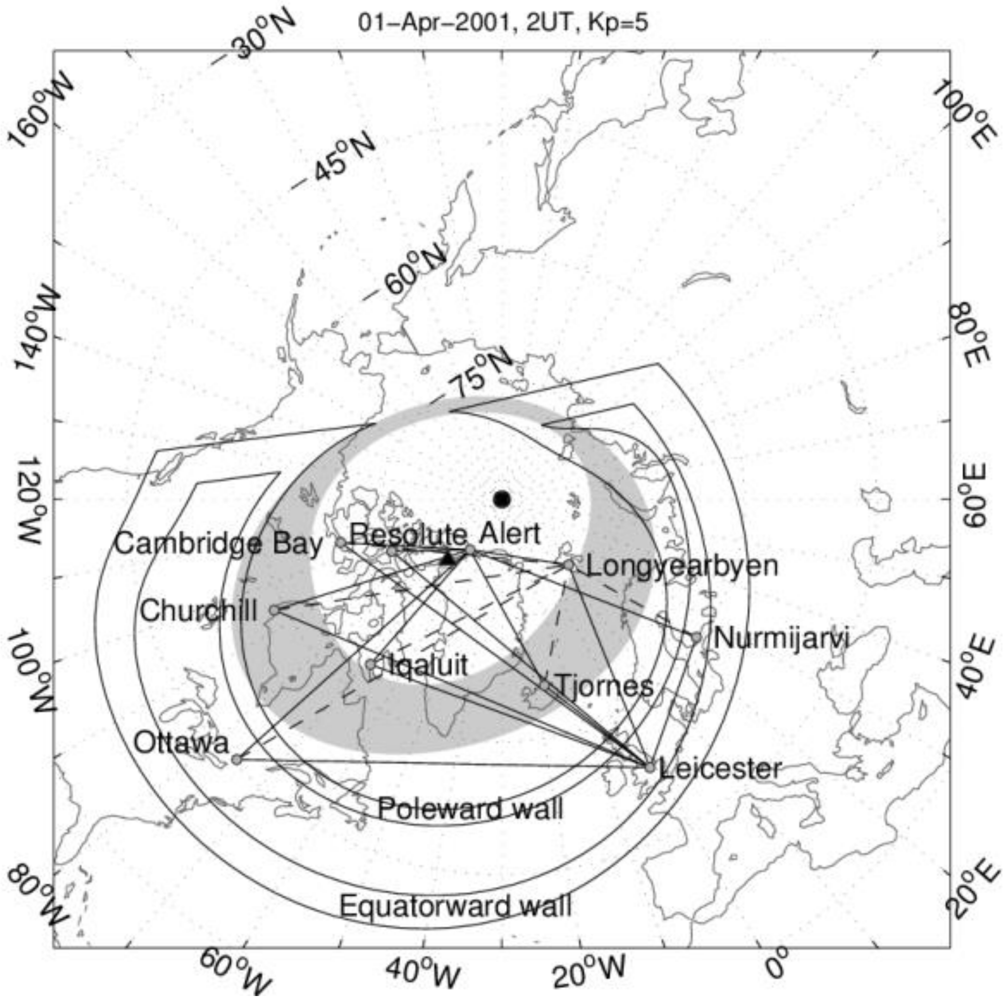
1. Project objectives
2. Modelling Polar Cap Absorption
3. Comparison of model with riometer measurements at Kilpisjärvi, Finland, for 94 Solar Proton Events, 1996-2006
4. Modifying the absorption map by assimilating multiple riometer measurements

Project Objectives

- Predict HF comms 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 comms.
  - * University of Leicester

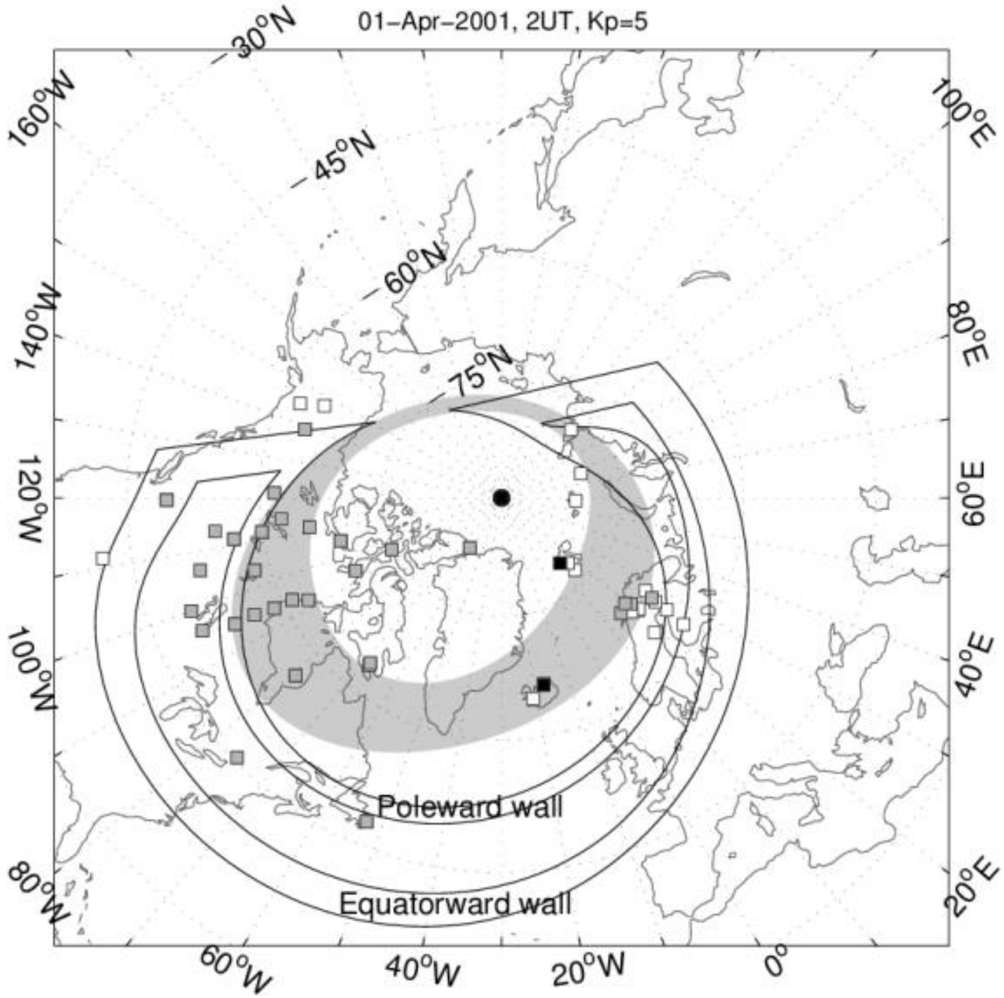
Trans-polar flight paths
[Neal et al. 2013]

Measurements - HF sounders and DF receivers



- *See presentation by Alan Stocker et al. tomorrow at 10:09 am (*Space Weather Impacts on Aviation session)

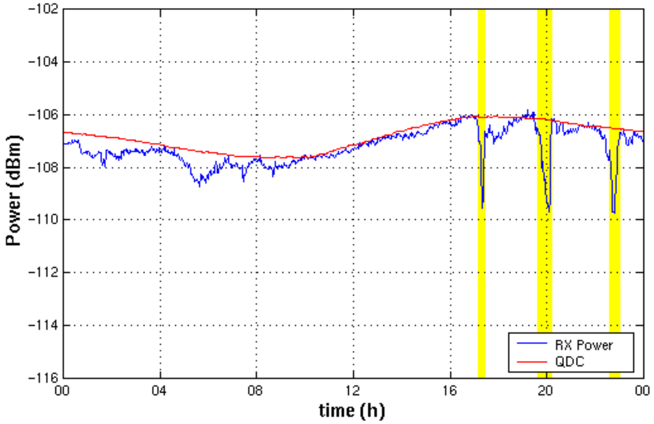
Measurements - Global Riometer Array (GloRiA)



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)

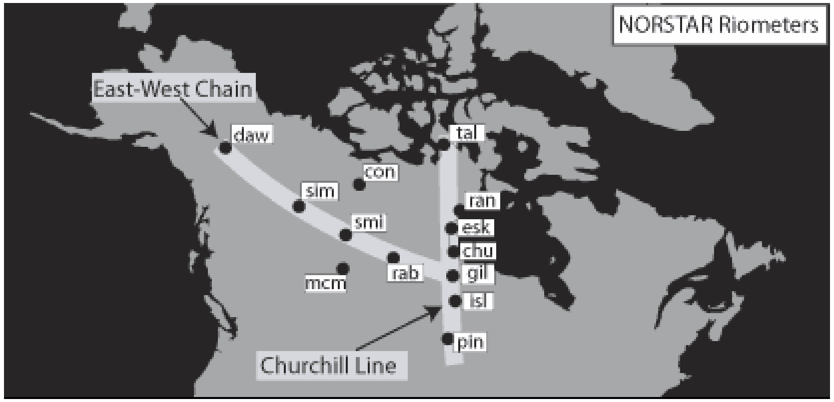
IRIS imaging riometer in Kilpisjärvi, Finland



Example of riometer noise power (blue) and QDC (red) [Marple, 2012]

CANOPUS / NORSTAR Riometers (University of Calgary)

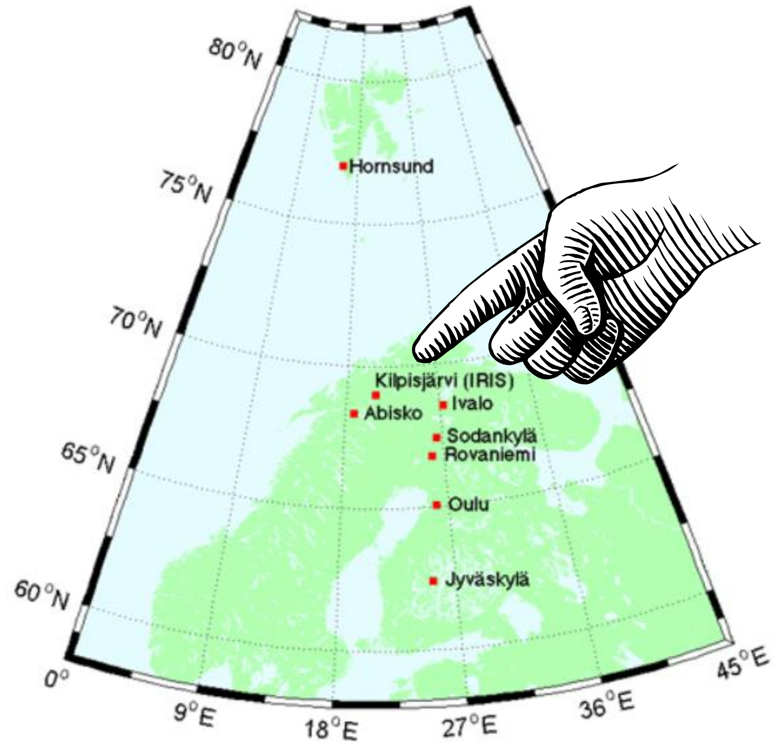
- pina Pinawa, Canada (50.2° N, 96.0°W)
- isll Island lake, Canada (53.9° N, 94.7° W)
- mcmu Fort McMurray, Canada (56.7° N, 111.2° W)
- fchu Fort Churchill, Canada (58.8° N, 94.1° W)
- eski Eskimo Point, Canada (61.1° N, 94.1° W)
- fsim Fort Simpson, Canada (61.8° N, 121.2° W)
- fsmi Fort Smith, Canada (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 Jyvaskyla, 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)**



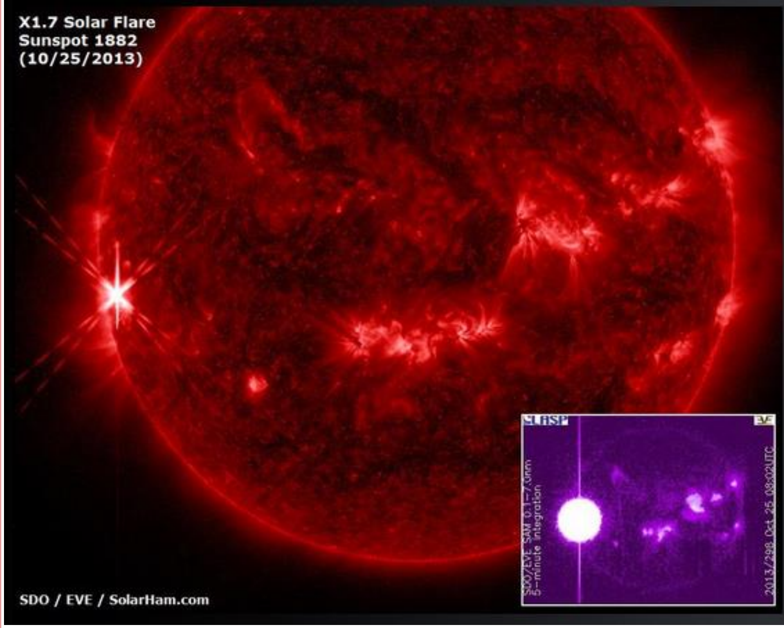
Finnish riometer chain [www.sgo.fi]

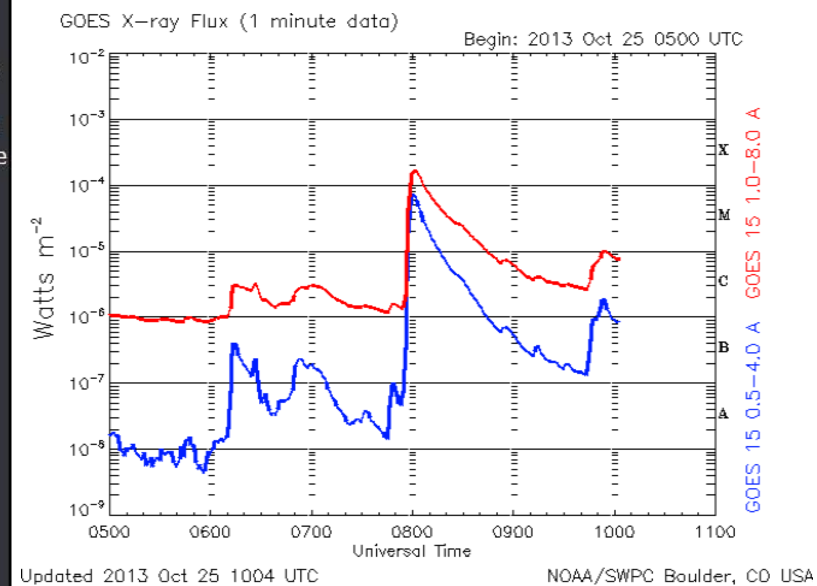
Modelling Polar Cap Absorption

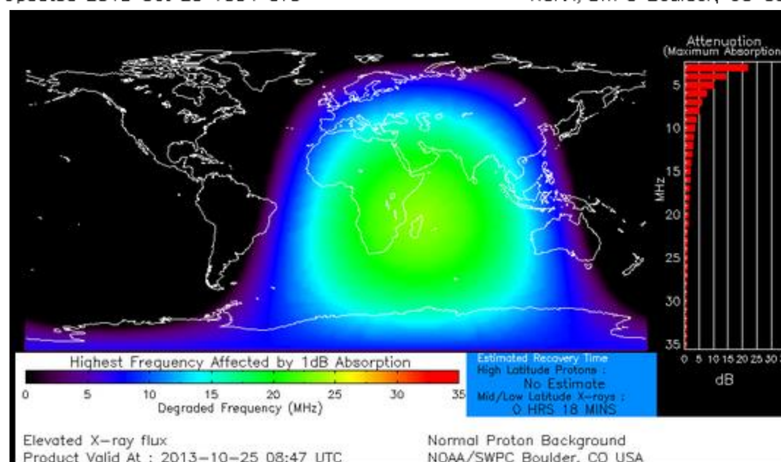
- D-Region Absorption Prediction model (DRAP)
  - Sauer & Wilkinson, 2008
  - NOAA Space Weather Prediction Center model
- Inputs
  - X-ray flux (1-8 Å band)
  - Integrated proton flux
  - Geomagnetic indices, K_p and D_{st}
  - Solar-zenith angles
- Outputs
  - absorption (30 MHz CNA)

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.







$$HAF = \{10\log(F(Wm^{-2}) + 65\}(\cos\chi)^{0.75} \quad \text{(MHz)}$$

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

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

The NOAA / DRAP model

- Daytime absorption

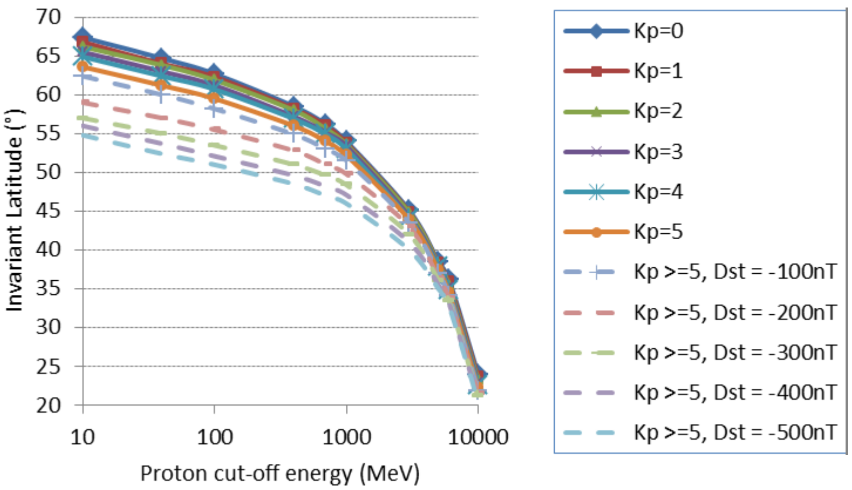
$$A_d = 0.115[J(E > 5.2\,\mathrm{MeV})]^{1/2} dB$$

- Night-time absorption

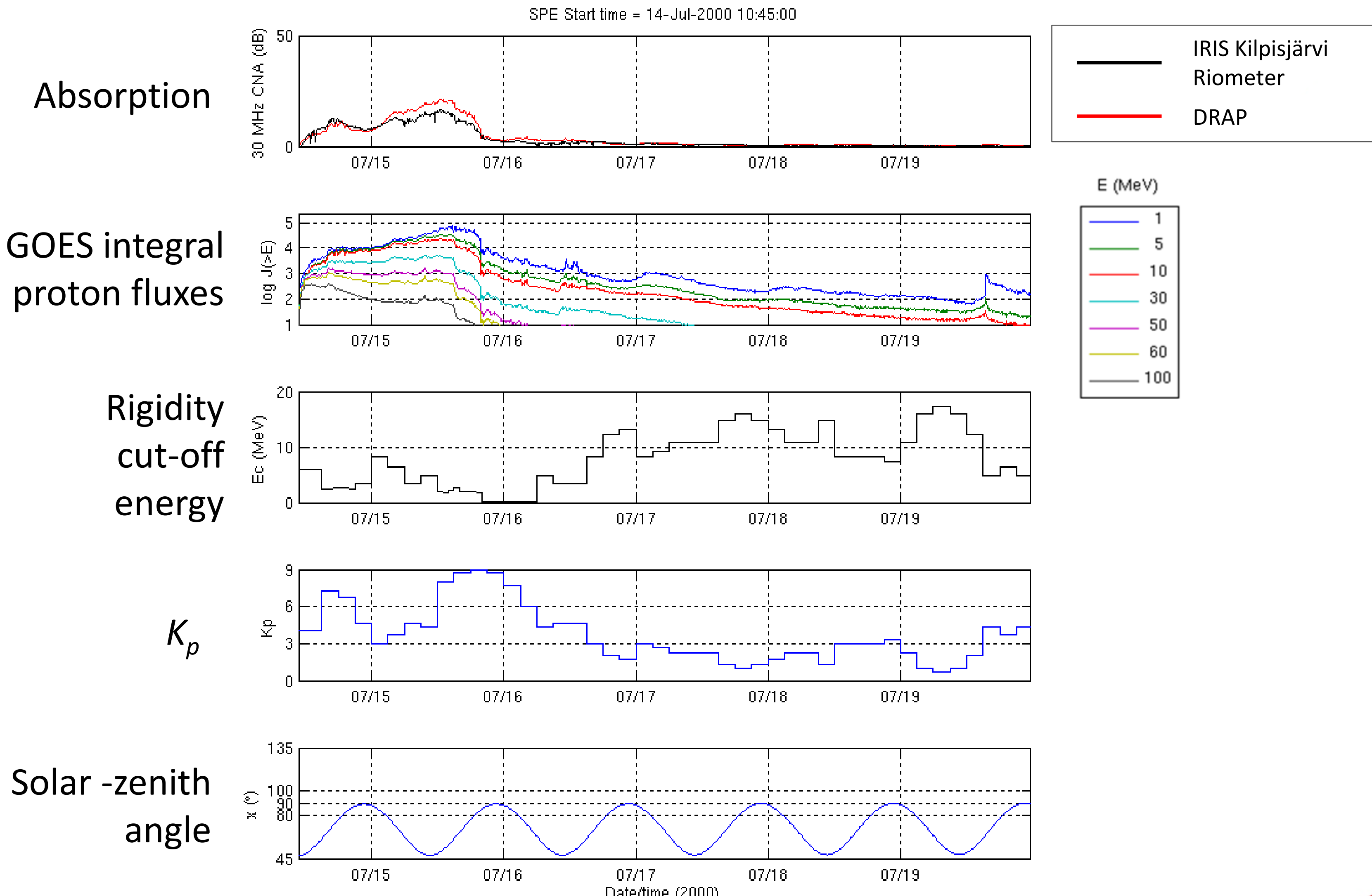
$$A_n = 0.020[J(E > 2.2\,\mathrm{MeV})]^{1/2} dB$$

  – (From a study of four SPEs/PCAs at the Thule 30 MHz Riometer [Sellers, 1977])

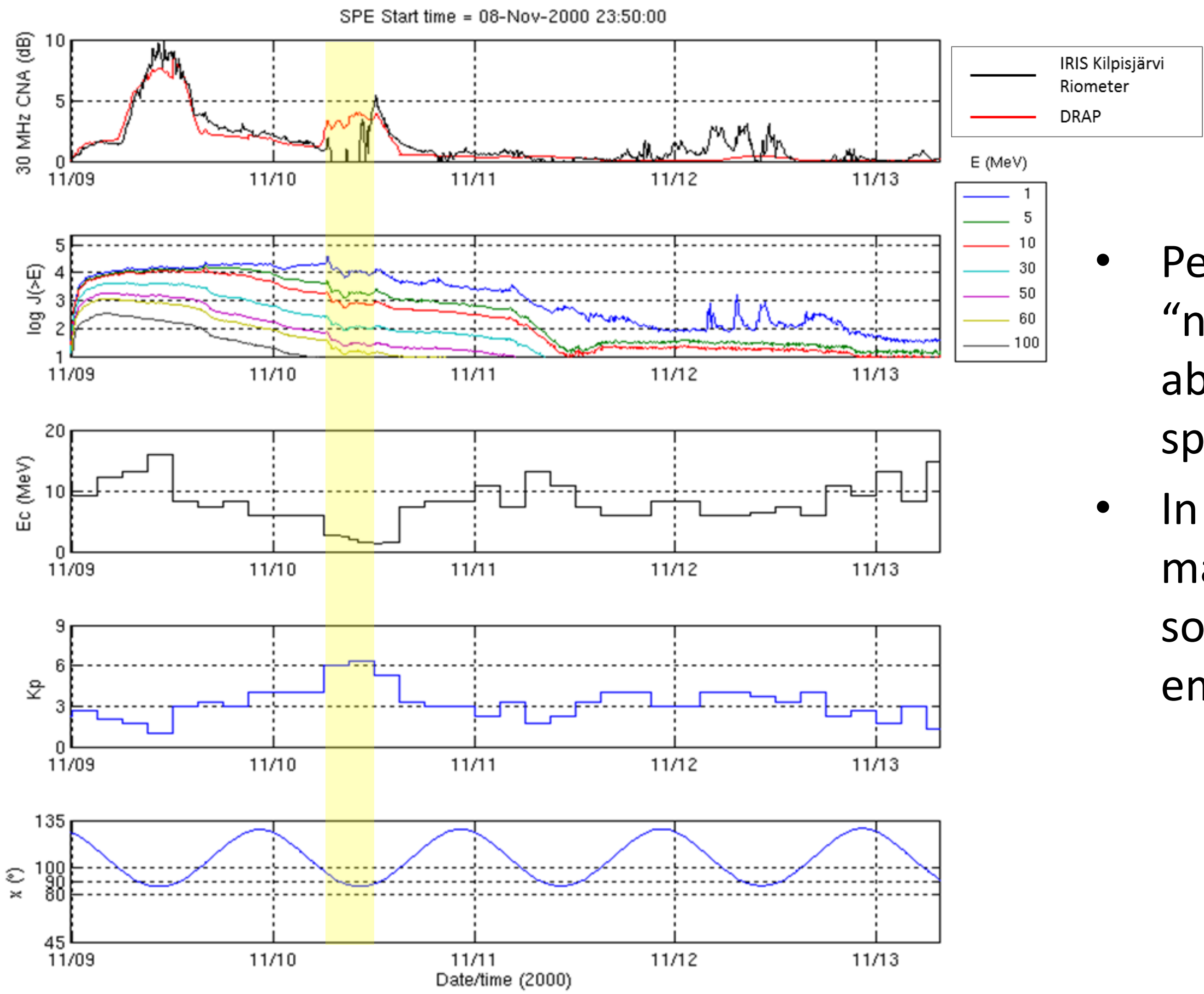
- Proton energy must also exceed a rigidity cut-off energy, E_c



Example 1: The Bastille Day Event

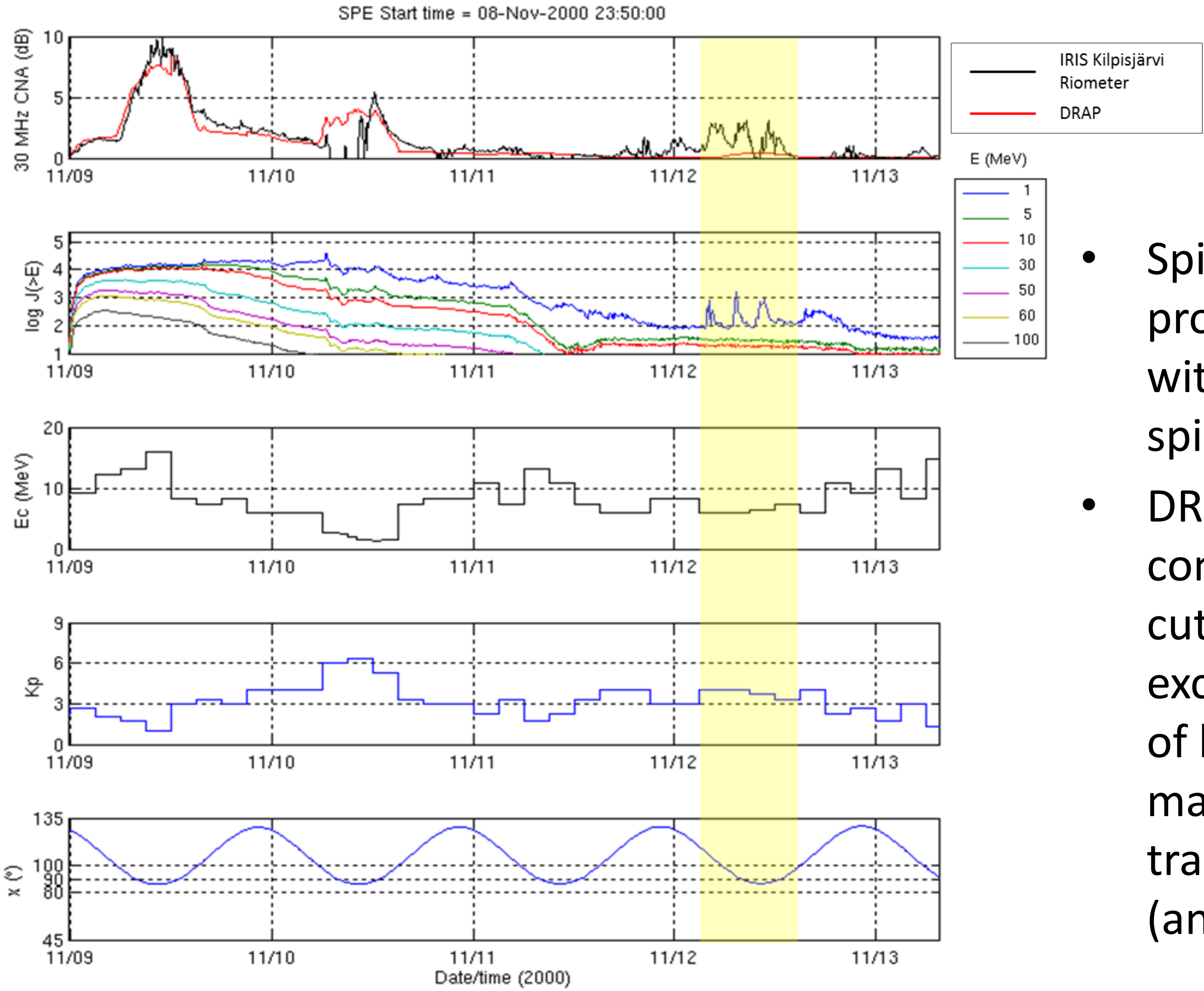


Example 2



- Periods of “negative absorption” are spurious
- In daytime these may be due to solar radio emissions

Example 2



- 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. √Proton Flux at IRIS Kilpisjärvi

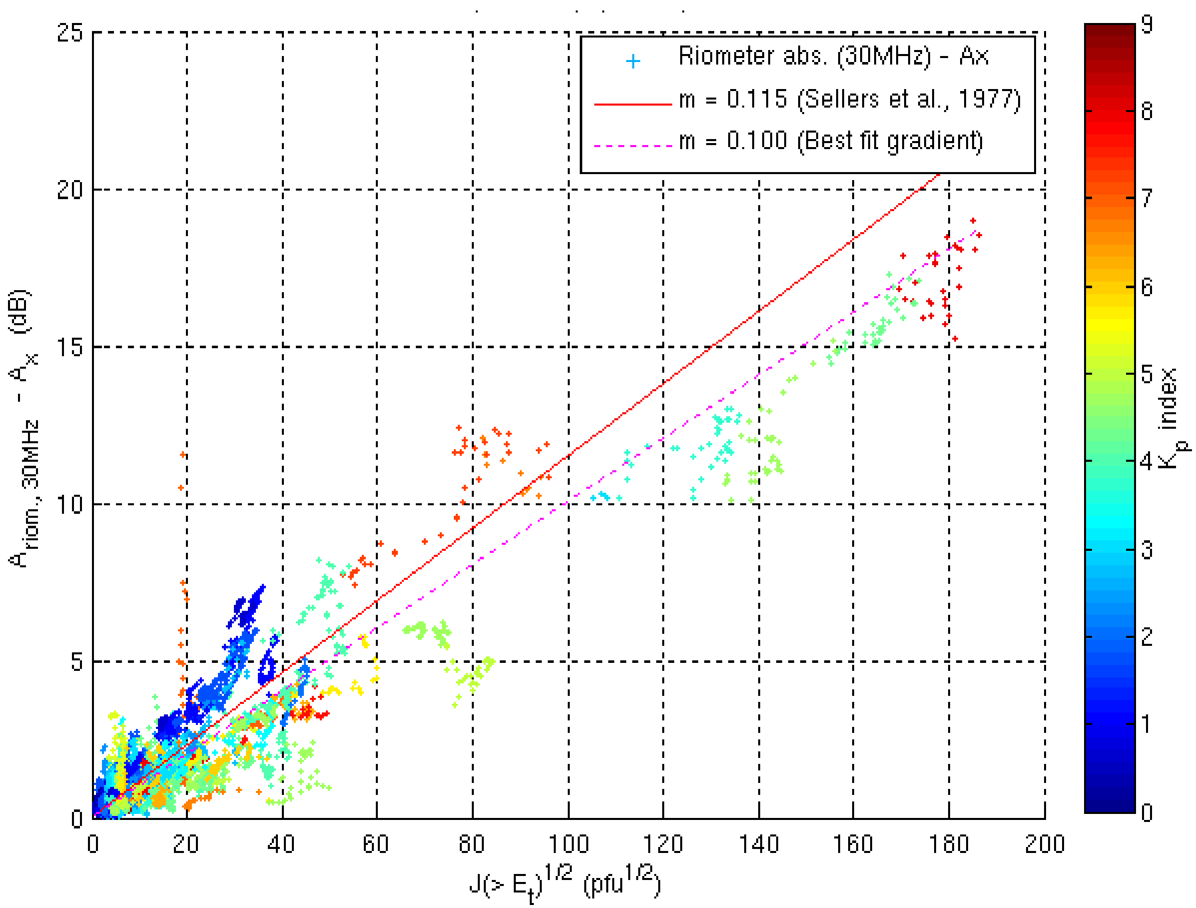
- Find least-squared error fit for the scaling factor *m* in

$$A_r = \boxed{m}\, J_p(> E_t)^{1/2} \qquad m = \begin{cases} m_d & day \\ m_n & night \end{cases}$$

- Select times of Solar Proton Events (1996-2006)
  - 94 periods for which $J_p(> 10\ MeV) > 10$ cm^{-2} s^{-1} sr^{-1}
- GOES 8 satellite (or GOES 11 after 17 June 2003)
- Remove periods of
  - Solar Radio Emissions
    - Times when $A_r < 0.1$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

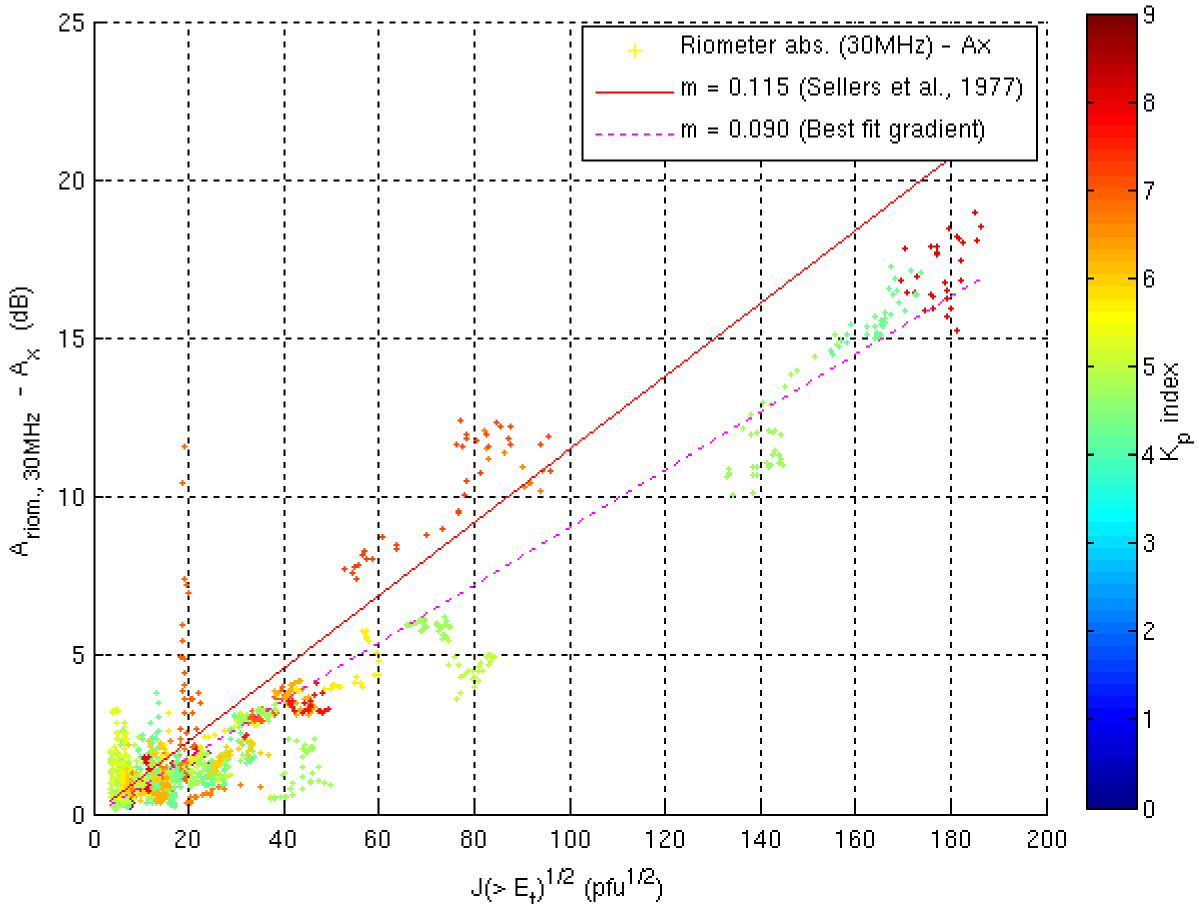
CNA vs. √Proton Flux at IRIS Kilpisjärvi

Daytime ($\chi < 80°$)



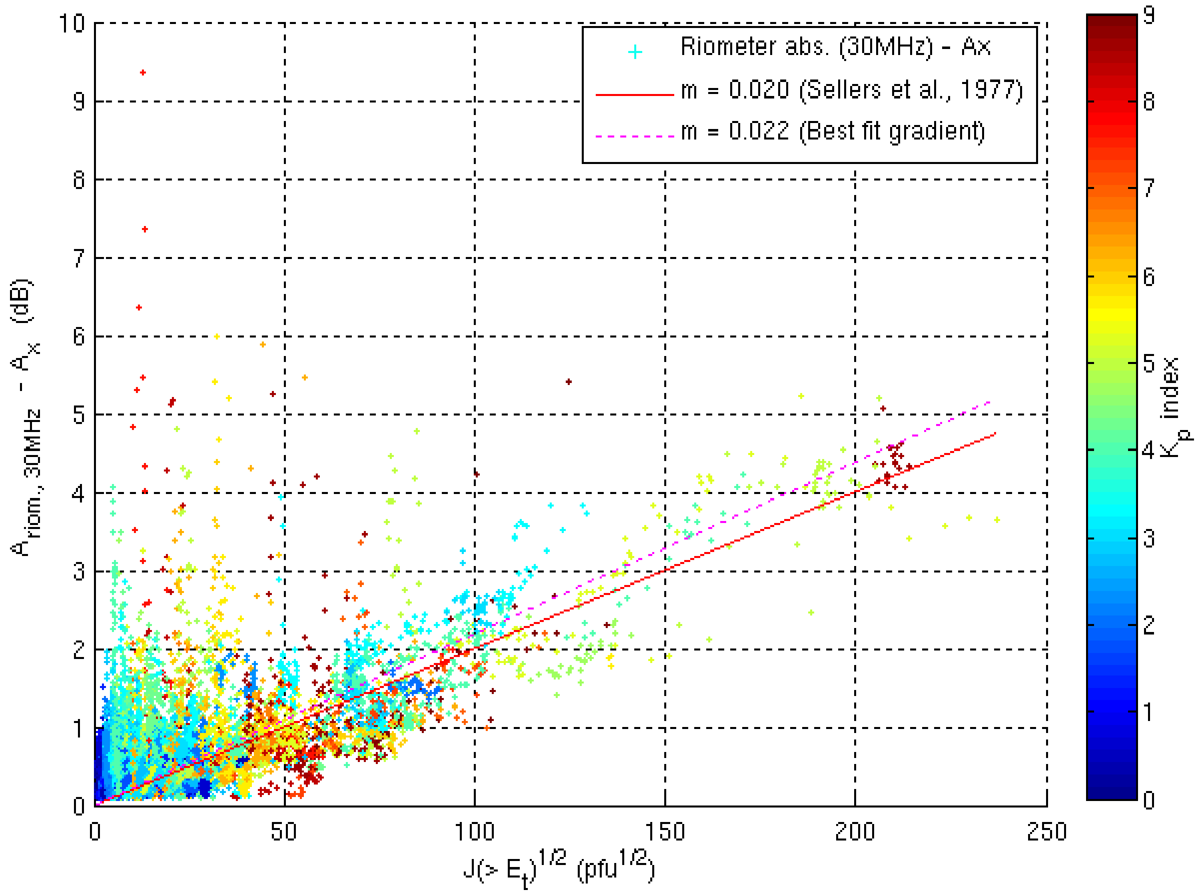
CNA vs. √Proton Flux at IRIS Kilpisjärvi

Daytime (χ < 80°): Restricting to "Inside Polar Cap" only (E_c < 5.2 MeV)



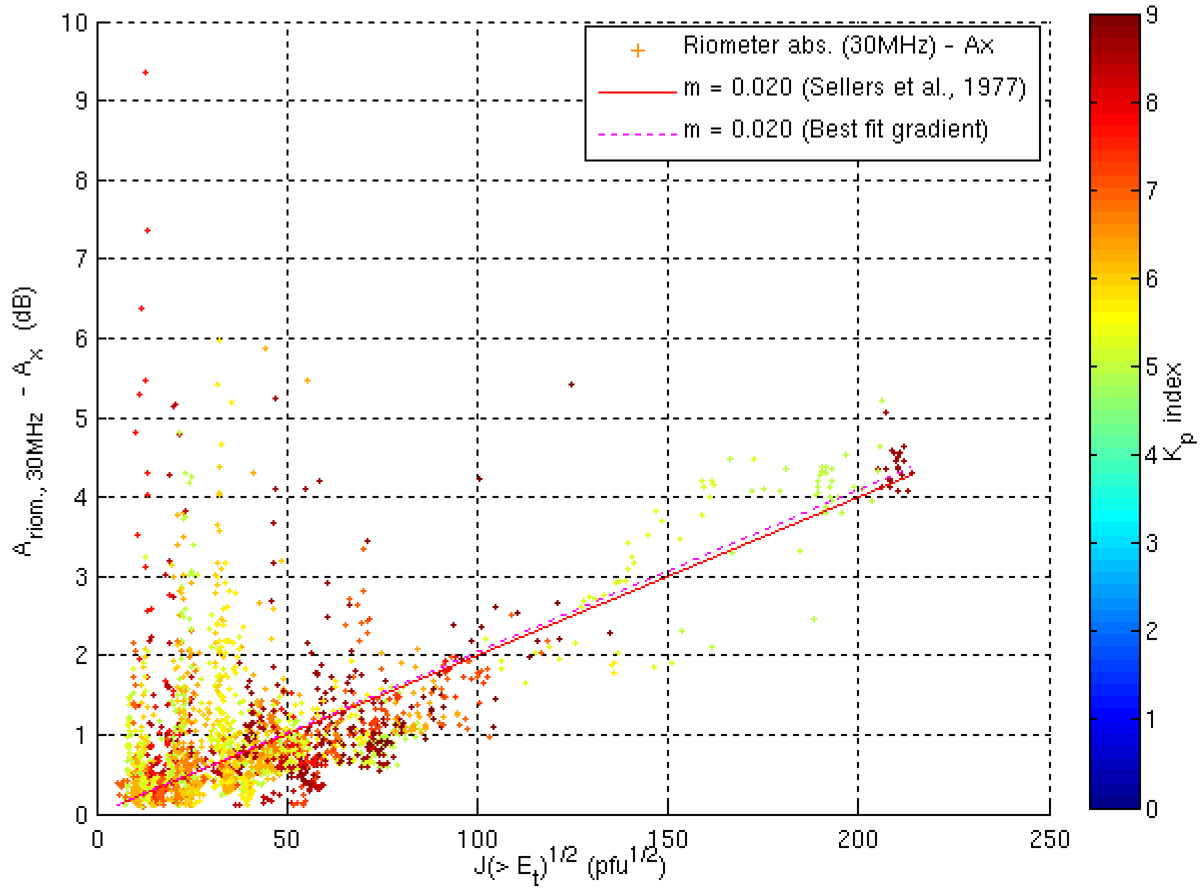
CNA vs. √Proton Flux at IRIS Kilpisjärvi

Night-time (χ > 100°)



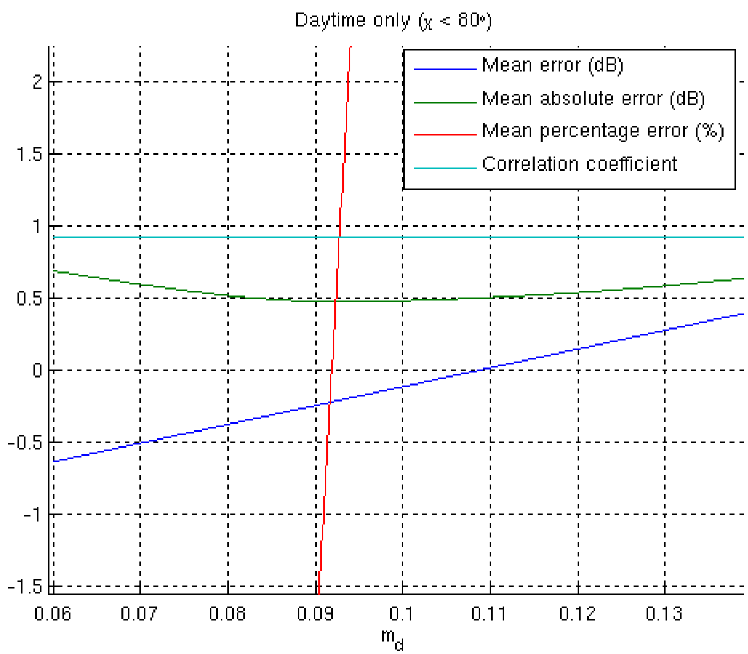
CNA vs. √Proton Flux at IRIS Kilpisjärvi

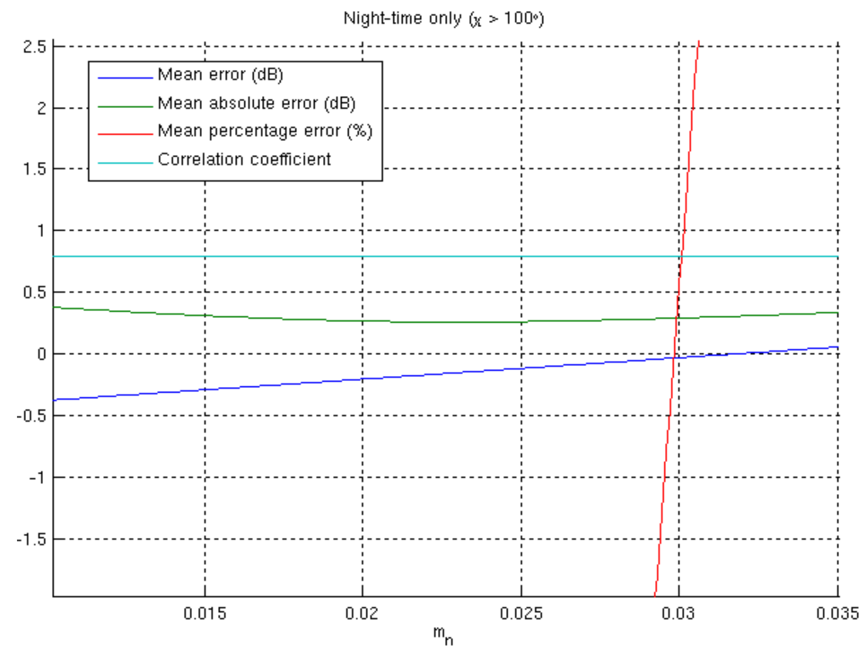
Night-time (χ > 100°): Restricting to "Inside Polar Cap" only (E_c < 2.2 MeV)



CNA vs. √Proton Flux at IRIS Kilpisjärvi

- Can also vary the scaling factors m_n and m_d to minimise other error statistics



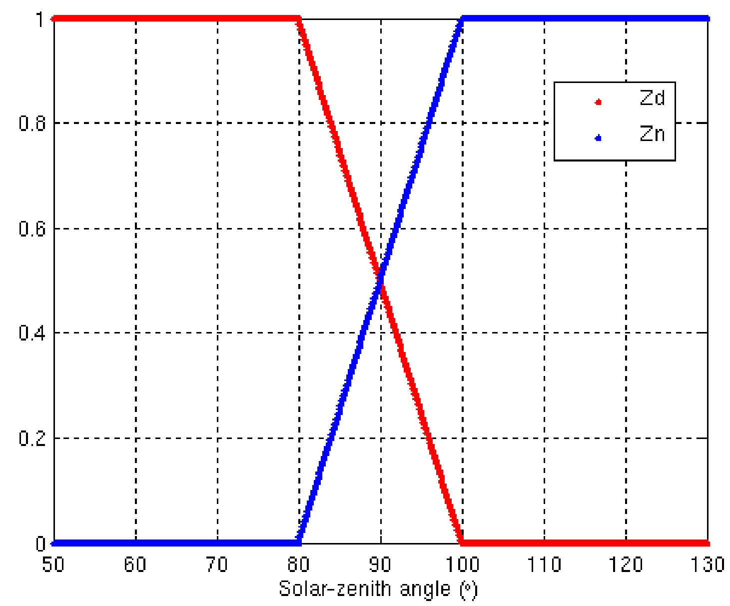


- Note: optimal values for m_n and m_d are higher for minimising signed errors

CNA vs. √Proton Flux at IRIS Kilpisjärvi

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

$$A = A_d Z_d + A_n Z_n$$

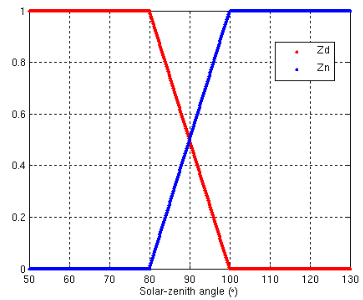


Zenith angle weighting functions

Real-time optimisation of DRAP scaling factors

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

$$\begin{array}{cccc} & & \text{Day} \qquad\qquad\qquad\qquad \text{Night} & \\ \text{Measurements} \; \begin{pmatrix} A_r(1) \\ A_r(2) \\ A_r(3) \\ \vdots \\ A_r(n) \end{pmatrix} & = & \begin{pmatrix} J^{1/2}\left(> E_{t,d}(1)\right) Z_d(\chi(1)) & J^{1/2}\left(> E_{t,n}(1)\right) Z_n(\chi(1)) \\ J^{1/2}\left(> E_{t,d}(2)\right) Z_d(\chi(2)) & J^{1/2}\left(> E_{t,n}(2)\right) Z_n(\chi(2)) \\ J^{1/2}\left(> E_{t,d}(3)\right) Z_d(\chi(3)) & J^{1/2}\left(> E_{t,n}(3)\right) Z_n(\chi(3)) \\ \vdots & \vdots \\ J^{1/2}\left(> E_{t,d}(n)\right) Z_d(\chi(n)) & J^{1/2}\left(> E_{t,n}(n)\right) Z_n(\chi(n)) \end{pmatrix} & \begin{pmatrix} m_d \\ m_n \end{pmatrix} \end{array}$$



$$\underline{A} = \boldsymbol{J}\underline{m}$$

$$\boldsymbol{J}^{\boldsymbol{T}}\underline{A} = \boldsymbol{J}^{\boldsymbol{T}}\boldsymbol{J}\underline{m}$$

$$(\boldsymbol{J}^T\boldsymbol{J})^{-1}\boldsymbol{J}^T\underline{A} = \underline{m}$$

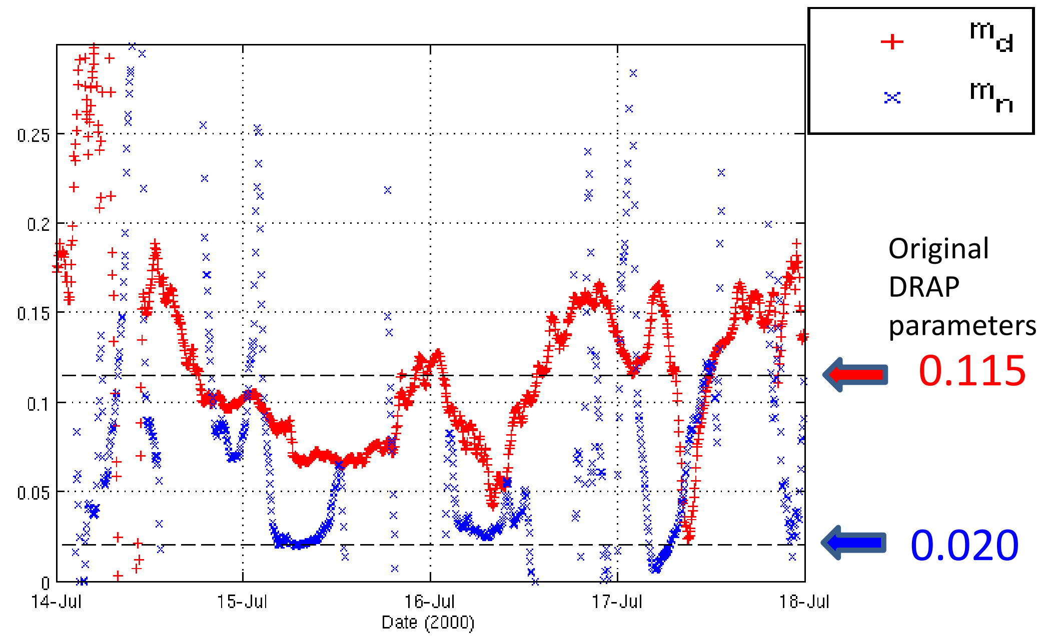
- Applying to full IRIS Kilpisjärvi data set (for SPE times) gives

m_d = 0.103 and m_n = 0.023

(*cf.* m_d = 0.115 and m_n = 0.020 in DRAP)

Real-time optimisation of DRAP scaling factors

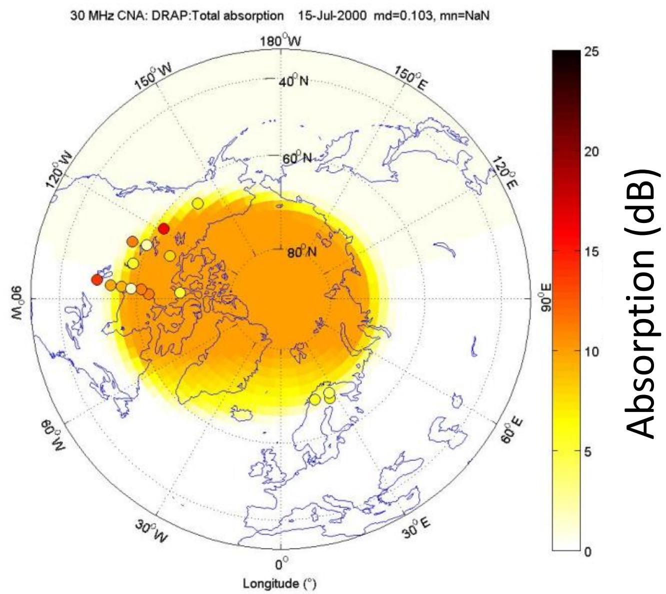
- Try this technique on the Bastille Day event (multiple riometers)
- Fit m_n and m_d to all riometer measurements over a 30-minute period
- Night measurements (for m_n) not always available so revert to standard model values at these times



Optimised DRAP

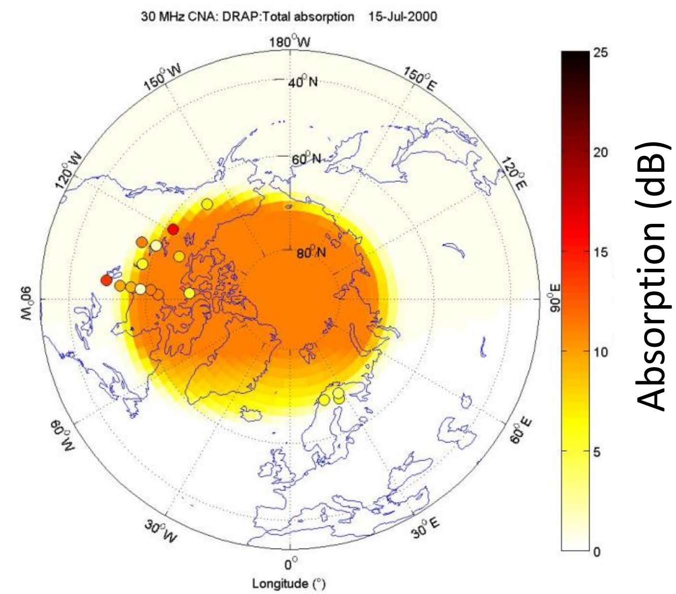
DRAP

m_d = 0.103, m_n = 0.020



m_d = 0.115, m_n = 0.020

Riometer

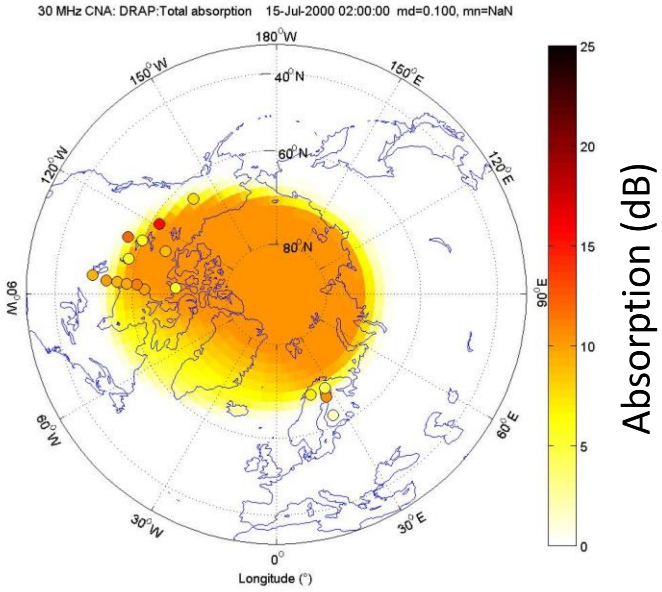


00:00 15 July 2000

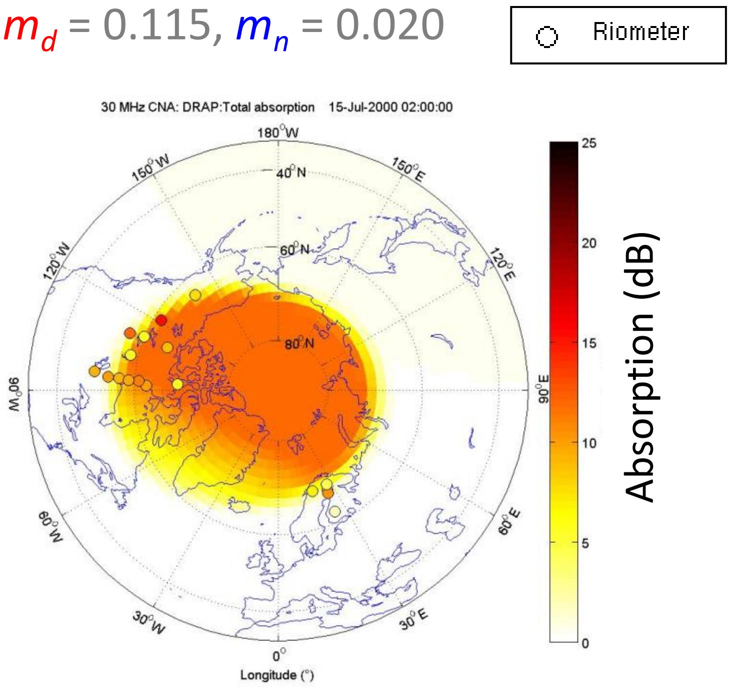
Optimised DRAP

DRAP

m_d = 0.100, m_n = 0.020



m_d = 0.115, m_n = 0.020

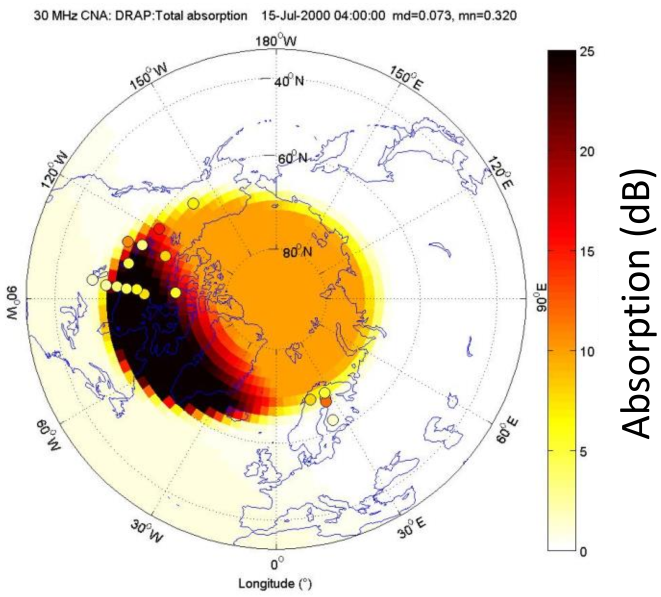


02:00 15 July 2000

Optimised DRAP

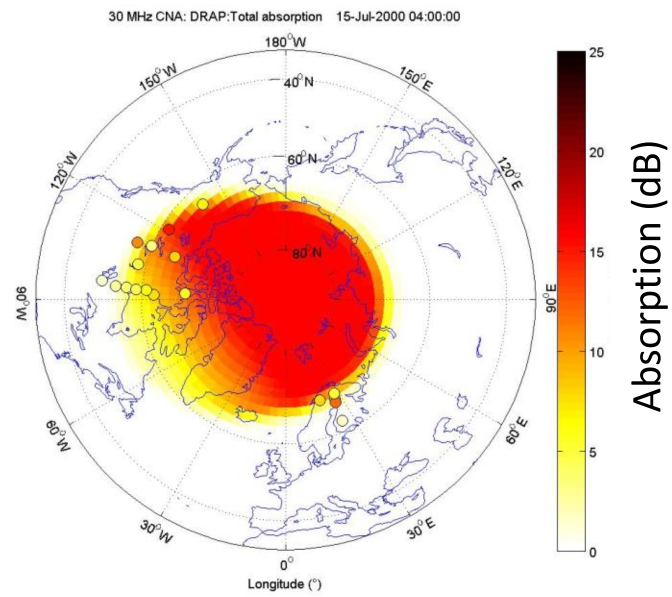
DRAP

$m_d = 0.073$, $m_n = 0.320$



$m_d = 0.115$, $m_n = 0.020$

Riometer



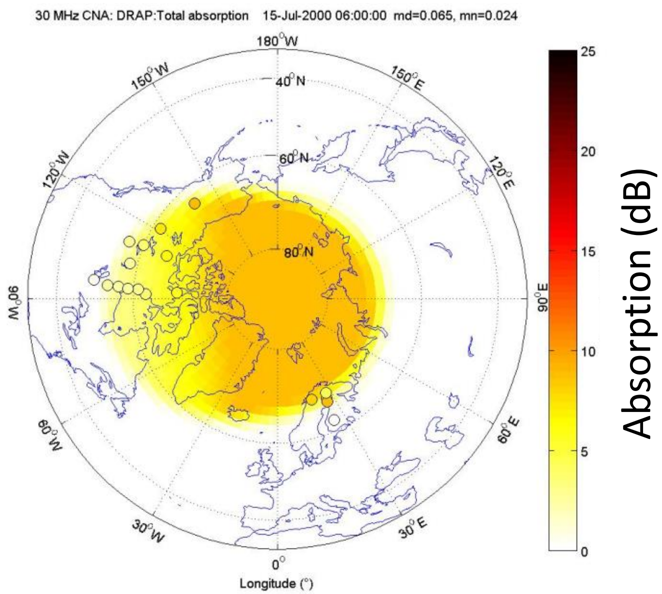
Extreme value of m_n used on nightside (from least-squares fit)

04:00 15 July 2000

Optimised DRAP

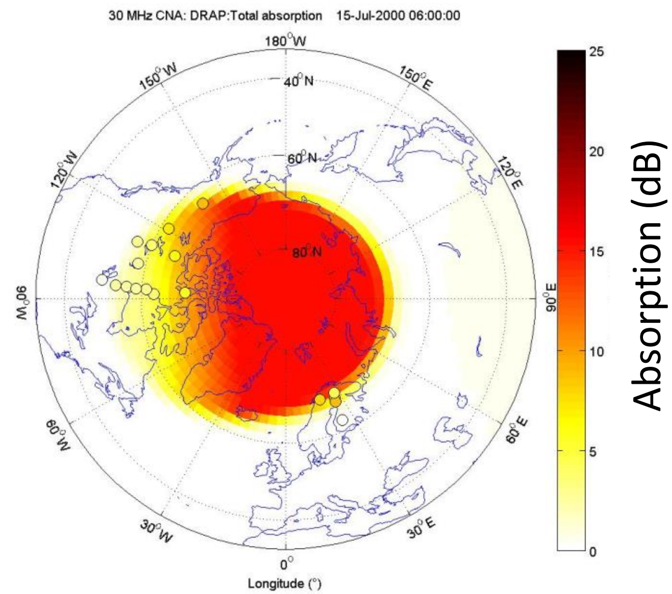
DRAP

$m_d = 0.065$, $m_n = 0.024$



$m_d = 0.115$, $m_n = 0.020$

Riometer

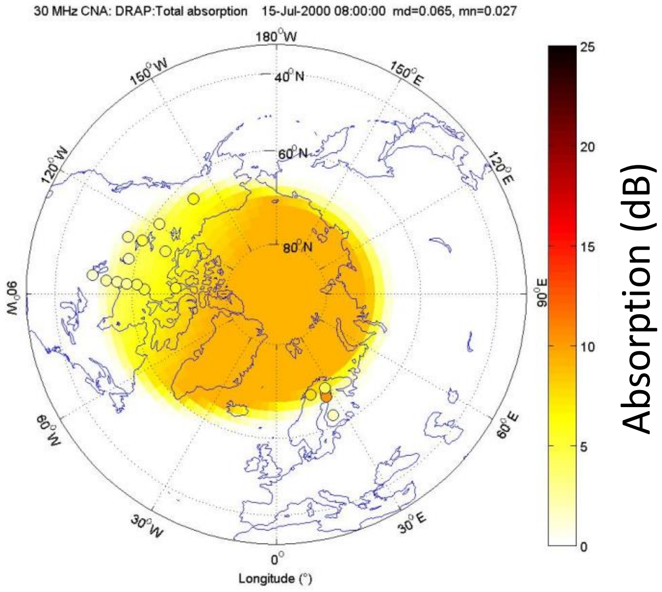


06:00 15 July 2000

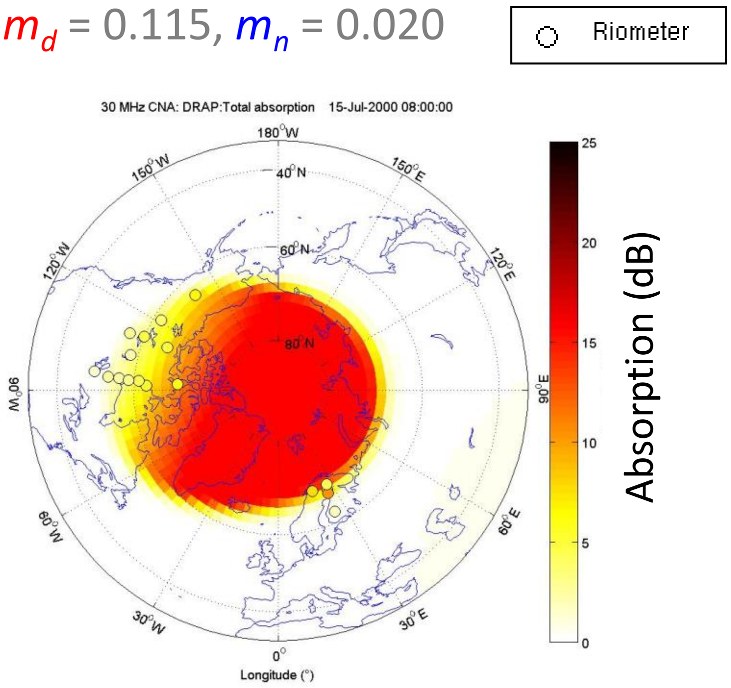
Optimised DRAP

DRAP

$m_d = 0.073$, $m_n = 0.027$



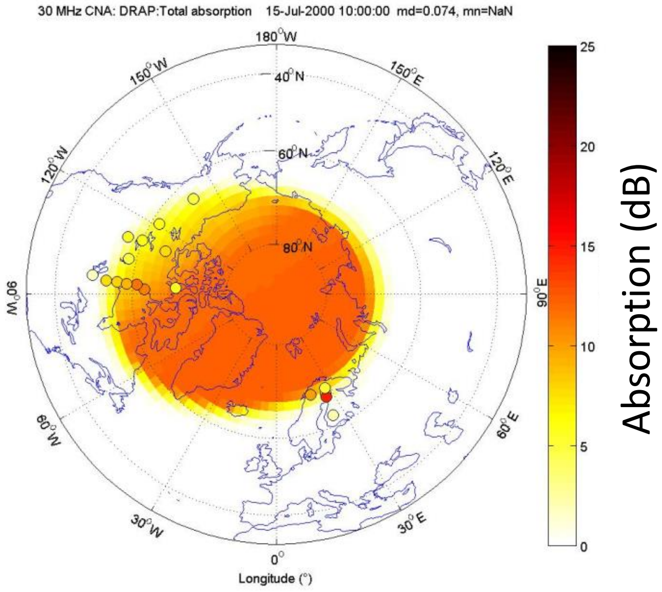
$m_d = 0.115$, $m_n = 0.020$



08:00 15 July 2000

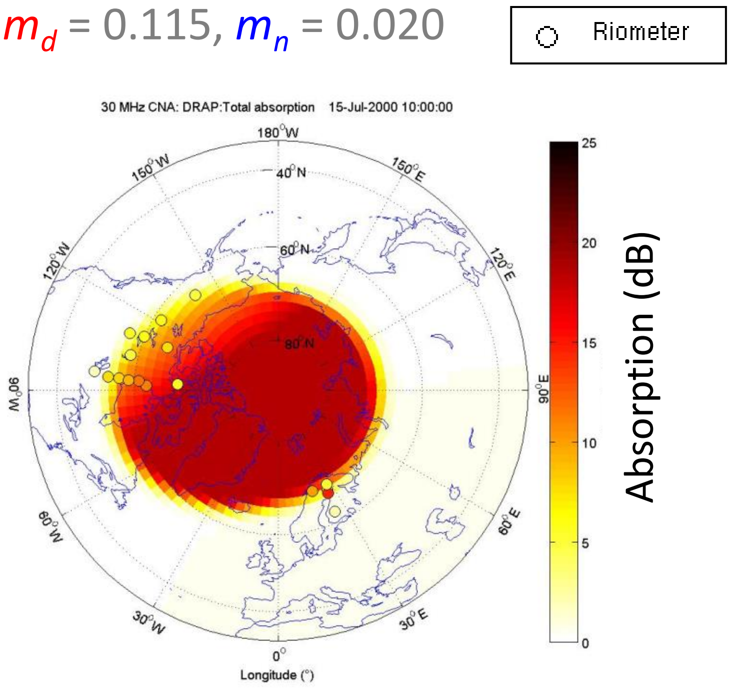
Optimised DRAP

m_d = 0.074, m_n = 0.020



DRAP

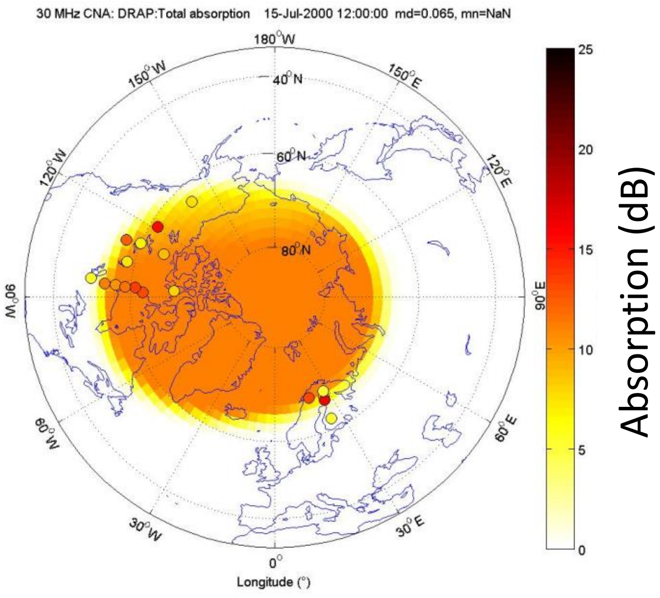
m_d = 0.115, m_n = 0.020



10:00 15 July 2000

Optimised DRAP

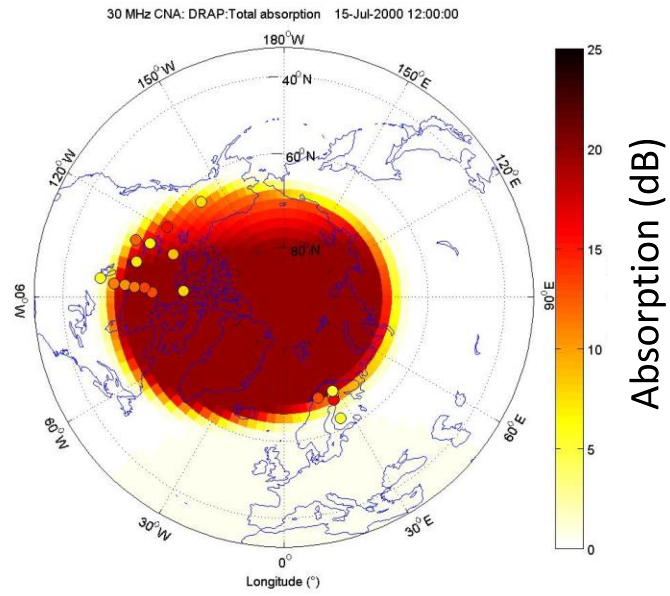
$m_d = 0.065$, $m_n = 0.020$



DRAP

$m_d = 0.115$, $m_n = 0.020$

Riometer

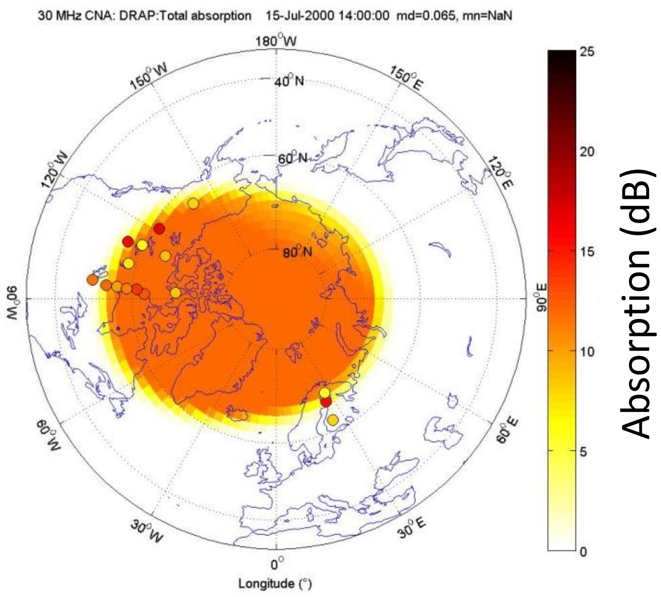


12:00 15 July 2000

Optimised DRAP

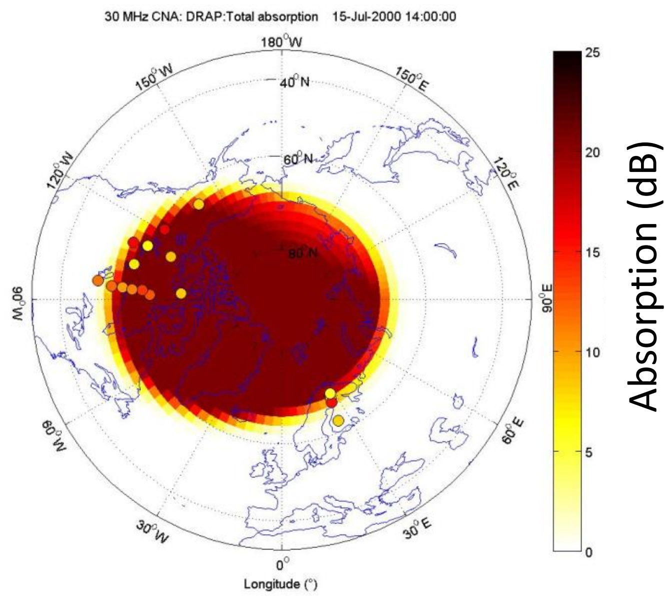
DRAP

$m_d = 0.065$, $m_n = 0.020$



$m_d = 0.115$, $m_n = 0.020$

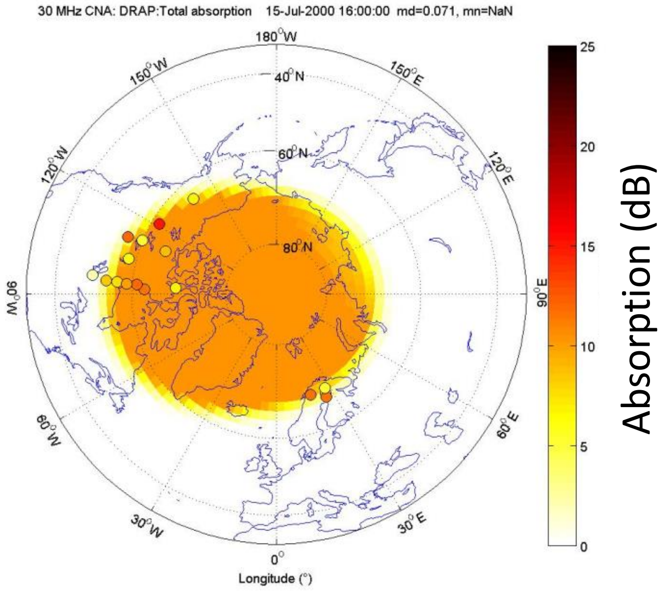
Riometer



14:00 15 July 2000

Optimised DRAP

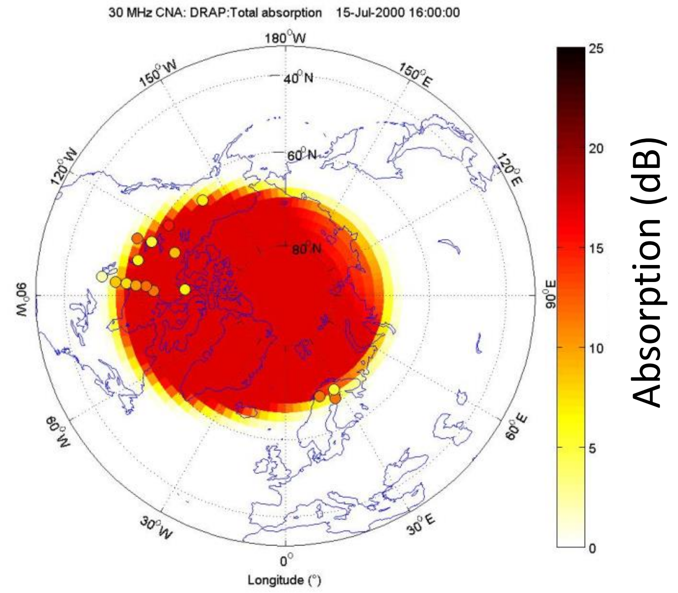
m_d = 0.071, m_n = 0.020



DRAP

m_d = 0.115, m_n = 0.020

Riometer

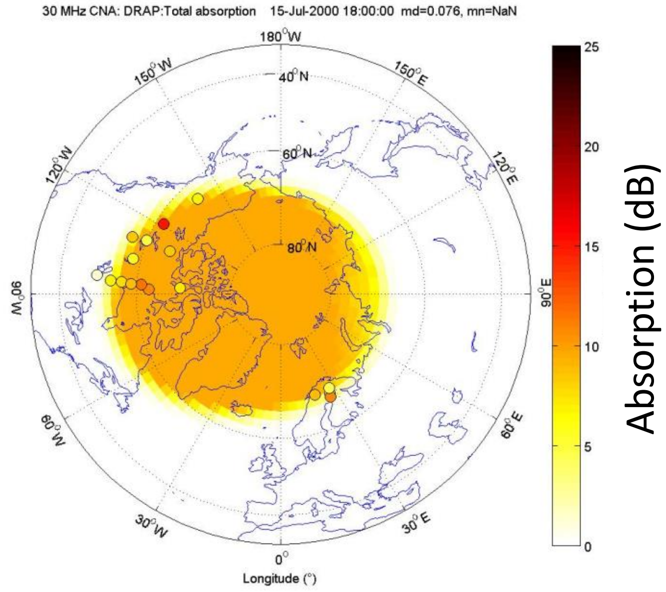


16:00 15 July 2000

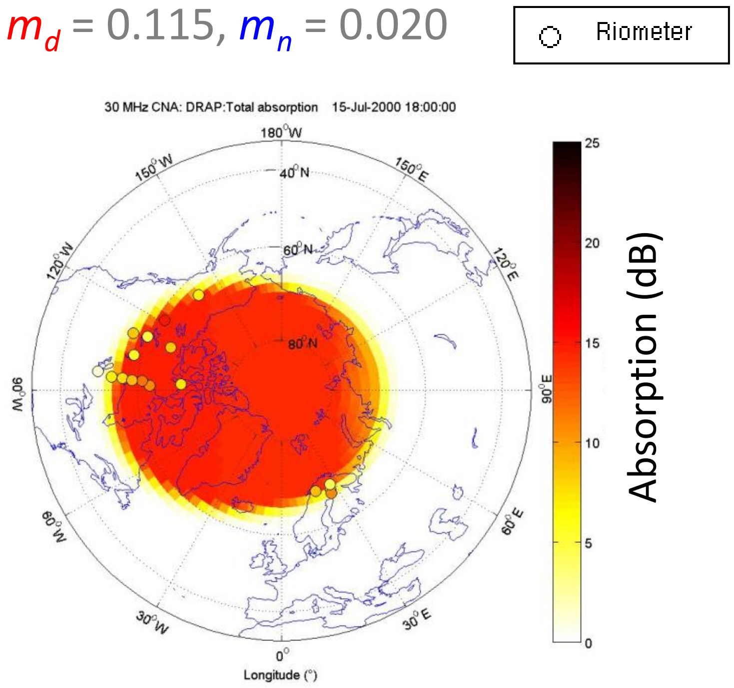
Optimised DRAP

DRAP

m_d = 0.076, m_n = 0.020



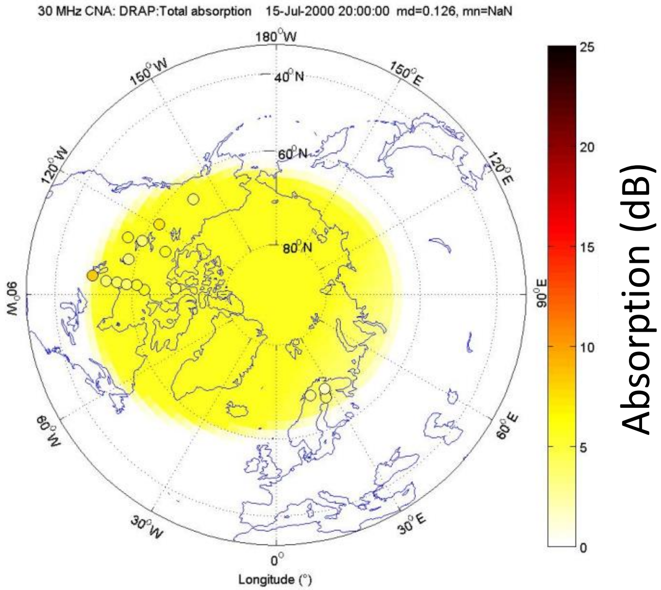
m_d = 0.115, m_n = 0.020



18:00 15 July 2000

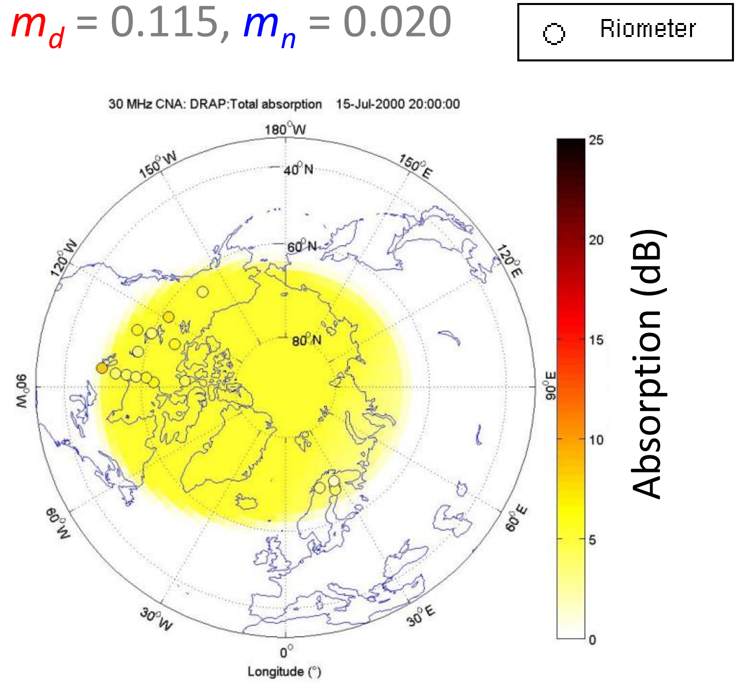
Optimised DRAP

$m_d = 0.126$, $m_n = 0.020$



DRAP

$m_d = 0.115$, $m_n = 0.020$

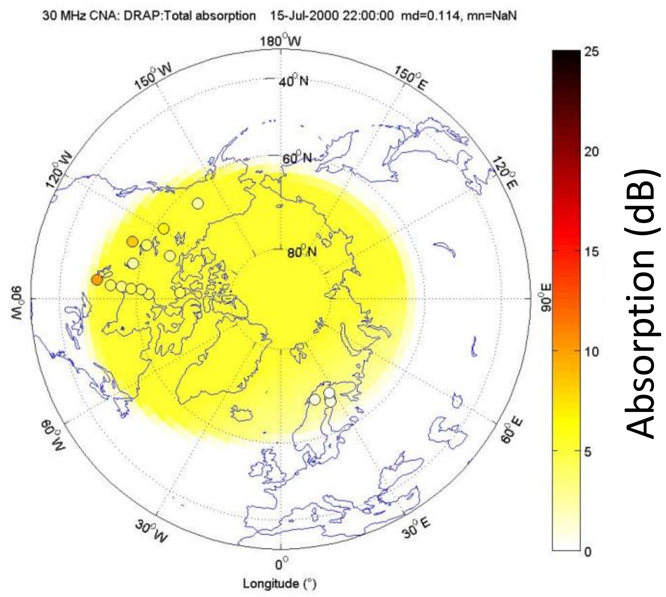


20:00 15 July 2000

Optimised DRAP

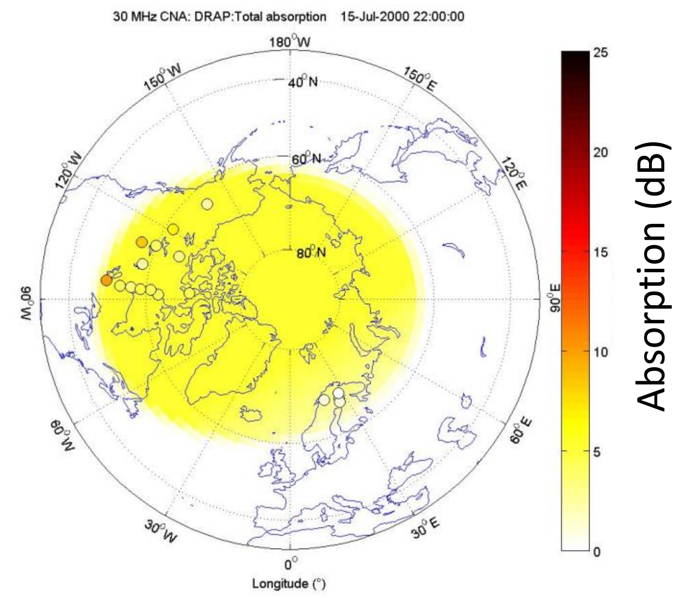
DRAP

m_d = 0.114, m_n = 0.020



m_d = 0.115, m_n = 0.020

Riometer

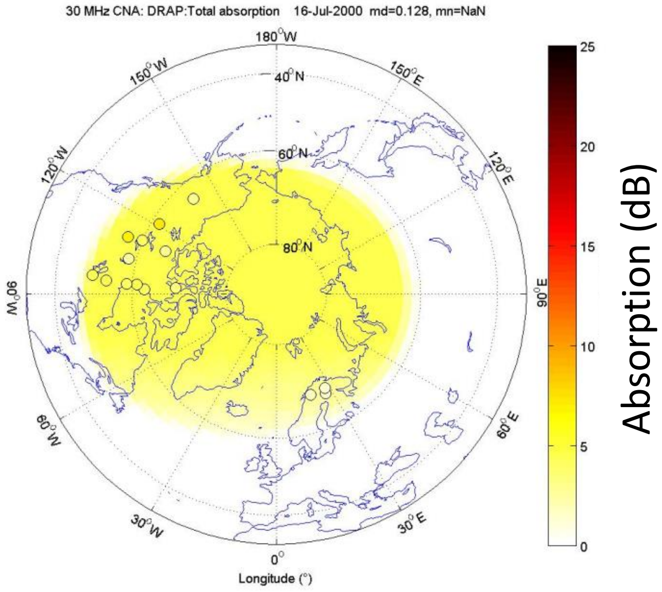


22:00 15 July 2000

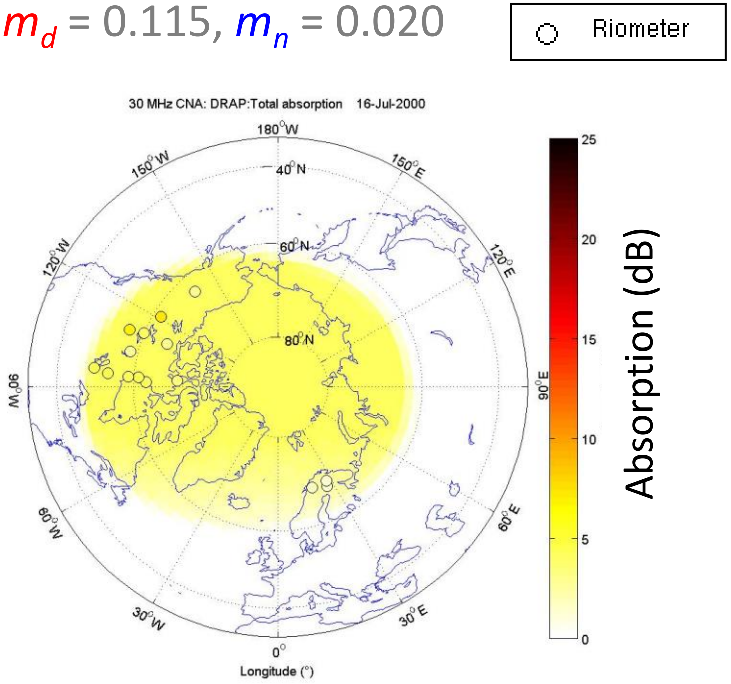
Optimised DRAP

DRAP

$m_d = 0.128$, $m_n = 0.020$



$m_d = 0.115$, $m_n = 0.020$



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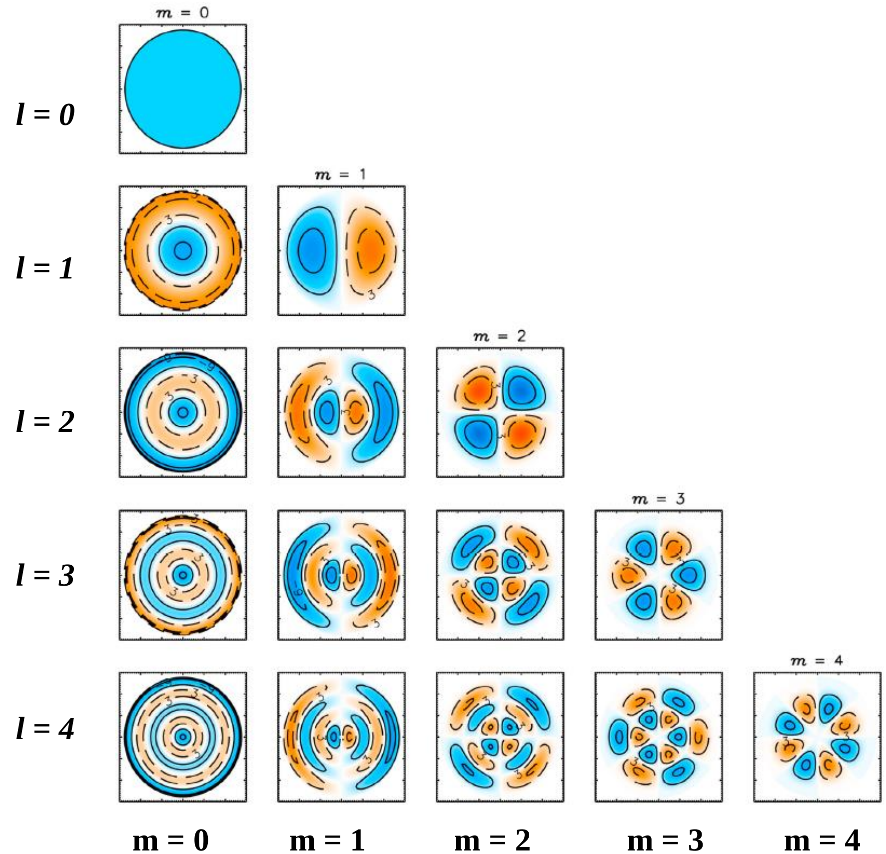
An Alternative Data Assimilation Method for Mapping PCA

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

$$\Phi(\theta,\phi) = \sum_{l=0}^{L\max} \sum_{m=-l}^{l} A_{lm} P_l^m(\cos\theta) e^{im\phi}$$

- Scale the colatitude, θ, 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, $\boldsymbol{f}$

Measurements

Spherical harmonic functions

Coefficients (unknown)

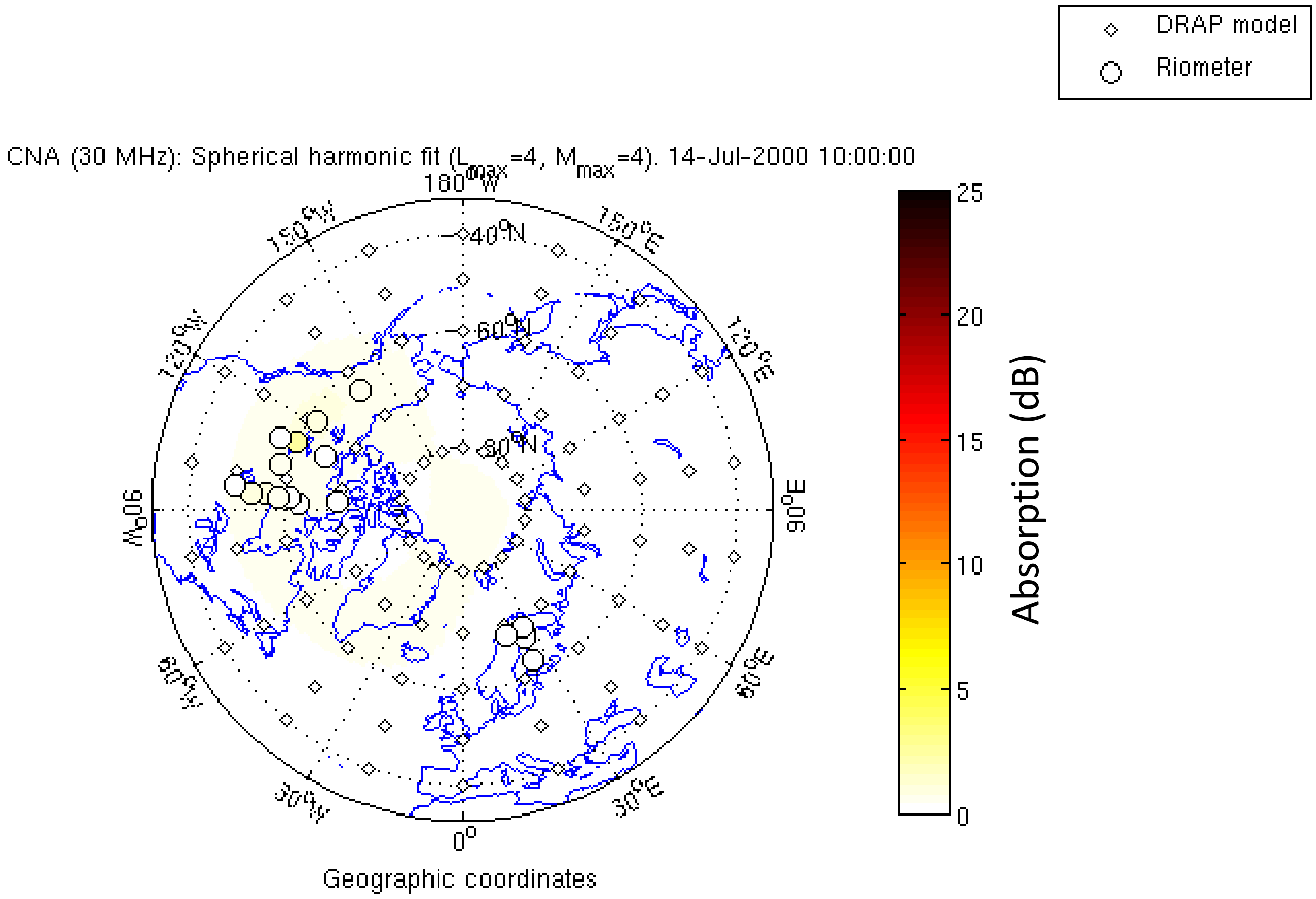
$$\begin{pmatrix} f_1(\theta_1,\varphi_1) \\ f_2(\theta_1,\varphi_1) \\ \vdots \\ f_n(\theta_n,\varphi_n) \end{pmatrix} = \begin{pmatrix} [Y_0^0(\theta_1,\varphi_1), Y_1^0(\theta_1,\varphi_1), \dots, Y_l^m(\theta_1,\varphi_1), \dots] \\ [Y_0^0(\theta_2,\varphi_2), Y_1^0(\theta_2,\varphi_2), \dots, Y_l^m(\theta_2,\varphi_2),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

$$\boldsymbol{f} = \boldsymbol{YA}$$

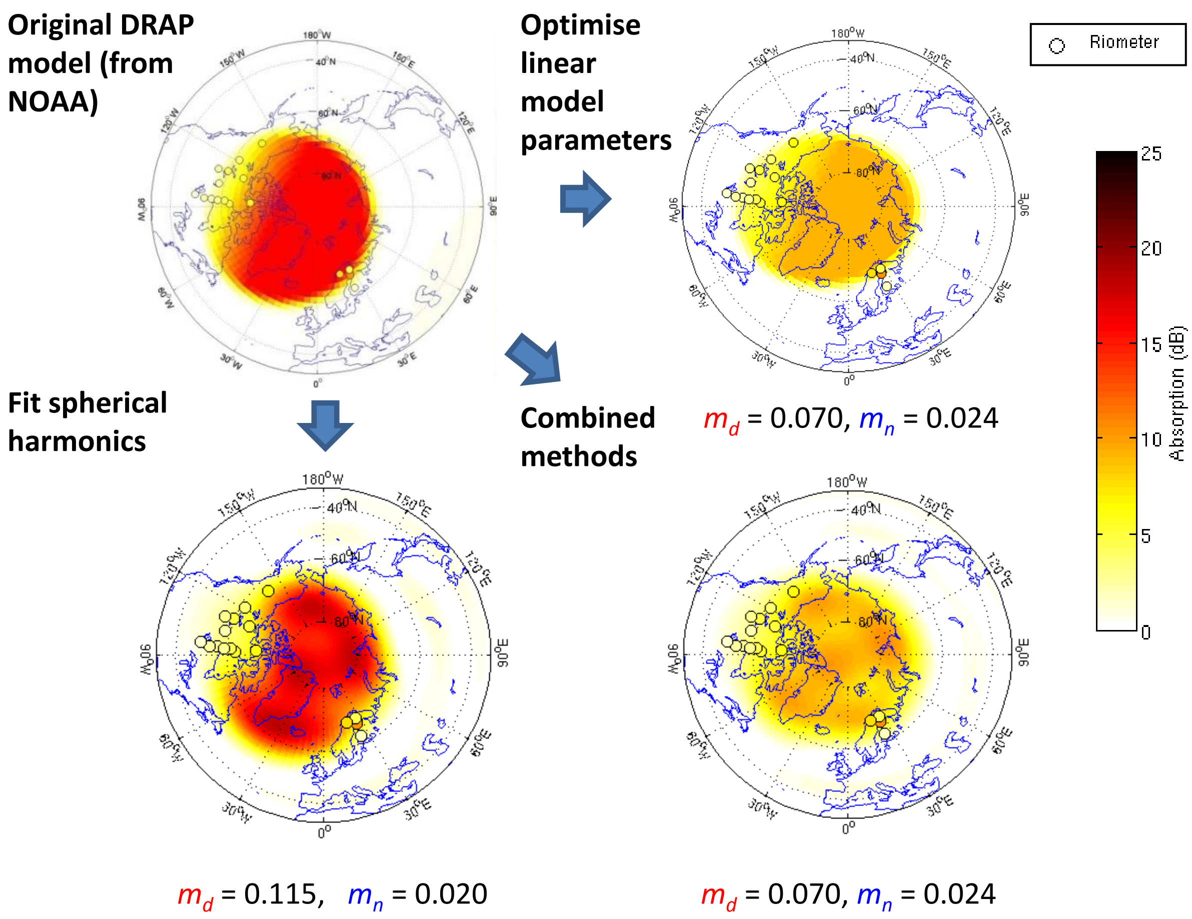
- A weighted linear regression is used, weighting the riometers more highly than the model, thus

$$\boldsymbol{A} = \left(\boldsymbol{Y}^{\boldsymbol{T}}\boldsymbol{WY}\right)^{-1}\boldsymbol{Y}^{\boldsymbol{T}}\boldsymbol{Wf}$$

An Alternative Data Assimilation Method for Mapping PCA



Combined Optimisation and Fitting



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