Converting Riometer Absorptions to Electron Energy Fluxes Based on the First Principle Modeling of Ionospheric Responses to Energetic Electrons, X-Rays and Solar Protons Precipitations

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Abstract

Based on satellites monitoring of the X-Rays Precipitations (Solar Flares), Solar Proton Precipitations (Solar Proton Events), and Riometer absorption in association with F region plasma patches formed in the cusp and propagating into the polar cap, we estimate ionospheric D-Layer ionization caused by energetic electrons precipitations based on our Computational Model of D-Region Ion Production. Knowing D-Layer ionization mechanisms will allow us to monitor precipitating electron source rates based on routine ionospheric absorption measurements by the Canadian Geospace Observatory Riometer Network (GO-RIO).

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Motivations

- During enhanced magnetic activities, ejections of energetic electrons from radiation belts ionize the D-Layer of the polar atmosphere, which greatly affects the propagation of the cosmic radio noise measured by riometers at 30 MHz.
- Based on our model of the D-region electron transport available, we monitor precipitating electron energy fluxes based on routine ionospheric absorption measurements by the Canadian Geospace Observatory Riometer Network (GO-RIO);

Models Applied

- The generalized Appleton theory is applied to obtain the expression for the complex refractive index n. If no or weak dependence of the refractive index on altitude occurs on the scale of a wavelength (~10 meters for 30 MHz signal), and the wave attenuation is low, the expression for the differential Cosmic Noise Absorption (DCNA) is proportional to the imaginary part of the refractive index, which depends on free electron density and electron-neutral collision frequency:

$$\begin{cases} n^2 = 1 - X\left(1 - iZ - \dfrac{\frac{1}{2}Y^2\sin^2\theta}{1-X-iZ} \pm \dfrac{1}{1-X-iZ}\sqrt{\frac{1}{4}Y^4\sin^4\theta + Y^2\cos^2\theta\,(1-X-iZ)^2}\right)^{-1} \\ X = \dfrac{\omega_0^2}{\omega^2};\, Y = \dfrac{\omega_H}{\omega};\, Z = \dfrac{\nu}{\omega}. \end{cases}$$

$\omega = 2\pi f$ Is a radial frequency;

ν Is an electron - neutral collision frequency;

$$\omega_0 = 2\pi f_0 = \sqrt{\frac{Ne^2}{\varepsilon_0 m}} \quad \omega_H = 2\pi f_H = \frac{B|e|}{m}$$

- We use our **electron transport model** freely available at https://ucalgary.ca/above/files/above/d-region-ion-production-model.zip to calculate ion productions in the D-Region of the ionosphere caused by energetic (10 keV-1 MeV) electrons using a general Monte Carlo approach implemented in the latest version of the MCNP6 code for electron tracking in magnetic fields.
- We convert ion production rates into the free electron density based on the Sodankylä Ion and Neutral Chemistry (**SIC**) model, and the **GPI** model of lower ionosphere relaxation [*Glukhov et al., 1992*];
- Collision frequencies for the electron-neutral interactions are calculated based on the [*Itikawa, 1974*], formalized by [*Schunk, 2009*];

DCNA Altitude Profiles

An example of DCNA altitude profiles calculated based on the above models shows sensitivity of the riometer signal to the precipitating electrons energy and the range of affected altitudes.

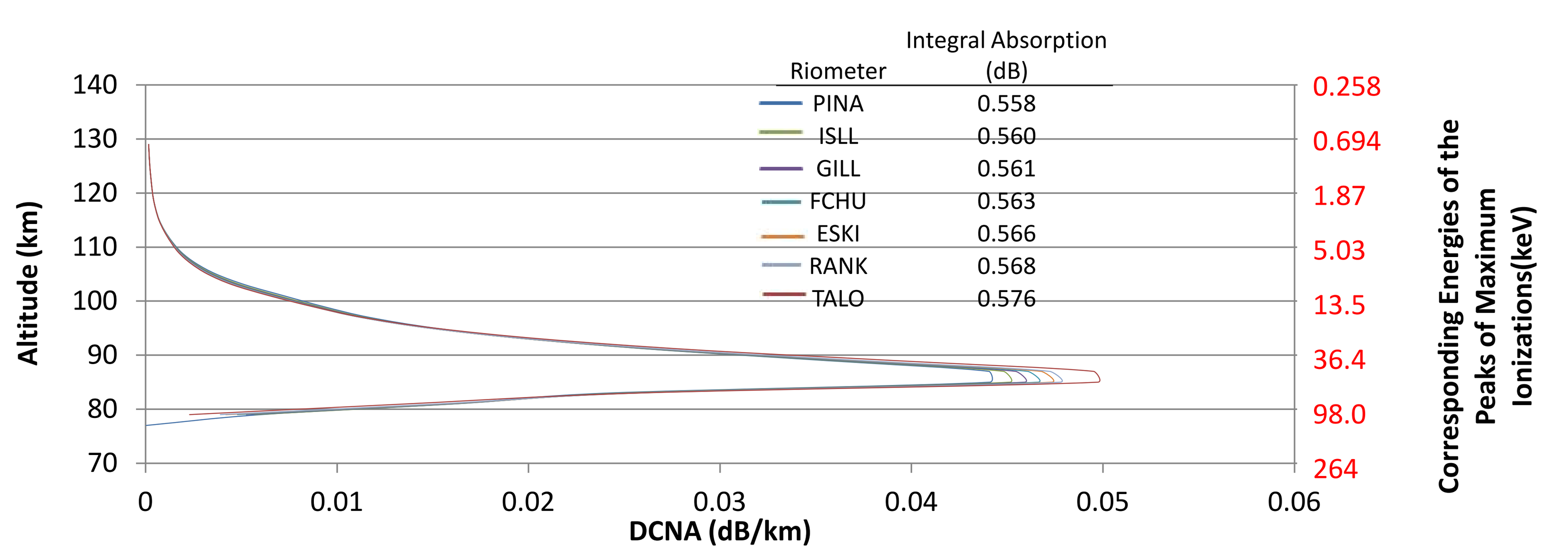


Fig. 1. All DCNA altitude profiles are calculated for the energy flux 1 erg/cm2/sec = 1 mW/m², and "-2.27" (power law spectrum) slope.

Model Calibration Curves

Under the assumption of the power law source spectrum with a slope -2.27 [*A. L. Vampola And D. J. Gorney*] and isotropic angular distribution, the model converts riometer absorption (dB) into the precipitating electrons energy flux (erg/cm^2/sec) calculating appropriate calibration curves.

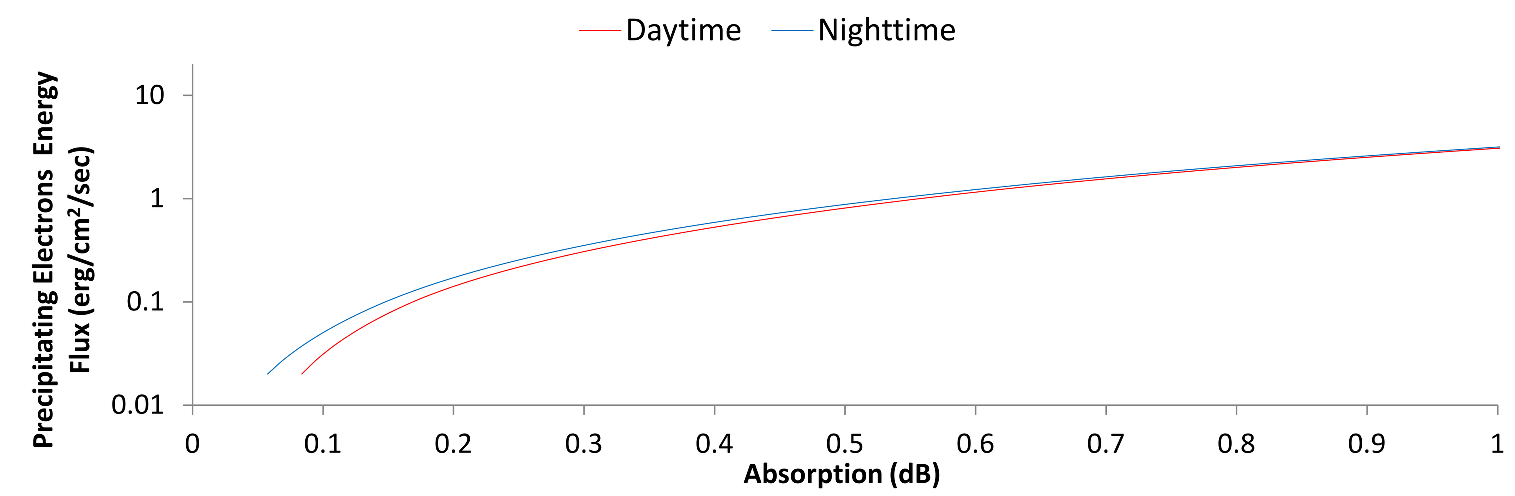


Fig. 2. Two calibration curves calculated for the PINA riometer on 1-st of June, 2005, at 18:16 (Daytime) and 6:16(Nighttime)

Time Series of a Conjunction Event

Forward model validation is based on direct measurements of precipitating electron and proton integral fluxes by MEPED particle telescopes during conjunctions with riometers. Conjunctions are calculated by the leapfrog field line tracing technique. We've found and analyzed **39,680** conjunctions in total, for all **13** riometers and **5** POES-METOP satellites.

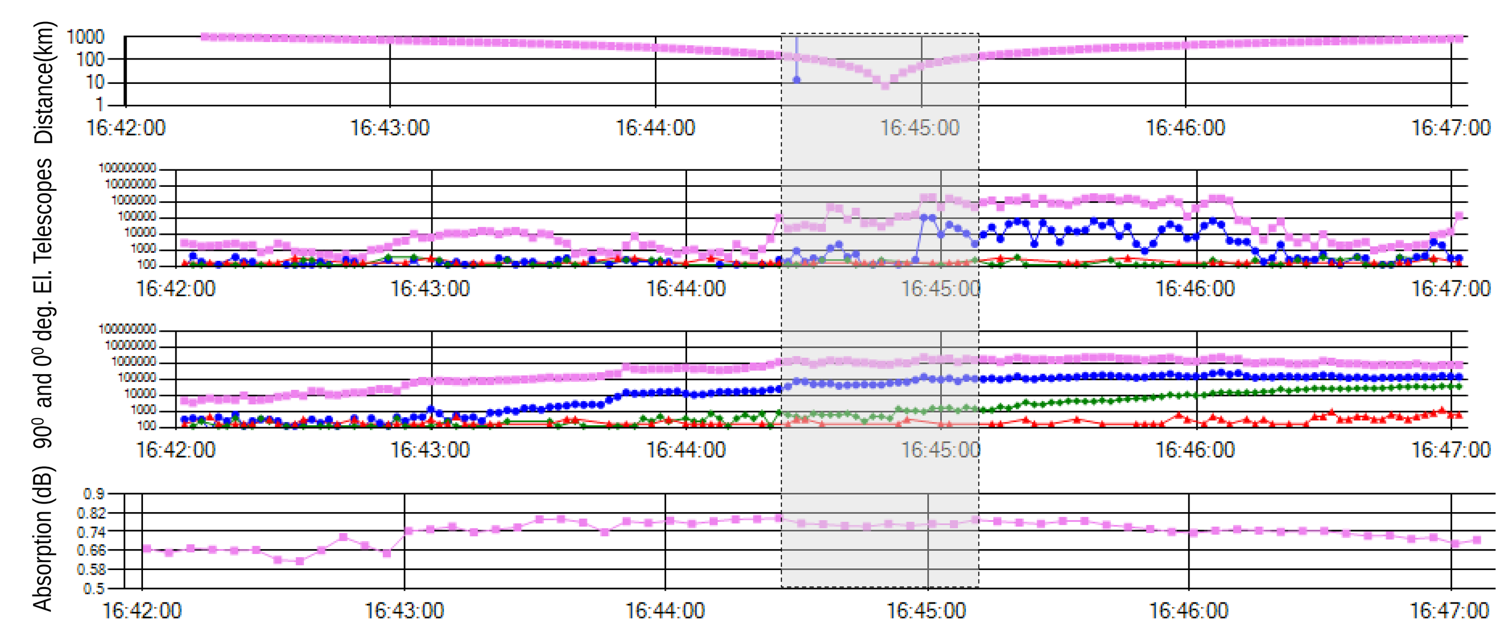
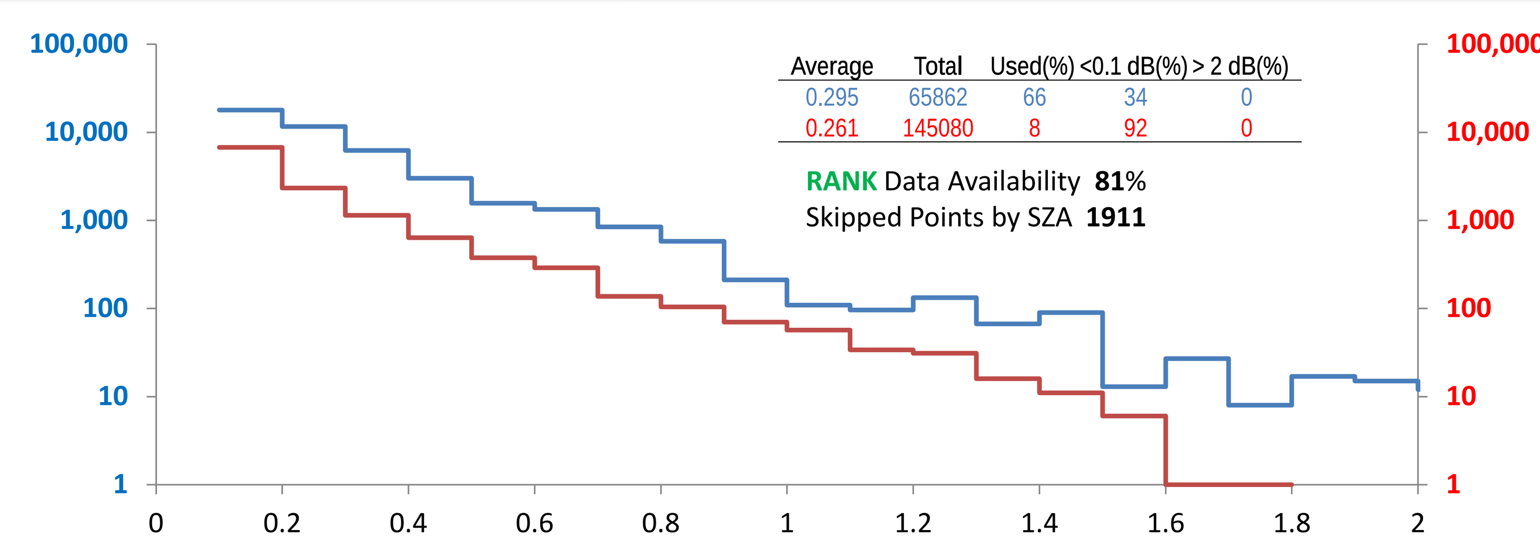


Fig. 3 . An example of a conjunction event time series on 2016-04-27. **Upper panel**: Distances calculated based on foot points from POES/METOP CDF files; **Next two panels**: Integral electron fluxes(el/cm²/sec/str); **Lower panel**: RANK riometer absorptions. A gray area in the middle shows time interval when METOP-B trajectory footpoints are crossing the RANK riometer field of view.

RANK Conjunctions Statistics



Average	Total	Used(%)	<0.1 dB(%)	> 2 dB(%)
0.295	65862	66	34	0
0.261	145080	8	92	0

Fig. 4. Absorptions frequency histograms (**blue** - measured, **red** - the model calculated) for the daytime 5 minutes conjunctions time interval (*Fig. 3*) collected at the RANK riometer location.

- Absorptions (in red) are calculated based on MEPED signals from all five POES/METOP satellites.
- The histogram has the same bin sizes (0.1 dB) and covers a range of absorptions from 0.1 to 2 dB.
- No absorptions have been calculated and measured above 2 dB, and the most calculated absorptions (92%) are below 0.1 dB.

Absorptions Scattered Plot

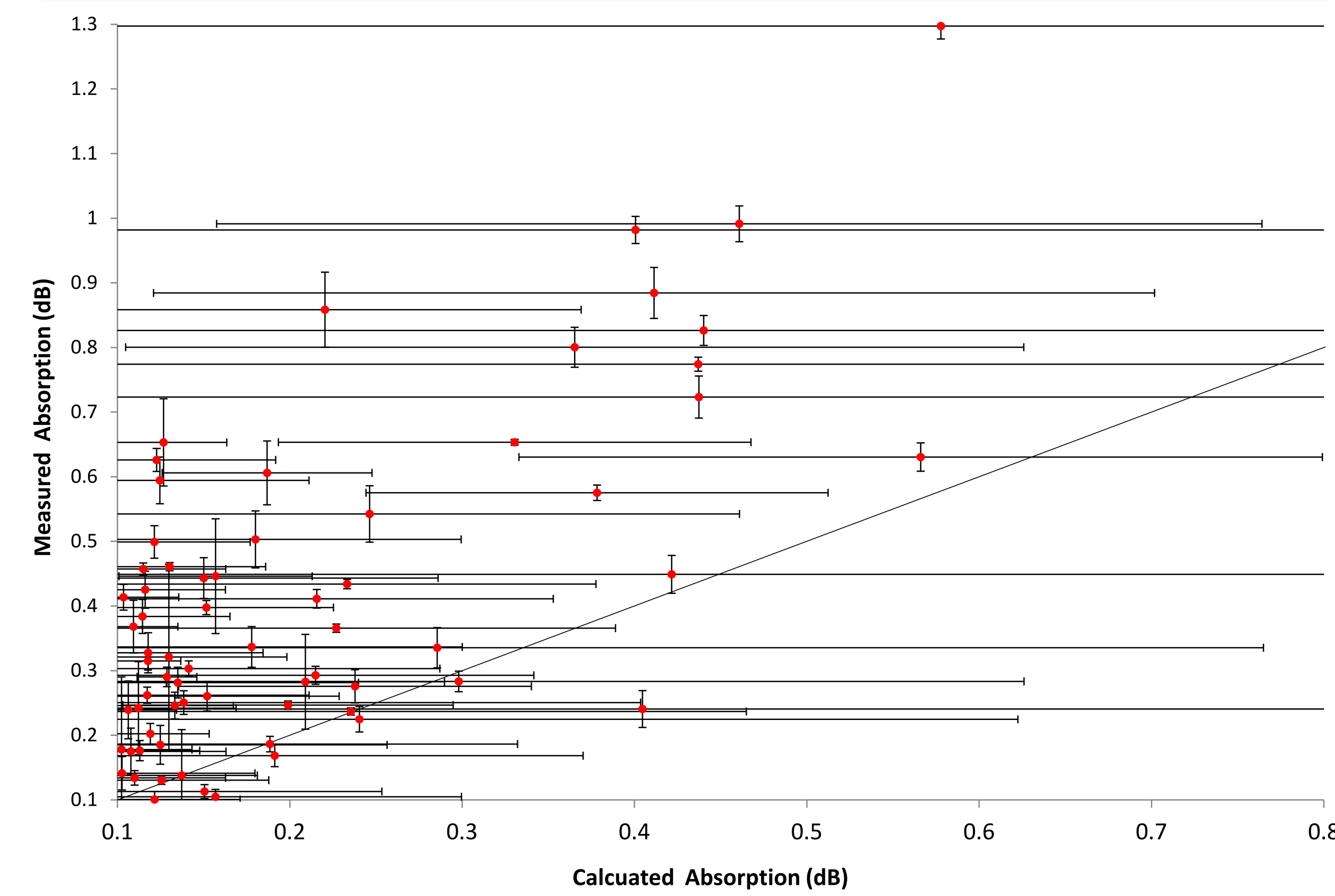


Fig. 5. The scattered plot of 68 conjunction events with the RANK riometer station collected from five POES-METOP satellites (NOAA-15, NOAA-18, NOAA-19, METOP-A, METOP-B), and covering half of a solar cycle period (years 2013 - 2018).

- A conjunction event is defined by a circular area around the riometer at altitude 85 km, with radius $85\sqrt{3} \approx 150$ km, so the distances of the closest satellite footpoint to the riometer beam center < 90 km (gray area in *Fig. 3*), and both measured and calculated absorption values exceed 0.1 dB.
- Horizontal and vertical error bars are calculated as a standard deviation of the event time series, with 10 riometer absorption points and 21 MEPED flux points per conjunction.

Conclusions, Discussion

- The cosmic radio noise propagation in the range of altitudes between 80 and 95 km is extremely sensitive to the precipitations of electrons with energies from 30 to 100 keV (*Fig. 1*);
- We see a large electron flux variations but somewhat stable riometer absorptions for most of the events (*Fig. 3*, time series; *Fig. 5*, error bars);
- Possible anisotropy in electron angular distributions will cause their focusing by the geomagnetic field, with particles mapping to small (up to tens kilometers) regions, and with low-energy particles being focused more than higher-energy ones [*A. Kouznetsov, D. Knudsen*].

We speculate that the spot-like precipitation events on a small (~conjunction event distances) spatial scale could be a possible explanation of our absorption calculations underestimations based on averaging of satellite point flux measurements along its trajectory (*Fig. 4, 5*).

Acknowledgments

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