Contrasting the responses of three different ground-based instruments to energetic electron precipitation

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Radiation Belt Storm Probes

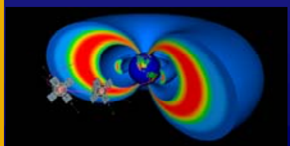
The RBSP launched late last week (30 August 2012). The mission's general scientific objectives are to:

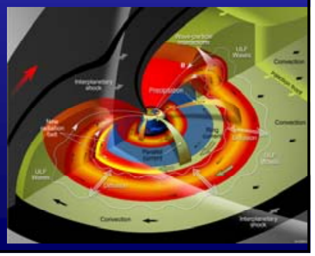
- Discover which processes -- singly or in combination -- accelerate and transport the particles in the radiation belt, and under what conditions.
- Understand and quantify the loss of electrons from the radiation belts.
- Determine the balance between the processes that cause electron acceleration and those that cause losses.
- Understand how the radiation belts change in the context of geomagnetic storms.

Radiation Belt Storm Probes - Link to VERSIM science

There are multiple examples of how the science undertaken by the VERSIM community link to the science goals of the RBSP mission (and relevant other missions, like DSX, RESONANCE, and ERG):

* VLF plasma wave activity and properties
* plasmaspheric density measurements
* observations of energetic particle acceleration & precipitation





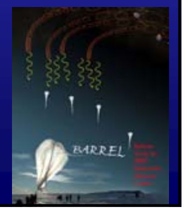
Radiation Belt Storm Probes - Losses

One of these cross-overs is a core RBSP science goal:

Understand and quantify the loss of electrons from the radiation belts.

However, RBSP spacecraft are not very well suited to address this science goal, as it does not make direct measurements of electrons losses. Due to this RBSP has associated missions to address loss measurements - like BARREL (Balloon Array for RBSP Relativistic Electron Losses) .

This is one area where ground-based measurements have a strong role to play.



Ground based measurements of EEP

Recently, I produced a study to compare the response of different ground-based instruments to energetic electron precipitation (EEP) from the radiation belts, and also during large substorms.

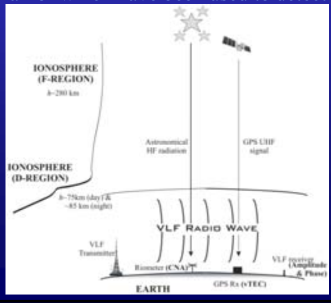
We contrasted the response of:

VLF subionospheric propagation &

Riometer changes in Cosmic Noise Absorption &

GPS receiver measurements in vertical TEC

all of which have been used to detect and describe EEP events.



I'm interested in **building the tools** by which I can extract EEP fluxes from ground-based observations.

This work has now been published as:
Rodger, C J, M A Clilverd, A J Kavanagh, C E J Watt, P T Verronen, and T Raita, Contrasting the responses of three different ground-based instruments to energetic electron precipitation, Radio Sci., 47(2), RS2021, doi:10.1029/2011RS004971, 2012.

Particle access to the upper atmosphere

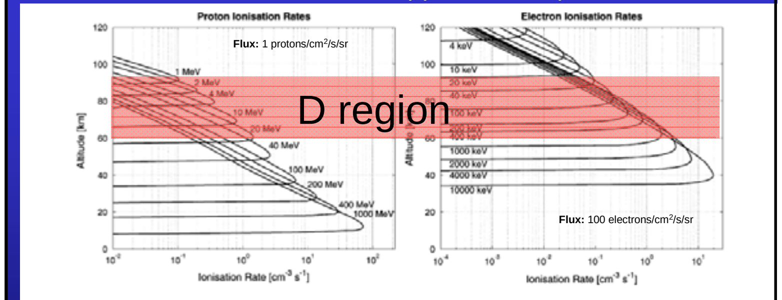
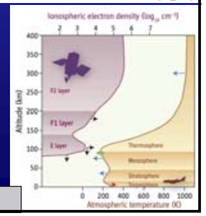


Fig. 3. Altitude versus ionisation rates for monoenergetic beams of protons 1–1000 MeV (left) and electrons 4–4000 keV (right).

Turunen et al., JASTP, 2009.

To produce 1 ion pair/cm^3/s at **60km** altitude
1 × 20MeV proton/cm^2/s
or **100** × 1MeV electrons/cm^2/s

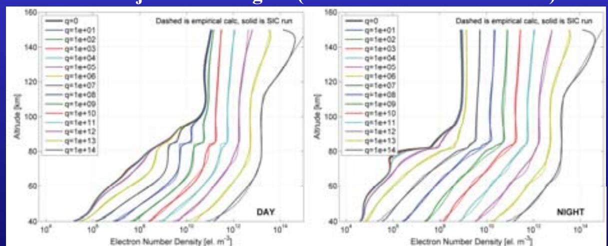


Lastovicka et al., Science, 2006

Determine the ionospheric density change

In order to make comparisons between how our three different ground-based instruments respond to Energetic Electron Precipitation (EEP), we need to first describe how EEP modifies the electron number density in the ionosphere.

From the known sensitivity of riometers I want to go to higher altitudes than just the D-region (where VLF tends to reflect).



Build on previous modelling of mine to make an empirical model to describe how EEP leads to a equilibrium electron number density from 4-150km, tested against the Sodankylä Ion and Neutral Chemistry (SIC) Model.

Response of instrument to EEP

With the ability to take EEP fluxes and convert it to ionospheric electron densities, we are now in a position to work how our instruments response to a given EEP event.

1. VLF subionospheric propagation

Use subionospheric modelling code (in our case an adapted version of the US Navy LWPC) to find the change in amplitude (**ΔAmplitude**) and change in phase (**ΔPhase**) after EEP occurs.

2. Riometer changes in Cosmic Noise Absorption (CNA) &

$$A = 4.61 \times 10^{-5} \int_{h_1}^{h_2} \left[\frac{N_e(h) \cdot v_{en}(h)}{v_{en}^2(h) + (2\pi f \pm \omega_{Be})^2} \right] dh \ [\mathrm{dB}]$$

$$A_T = \frac{2A_X A_O}{A_X + A_O} \ [\mathrm{dB}]$$

Total absorption of O and X modes for a widebeam (but remember the QDC to give **ΔCNA**, which is what is measured).

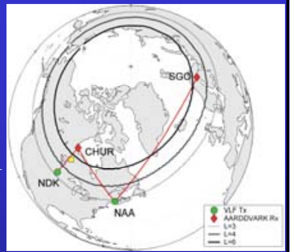
3. GPS receiver measurements in vertical TEC

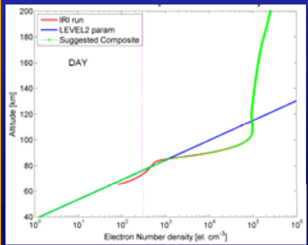
$$\text{vertical TEC} = 10^{-16} \int_{h_1}^{h_2} N_e(h) \ dh \ [\mathrm{TECu}]$$

For the purposes of determining the effect of the EEP, we determine a **ΔvTEC**, by removing the ambient electron density.

Select a modelling point

Initial Modelling point:
Island Lake (53.86°N, 265.34°E, L=5.2), Canada which hosts a riometer and is on the NDK-CHUR great circle path.



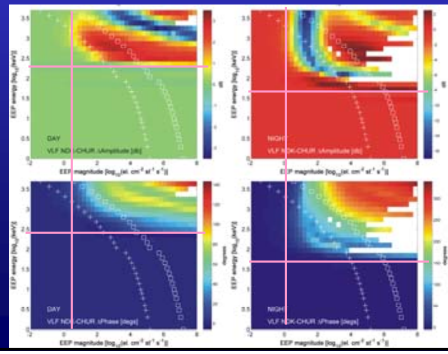


We need to determine ambient electron number density profiles (i.e., no EEP forcing) to look for changes due to the energetic electron precipitation. Do this by using IRI for high altitudes and a Wait ionosphere from Neil Thomson's work for low altitudes.

Subionospheric VLF impact of mono-*E* EEP

Initially, start with monoenergetic electron fluxes and determine responses for the ionosphere and then the VLF instrument.

For subionospheric VLF the minimum detectable EEP energy of ~150 keV (day) and ~50 keV (night) is controlled by the differing reflection heights of VLF waves propagating under the undisturbed ionospheres.



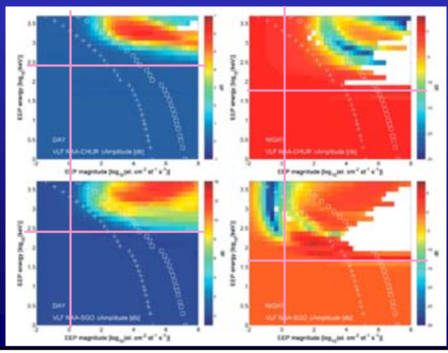
VLF is more sensitive to EEP during the night than day.

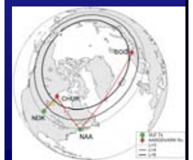
+ represent an extreme EEP flux, where the entire ESA-SEE1 model tube population is precipitated in 10 min, while the □ are the highly extreme storm-time case with 10^2 larger EEP magnitudes.

Subionospheric VLF impact of mono-*E* EEP

Now try some other VLF paths (NAA-CHUR and NAA-SGO, instead) to show the importance of the choice of paths.

The minimum energy thresholds are more or less the same (as the reflection heights are very similar), but the EEP magnitude thresholds and the complex patterns of ΔAmplitude and change in phase ΔPhase are strongly dependant upon the Tx-Rx great circle paths.

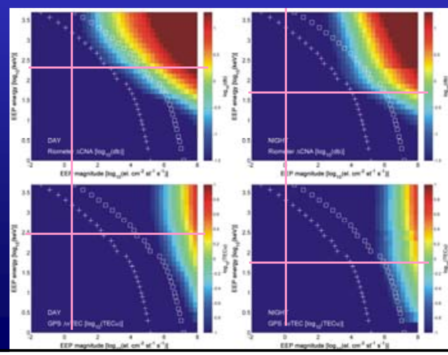




Riometer & TEC impact of mono-*E* EEP

Riometers and vTEC don't have the same sort of minimum energy for EEP to be detectable, as they both pass through the ionosphere rather than reflecting at a given height in the ambient D-region.

Can see from comparison with subionospheric VLF-defined sensitivity lines that subionospheric VLF is generally more sensitive a tool for monitoring EEP than riometers (and particularly TEC measurements which need extreme fluxes).

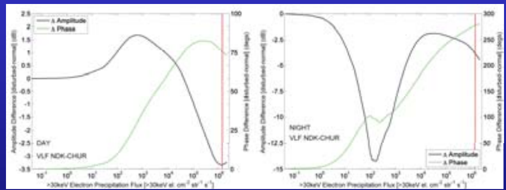


Riometers are more sensitive to EEP during day than night. vTEC is about the same.

+ represent an extreme EEP flux, tube population is precipitated in 10 min. □ are the highly extreme storm-time case with 10^2 larger EEP magnitudes.

Impact of "Real" EEP from the Radiation Belts

Earlier, we took monoenergetic electrons, but generally real precipitation from the radiation belts are over a broad energy range with a spectral dependence. We use the energy spectra reported by *Clilverd et al.* [2010] determined from DEMETER observations.



- represents an extreme EEP flux, tube population is precipitated in 10 min.

A clearly detectable subionospheric VLF response (~0.5 dB in amplitude and ~10° in phase) is produced by nighttime >30keV electron flux of $\sim 1\times10^{0}$ electrons cm^{-2} st^{-1} s^{-1} and a daytime flux of $\sim 5\times10^{1}$ electrons cm^{-2} st^{-1} s^{-1}.

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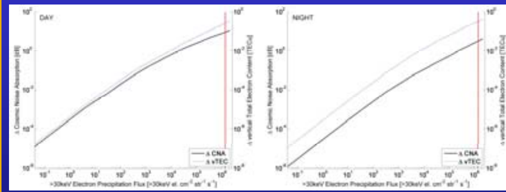


- represents an extreme EEP flux, tube population is precipitated in 10 min.

A minimum detectable CNA change of ~0.1 dB requires a >30 keV EEP flux of $\sim 10^{4}$ electrons cm^{-2} st^{-1} s^{-1} for nighttime conditions when riometers are least sensitive, but the same response can be generated by a flux of only $\sim 5\times10^{2}$ electrons cm^{-2} st^{-1} s^{-1} for daytime conditions, i.e. 10,000 and 10 times higher respectively compared to subionospheric VLF.

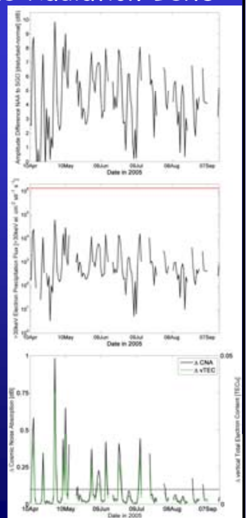
GPS derived vTEC is unlikely to be significantly disturbed by radiation belt EEP at all (we simply won't be able to measure the changes from the EEP).

Impact of "Real" EEP from the Radiation Belts

Clilverd et al. [2010] showed that the NAA to SGO path could be successfully used to extract EEP magnitudes for a ~160 day period (when entire path sunlite).

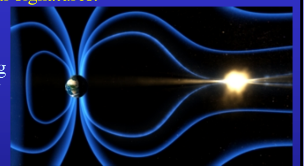
Here we compare the VLF ΔAmplitude observations from this period, the EEP fluxes which generate them & the predicted riometer and TEC responses. There is a clearly detectable change in riometer response during the periods of peak EEP fluxes, i.e., during storm times. However, no change in vTEC in the presence of stormtime high energy precipitation (>0.1 TECu threshold).

It is therefore unlikely that riometers, or GPS-derived TEC can be used to measure radiation belt EEP in "normal" or "small" storm conditions, although that riometers will respond during the largest precipitation events.

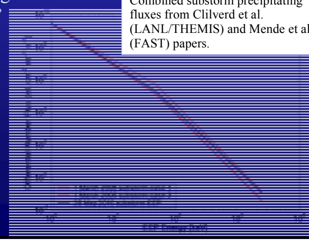


What about vTEC? What about substorms

Substorms generate EEP when the energy stored in the Earth's magnetotail is converted into particle heating and kinetic energy, and make particle precipitation. Clilverd has published a couple of studies where substorms make big subionospheric VLF and riometr signatures.



Recently, *Watson et al.* [JGR, 2011] examined GPS TEC measurements during substorms and reported vTEC changes of several TEC units associated with the substorm. They argued the bulk of the ΔvTEC change occurred at altitudes of approximately ~100km, which I thought was unlikely given the fluxes of "auroral" electrons at ~1keV are very high.



Combined substorm precipitating fluxes from Clilverd et al. (LANL/THEMIS) and Mende et al. (FAST) papers.

So lets test this idea against events reported in the literature, using the modelling we have developed.

What about vTEC? What about substorms

Table 1. Summary of Ground-Based EEP Instrument Responses During Two Substorms Reported by *Clilverd et al.* [2008, 2012][a]

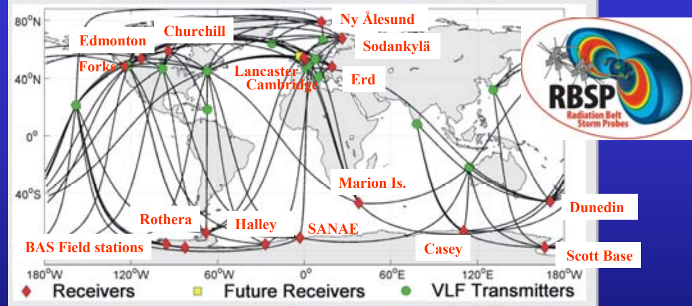
Event	ΔCNA	ΔVLF	ΔvTEC	EEP
1 March 2006				
Observed experimental	2.9 dB	−15 dB	–	–
Calculation results	2.9 dB	−9 dB	3.1 TECu	0.8×10^7
	5.4 dB	−15 dB	4.2 TECu	2.6×10^7
28 May 2010				
Observed experimental	3.2 dB	210°	–	–
Calculation results	3.2 dB	210°	4.8 TUCu	1.1×10^7

The EEP values listed are >30 keV electron fluxes with units of electrons cm^{-2} st^{-1} s^{-1}.

Note these EEP levels are really large (10 to 30 times larger than what Aaron will report in his big events), with clear signatures in all 3 instruments. AND with a strong vTEC signature (~half of which comes from <100km).

Our AARDDVARK

ANTARCTIC-ARCTIC RADIATION-BELT (DYNAMIC) DEPOSITION - VLF ATMOSPHERIC RESEARCH KONSORTIA



An aarmory of AARDDVARKs. This map shows our existing network of sub-ionospheric energetic precipitation monitors.

MORE INFORMATION: www.physics.otago.ac.nz\space\AARDDVARK_homepage.htm

Summary & Conclusions

- We have developed the tools by which we can extract EEP fluxes from ground-based observations, and published them in a recent paper.
- In the monoenergetic beam case, we find riometers are more sensitive to the same EEP event occurring during the day than during the night, while subionospheric VLF shows the opposite relationship, and the change in vTEC is independent.
- In general, the subionospheric VLF measurements are much more sensitive than the other two techniques for EEP over 200 keV, responding to flux magnitudes two-three orders of magnitude smaller than detectable by a riometer. Detectable TEC changes only occur for extreme monoenergetic fluxes.
- For the radiation belt EEP case, clearly detectable subionospheric VLF responses are produced by daytime fluxes that are ~10 times lower than required for riometers, while nighttime fluxes can be 10,000 times lower. Riometers are likely to respond only to radiation belt fluxes during the largest EEP events and vTEC is unlikely to be significantly disturbed by radiation belt EEP.
- For a large substorm both the riometer absorption and subionospheric VLF respond significantly, as does the change in vTEC,

Acknowledgement: The research leading to these results has received funding from the European Union Seventh Framework Programme [FP7/2007-2013] under grant agreement n°263218.

England. Craig standing in front of Oxburgh Hall. This castle-like manor house with its moat is a 15th century construction. Craig was visiting the British Antarctic Survey in Cambridge for a collaboration visit [25 June 2012].

Thankyou!

Are there any questions?