Radiation Belt Modeling: Ground-based Contributions

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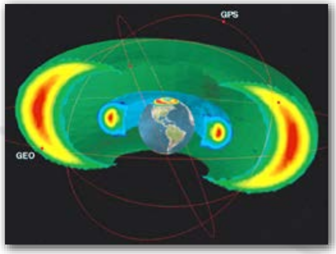
Intermagnet meeting, Hermanus, September, 2017

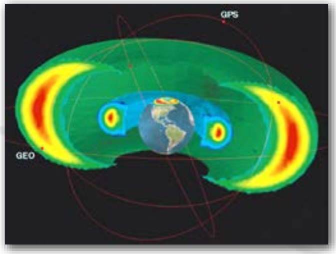
Motivation



- Focus is on energetic (~MeV) electron radiation belt modeling (but also applicable to ring current modeling)
- This population is the cause of deep dielectric charging and contributes to overall dose
- The region to be covered is from Geosynchronous orbit to LEO

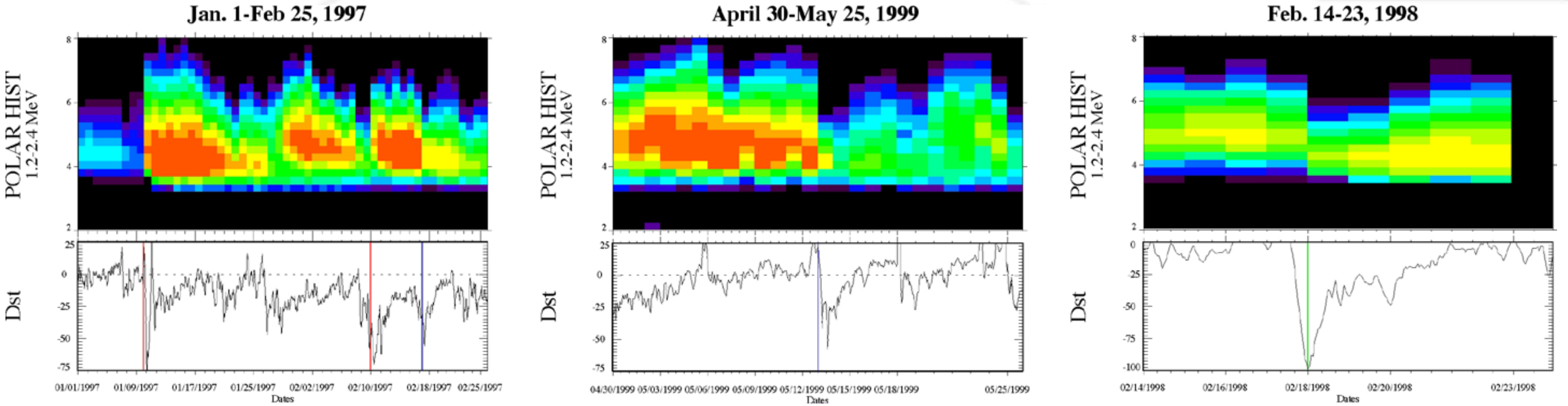
We ask the question:

What currently are the main limitations in Modeling this population in the Earth's Radiation Belts?



Background

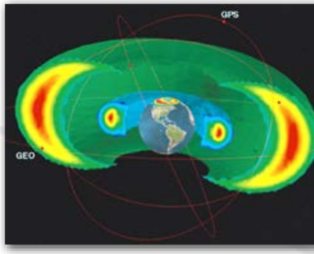
Results from Reeves et al, 2003 [514 citations]



Difficulty in understanding dynamics of system: Wide range of responses for similar geomagnetic storms – Increase / Decrease / Shift of peak / No change - are all possible responses

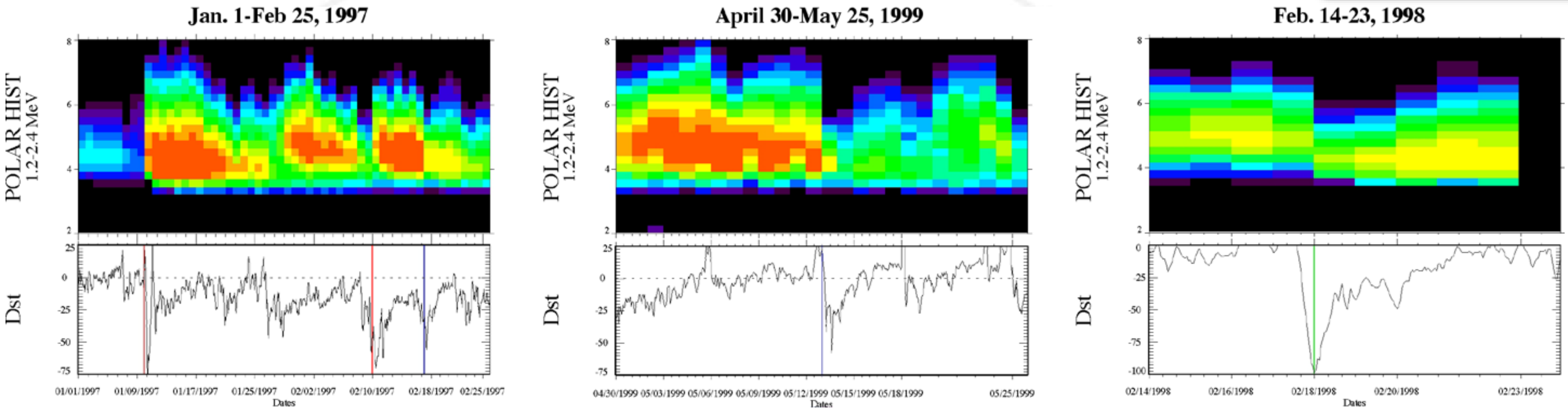
Many processes operate simultaneously that cannot be separated observationally

Response thought to be result of a delicate balance of loss, transport and internal energization processes.



Quick Question:

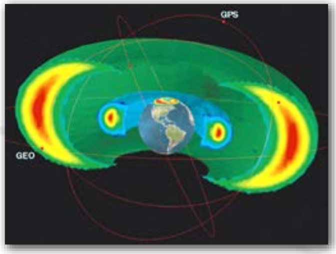
Why can't current models reproduce the observed dynamics?



We have a range of quite sophisticated modelling approaches for the inner radiation belts, that include transport, acceleration, and losses. What's missing?

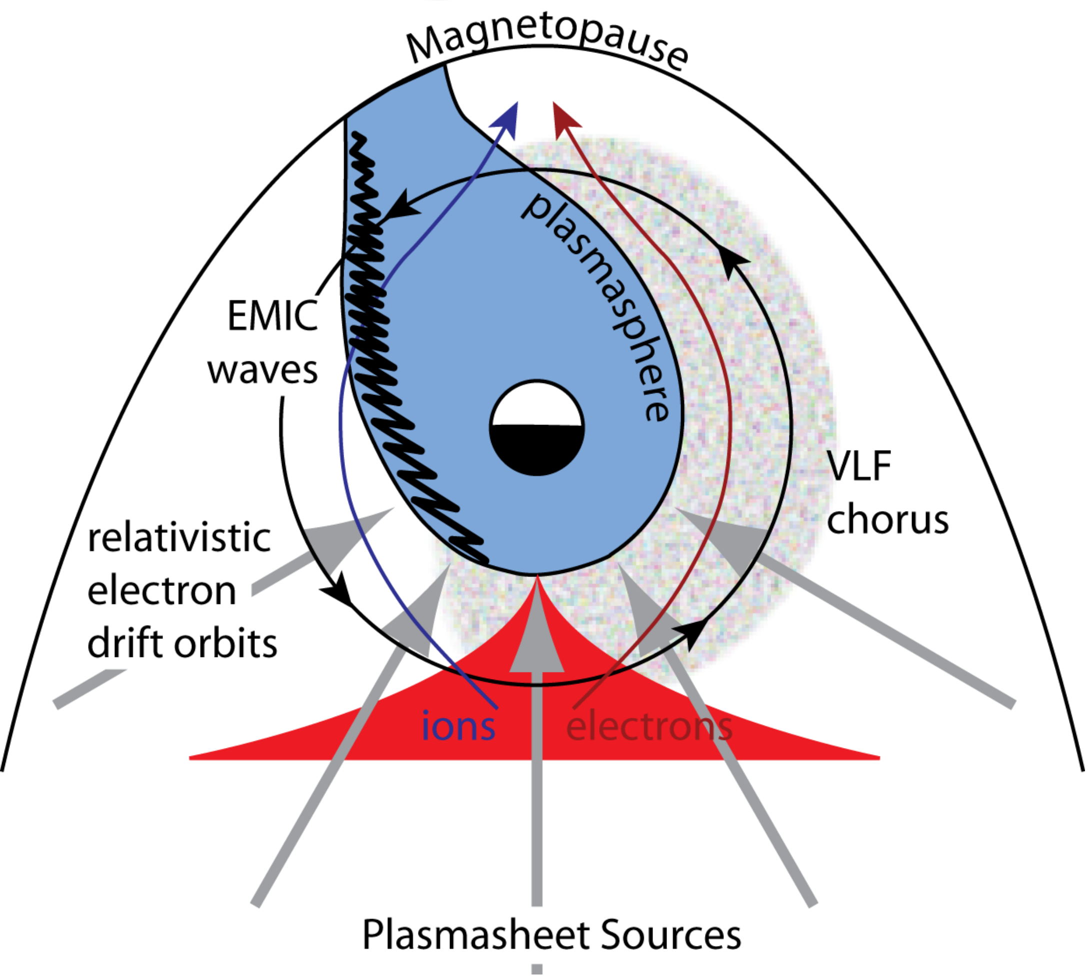
I would hold that our current models DO include the major physical processes, but that we are driving these models with broad statistical inputs (D_{LL}, wave statistics driving D_{EE} and $D_{\alpha\alpha}$, simple background density models), and badly constrained boundary conditions.

Simply: Average inputs in -> average behaviour out



Background

Current understanding of processes



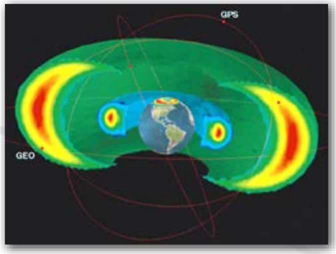
Plasmasheet:
Source of seed population (convection & impulsive injection)

Magnetopause:
Possible loss mechanism, shadowing + outward diffusion

Waves:
Drifting electrons encounter several possible wave regions
Hiss (loss) inside plasmasphere/plumes,
Chorus (energization) outside plasmasphere, and *EMIC* (strong loss) at edge of plasmasphere / plumes.
New: magnetosonic waves near equator

Background

Inner Radiation Belt Modeling Approaches

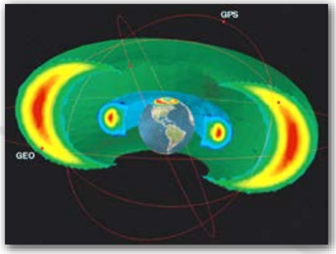


Main classes of models:

1. Diffusion models based on Fokker-Planck Equation.
   - ➢ Uses diffusion coefficients to model the effects of waves on radial, pitch angle, energy and cross diffusion
   - ➢ Simple lifetimes to model pitch angle diffusion loss
2. RAM-type drift physics codes
   - ➢ Uses D_{LL} in static fields or calculates drifts in self consistent magnetic and electric fields
   - ➢ Simple lifetimes to model pitch angle diffusion loss
   - ➢ Uses D_{EE} and $D_{\alpha\alpha}$ + cross terms) with statistic wave amplitudes or with calculated growth rates -> wave amplitudes
3. MHD codes with particle tracers
   - ➢ Radial diffusion from self-consistent fields
   - ➢ Traced particles use D_{EE} and $D_{\alpha\alpha}$ with statistic wave amplitudes
4. Hybrid codes
   - ➢ Can treat self-consistent EMIC / whistler growth & interaction
   - ➢ Limited coupling to global codes
5. PIC codes
   - ➢ Once these do the global magnetosphere we may all be able to go home…
   - ➢ Prohibitive computational needs

Background

Inner Radiation Belt Modeling Approaches

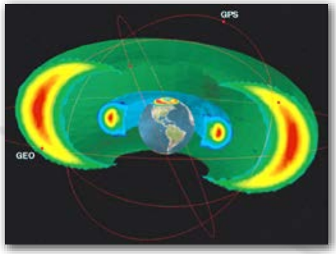


Main classes of models:

1. Diffusion models based on Fokker-Planck Equation.
   - Uses diffusion coefficients to model the effects of waves on radial, pitch angle, energy and cross diffusion

Likely to be the only candidate for an operational MeV radiation belt model for the foreseeable future, eg.

Salammbô (ONERA)
SpaceCast/SpaceStorm (BAS)
VERB (UCLA/GFZ)
DREAM3D (LANL)
…



Background

Diffusion coefficient calculation (Glauert, Summers, Albert)

Wave particle interaction diffusion coefficient calculations based on quasi-linear theory are computationally expensive and the community has spent a lot of effort to perform these calculations with varying degrees of approximations:

For background environmental conditions:

- Dipole magnetic field
- Advanced dynamic field models
- **Simple background density models**
- Simple ion composition models

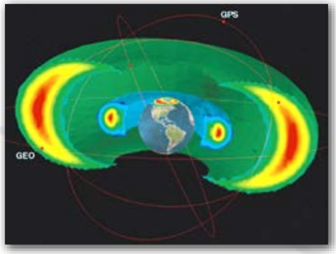
For the waves:

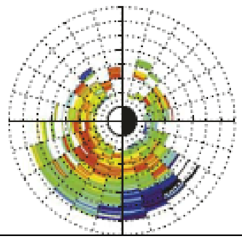
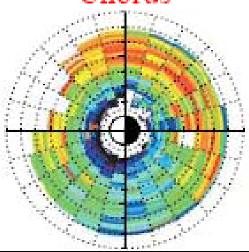
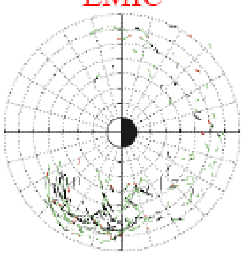
- First order resonances
- Parallel propagation of waves
- Assumed k-distribution of waves (guided by data)
- Assumed frequency distribution of waves (guided by data)
- Fixed K-distribution along field lines
- No feedback of particles on waves, no damping
- Currently parameterized by wave power only

For global wave power distribution:

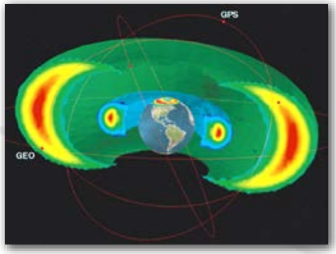
- We do not have global in-situ wave data
- **Simple statistics based on geomagnetic activity indices**
- **Assumes instantaneous MLT distribution = statistical MLT distribution**

Chorus / Hiss / EMIC Statistical Wave Models



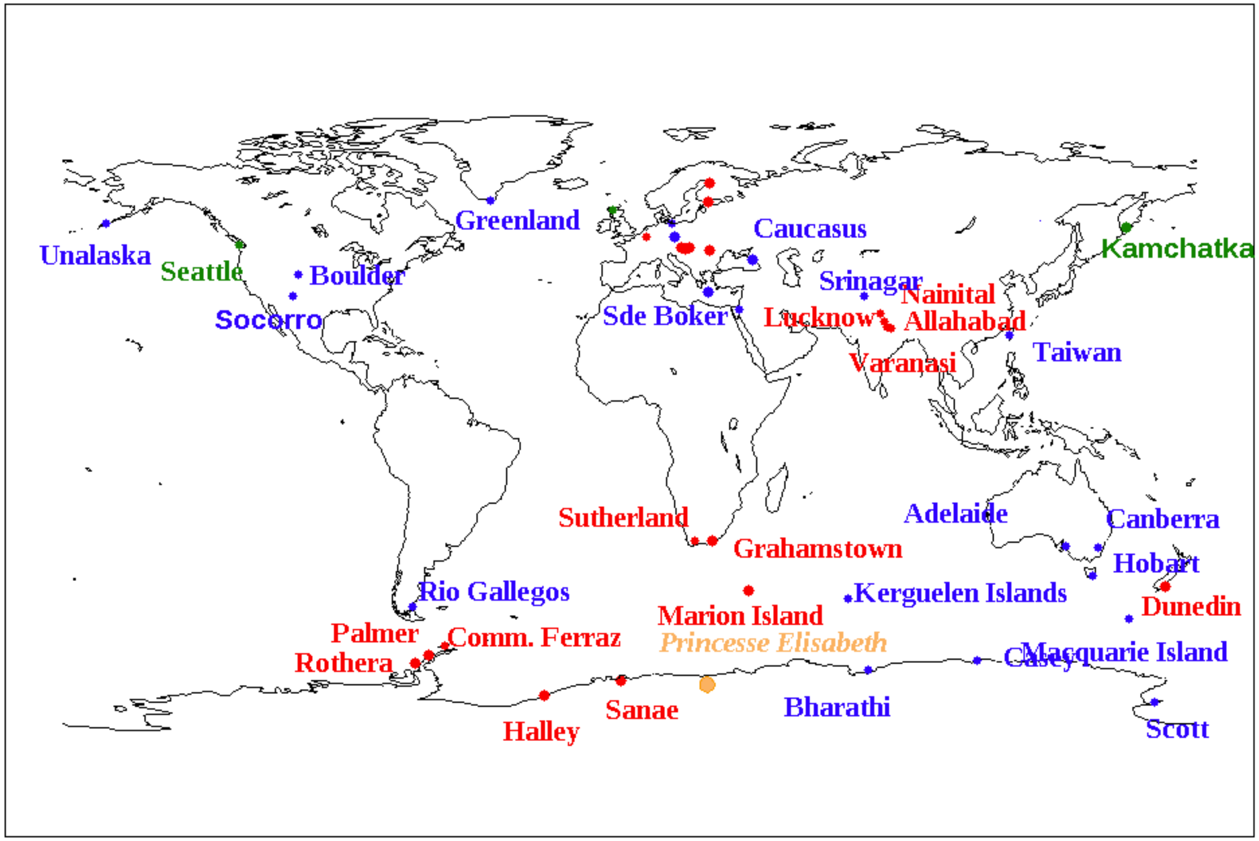
Wave Distribution	Location (L, LT)	Resonant E range	Time scale	Observation
Hiss 	2< L < 4 (mainly inside PP) 0600 < MLT < 2100	~100keV (L=3) dE/dL<0	~ 5-10 days	Yes!! (the slot region)
Chorus 	3 < L (mainly outside PP) 2100< MLT < 1300	<100keV near loss-cone ~1MeV off-equator	~ 1day	Yes (microburst?)
EMIC 	By the dusk-side PP; Plume	> ~1MeV (He-band)	hours	Indirect evidence (balloon observation?)

* Wave distribution plots taken from [Meredith et al., 2003a; Meredith et al., 2003b; Meredith et al., 2004]



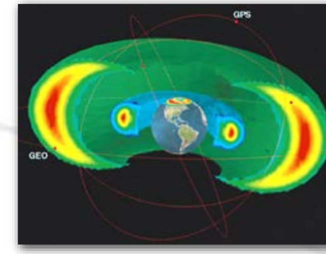
Chorus / Hiss / EMIC

- Estimate in-situ wave distribution and properties from ground based VLF measurements
- Huge availability of ground based data, e.g. ADWANET



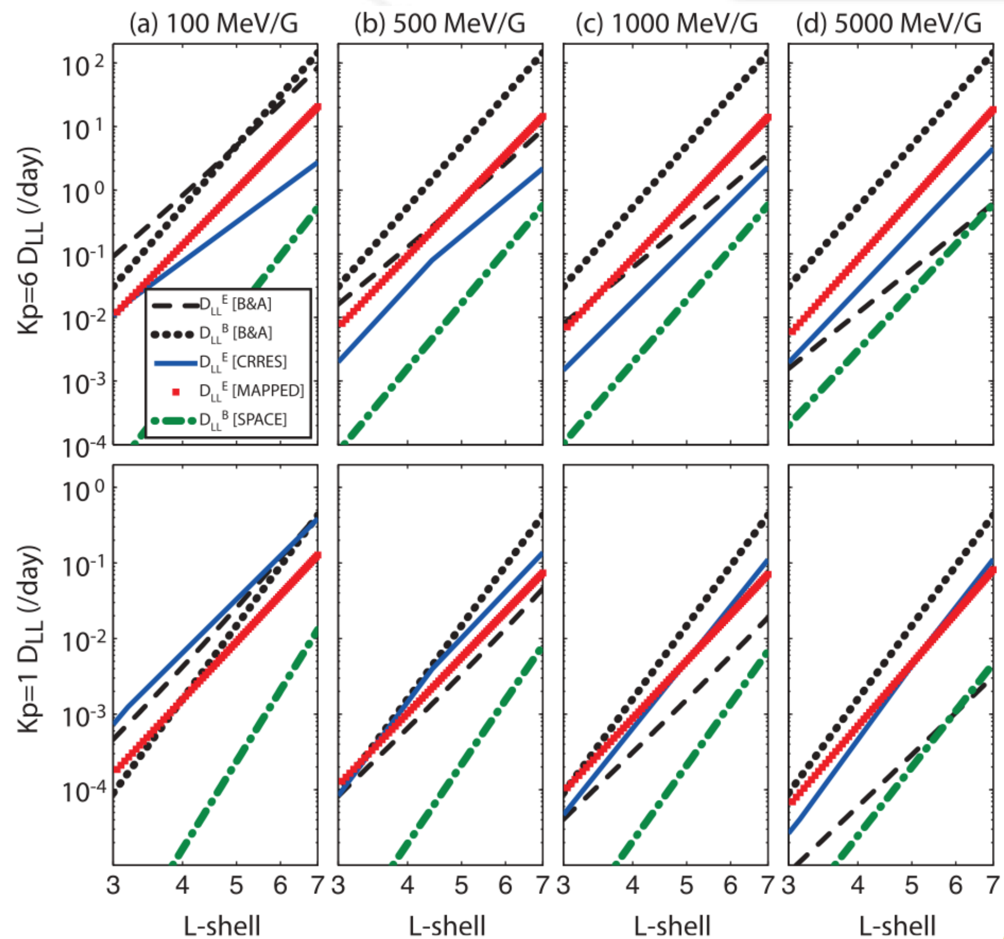
Ground based observations as proxies:

Need research to establish transfer functions between ground observations and in-situ waves.



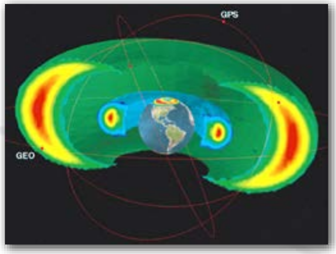
ULF

- Radial diffusion is one of the major physical process in the radiation belt yet there is little agreement on the best way to obtain it!
- Ground based, global ULF measurements offer the only viable route for obtaining ongoing, time-varying D_{LL}.

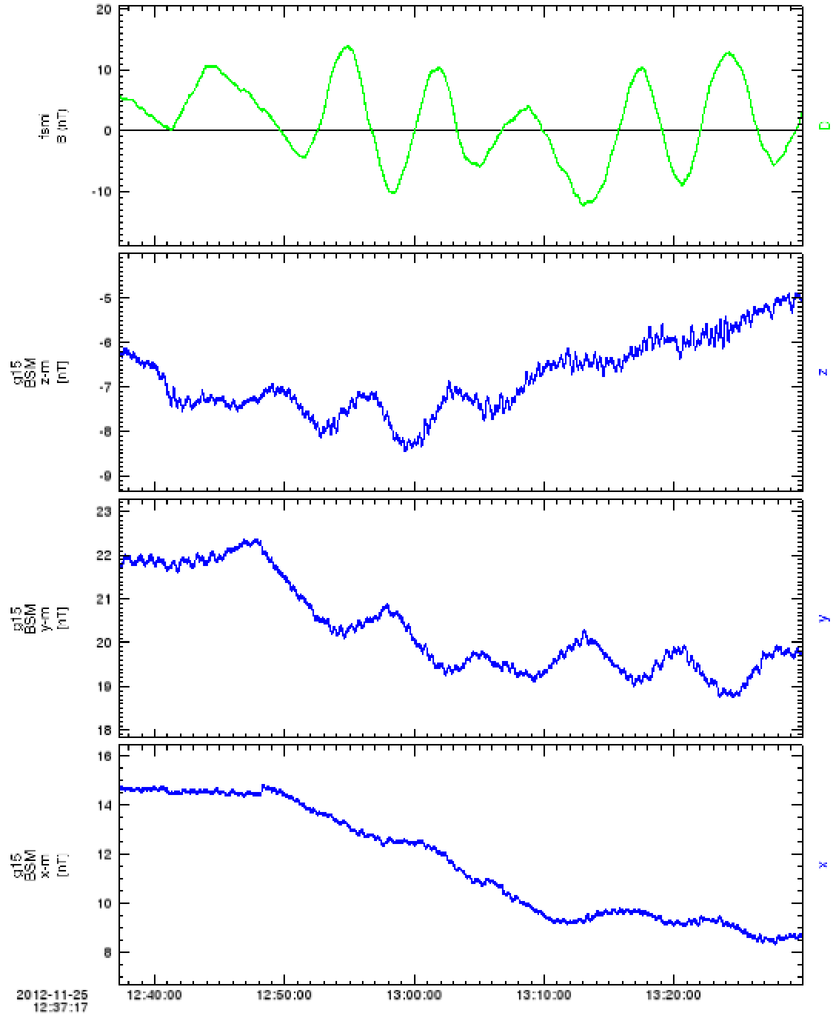


Plot from “ULF wave derived radiation belt radial diffusion coefficients”, JGR, Ozeke at al, 2012

In-situ to Ground ULF

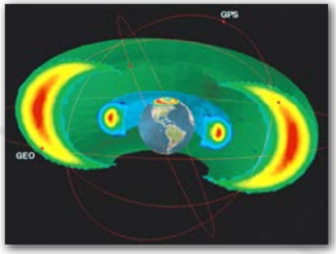


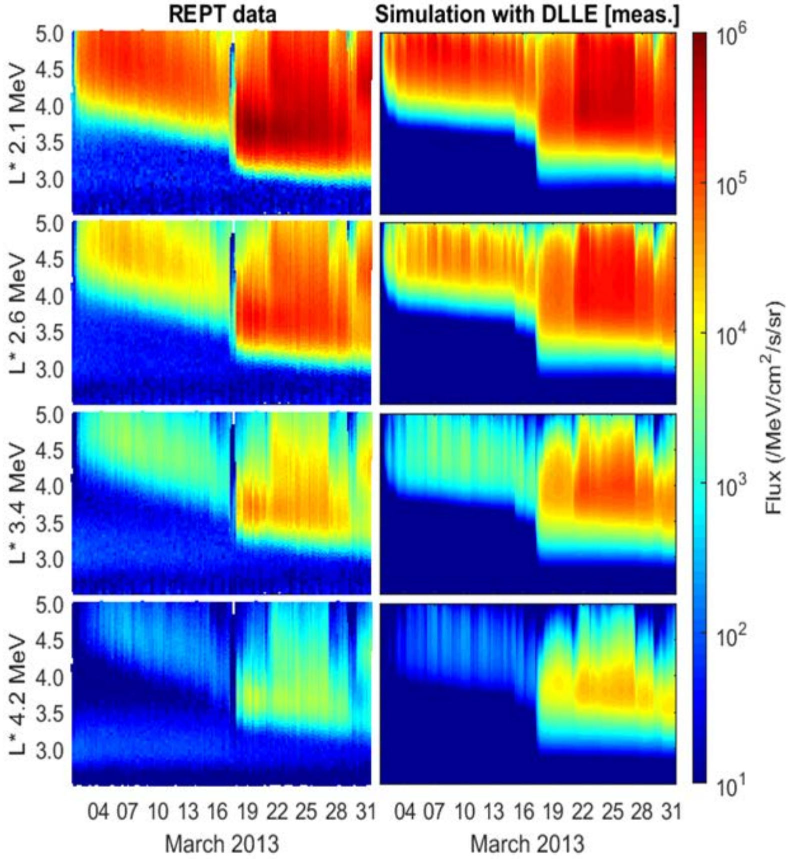
November 25, 2012 12:37 to 13:30



Often (but not always) ground based data can be used to infer in-situ ULF:
No global transfer function (statistical, neural net or physical) exists mappring ground ULF to space!

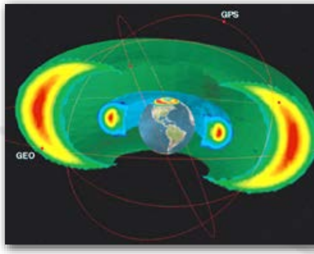
Grond Based ULF -> Radial Diffusion Coefficients D_{LL}





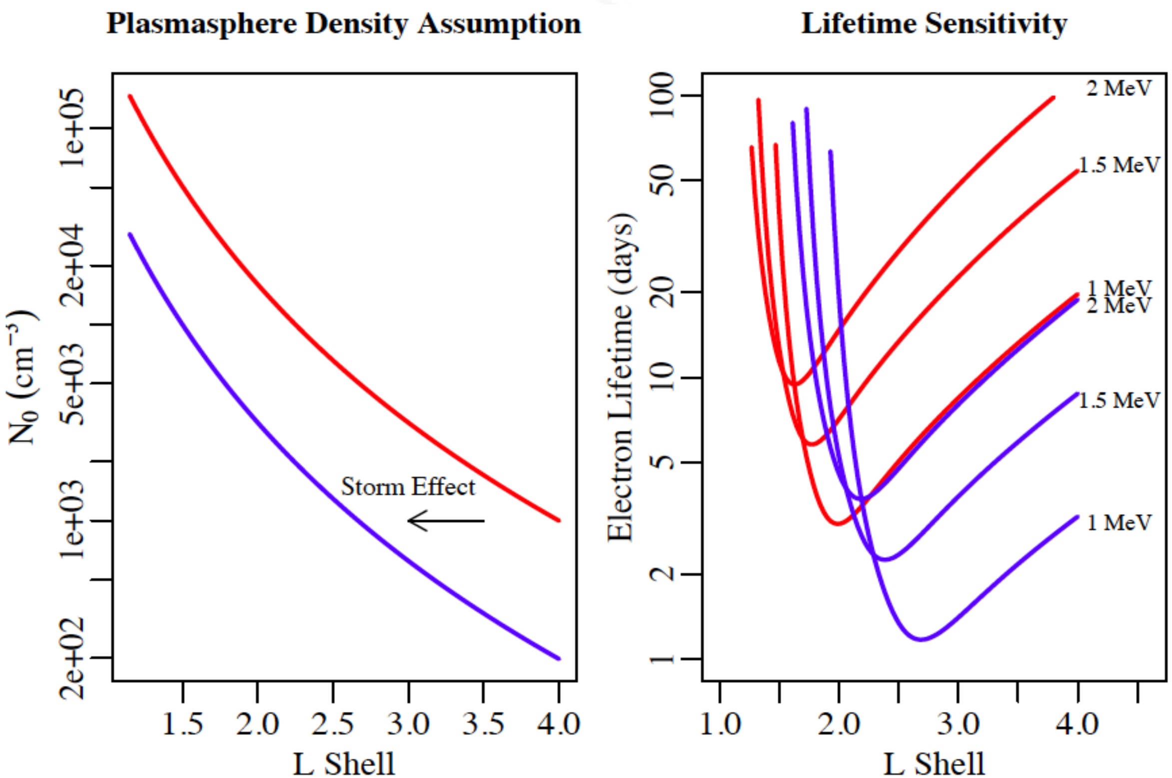
Accurate representations of ULF wave power and hence radial diffusion rates, ***defined and constrained by real-time observation of magnetic wave power from ground-based magnetometers***, and mapped into electric fields in the equatorial plane [cf. Ozeke et al., 2012a; 2012b; 2014a; 2014b; Mann et al., 2012, 2013, 2016, Ian Mann, University of Alberta]

NEED: 1 Hz data from the Canadian Array CARISMA, the European Array EMMA, IMAGE Array Stations, Greek ENIGMA Stations, Intermagnet Stations, 210 Array, etc



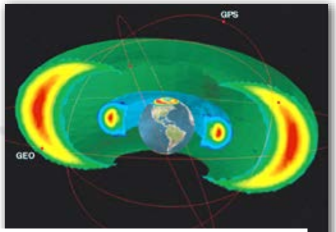
Background electron density

- Needed in the calculation of all diffusion coefficients
- “Nowcast” of the plasmasphere density possible using ground based inputs (whistlers, field line resonances together with a data assimilative code)
- (PLASMON FP7 project, J Lichtenberger)



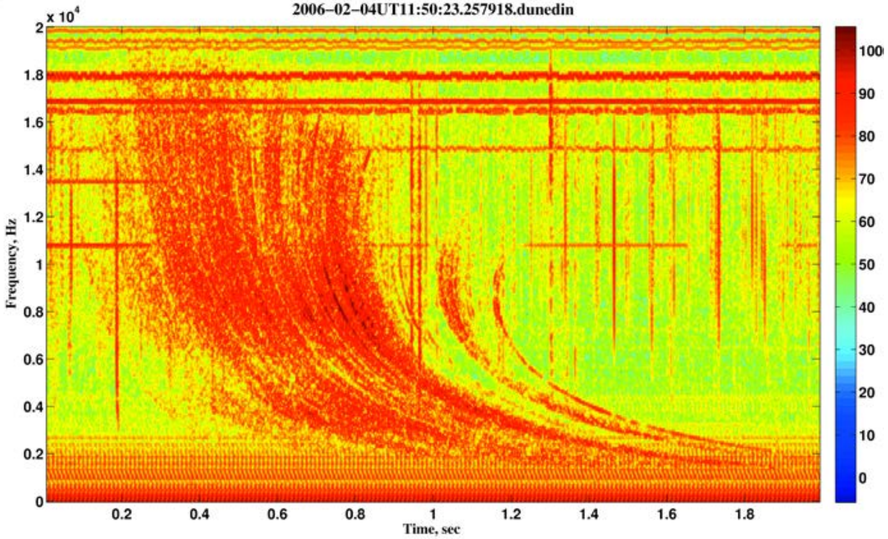
Modeled electron lifetimes from Hiss, C. Jeffery, LANL

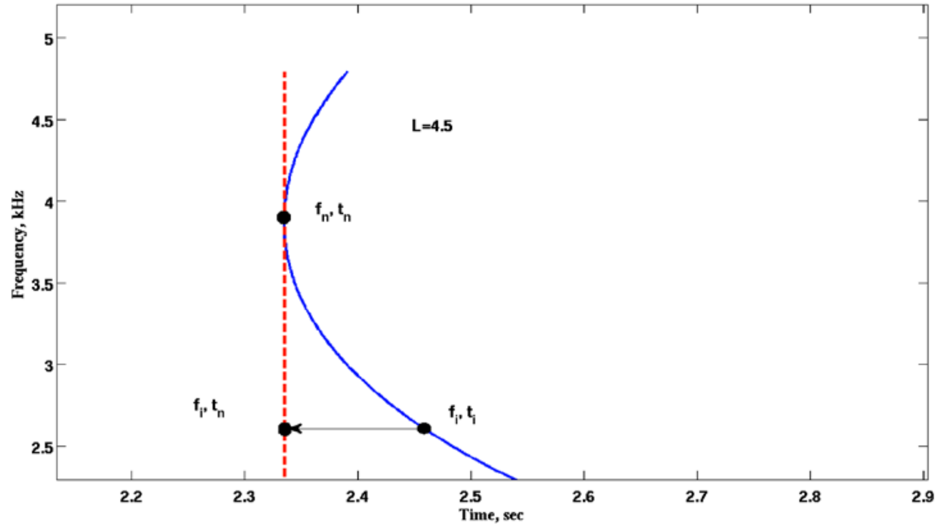
UNCLASSIFIED

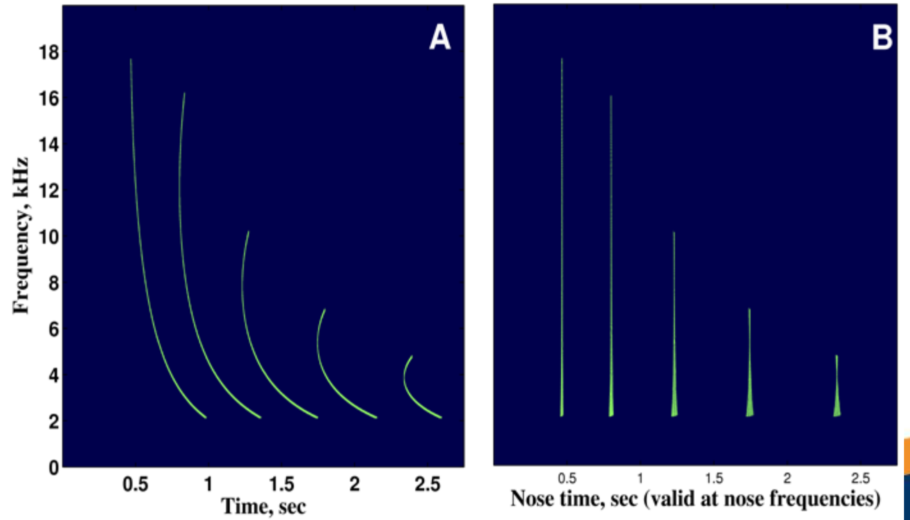


Automated analyses of whistlers

virtual (whistler) trace transformation [Lichtenberger, JGR, 009]

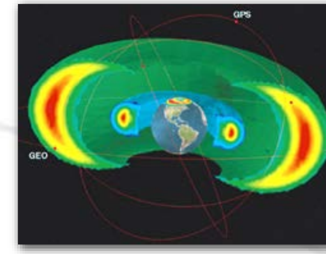






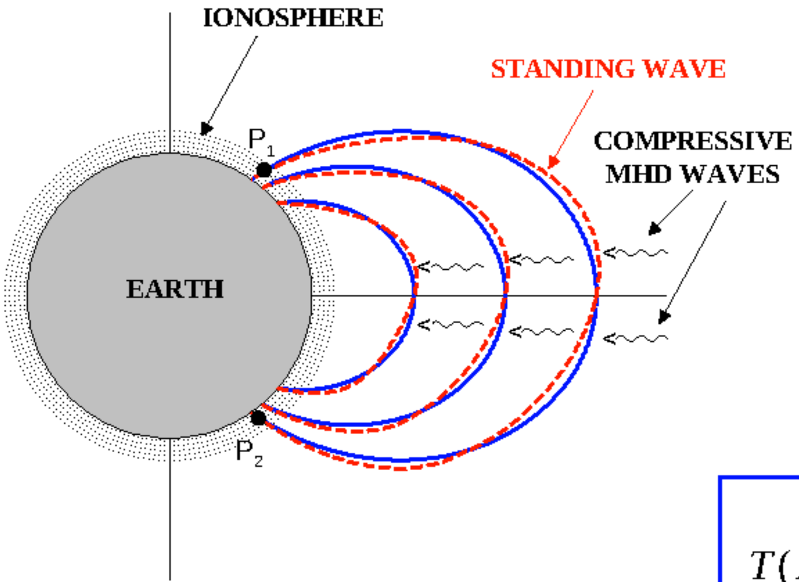
Whistler Nose frequency related to equatorial electron density and density profile along field line.

$\log_{10} neq = A + B \cdot L$



Automated analysis of field line resonances

Cross phase method, FLRINV [*Berube et al. 2003*]



$$T(L) \cong \int_{P_1}^{P_2} \frac{ds}{V_A(s)}$$

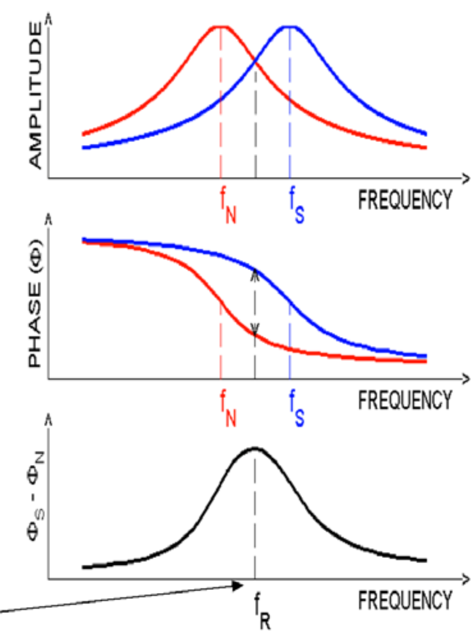
$\mathbf{V_A}$: Alfvén velocity

$$T(L) = 2\mu_0 \int_{P_1}^{P_2} \frac{\rho^{1/2}(s)}{B(s)}\, ds$$

—Higher latitude field line → Lower resonance frequency (f_N)

—Lower latitude field line → Higher resonance frequency (f_S)

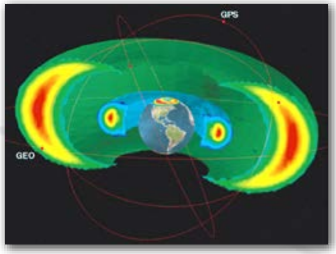
FREQUENCY RESPONSE OF TWO OSCILLATORS



Method yields mass density along field line

CROSS-PHASE TECHNIQUE

Resonance frequency at the middle point.
Identified by a maximum in the phase difference



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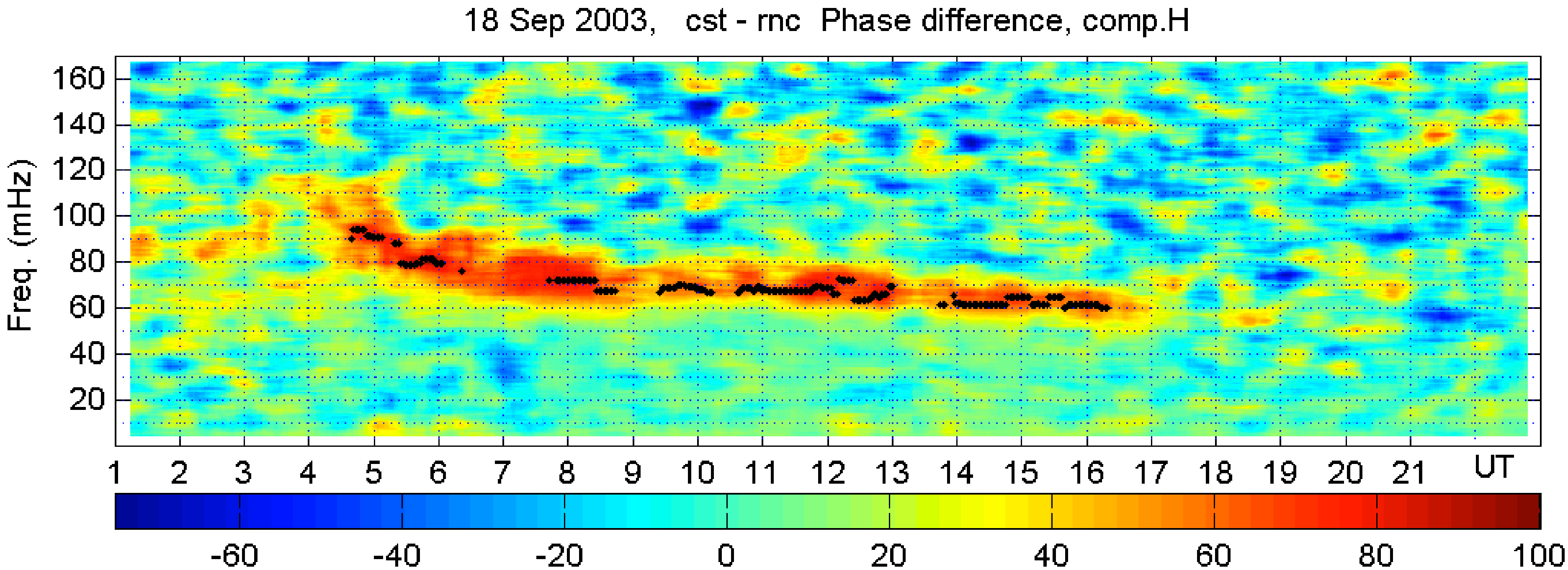
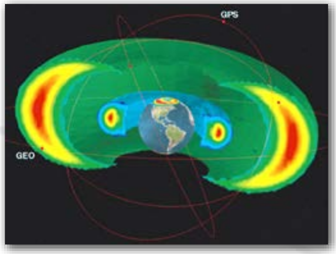


Example of automated detection of resonance frequency – example of continuous detection over ~12 hours from European EMMA chain of magnetometer stations

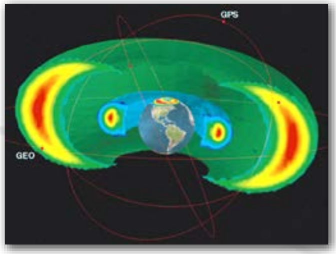


Path Forward?

- ~$1M = one Cubesat
- ~$20K = One VLF / Mag Ground Station
- 50 Ground Stations for the price of one Cubesat
- *So where should we invest?*

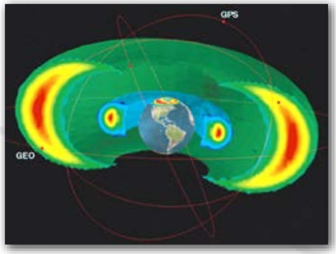
Invest in the research needed to relate high quality in situ data to corresponding ground based data!

- Ground based data



Wish List!

- Global ground based stations doing both magnetometer and VLF
- Ongoing, continuous analysis of the data in as real time as possible to provide global (as a function of L, MLT):
- **Chorus, Hiss, EMIC and ULF wave amplitude fields**
- **Measure of background electron density**
- **Estimates of radial diffusion coefficients**



Wish List!

- Is Intermagnet a possible conduit for defining and providing a range of ***derived data products*** along side the IMO data?
- Need and can go beyond Kp, Dst, Ae indices.
- Doing the "transfer function" between ground and space requires a lot of basic and applied research. Intermagnet lead of scientific sessions on these topics at IAGA, AGU, ESWW, etc…?