University of Colorado **Boulder**

Active Experiments
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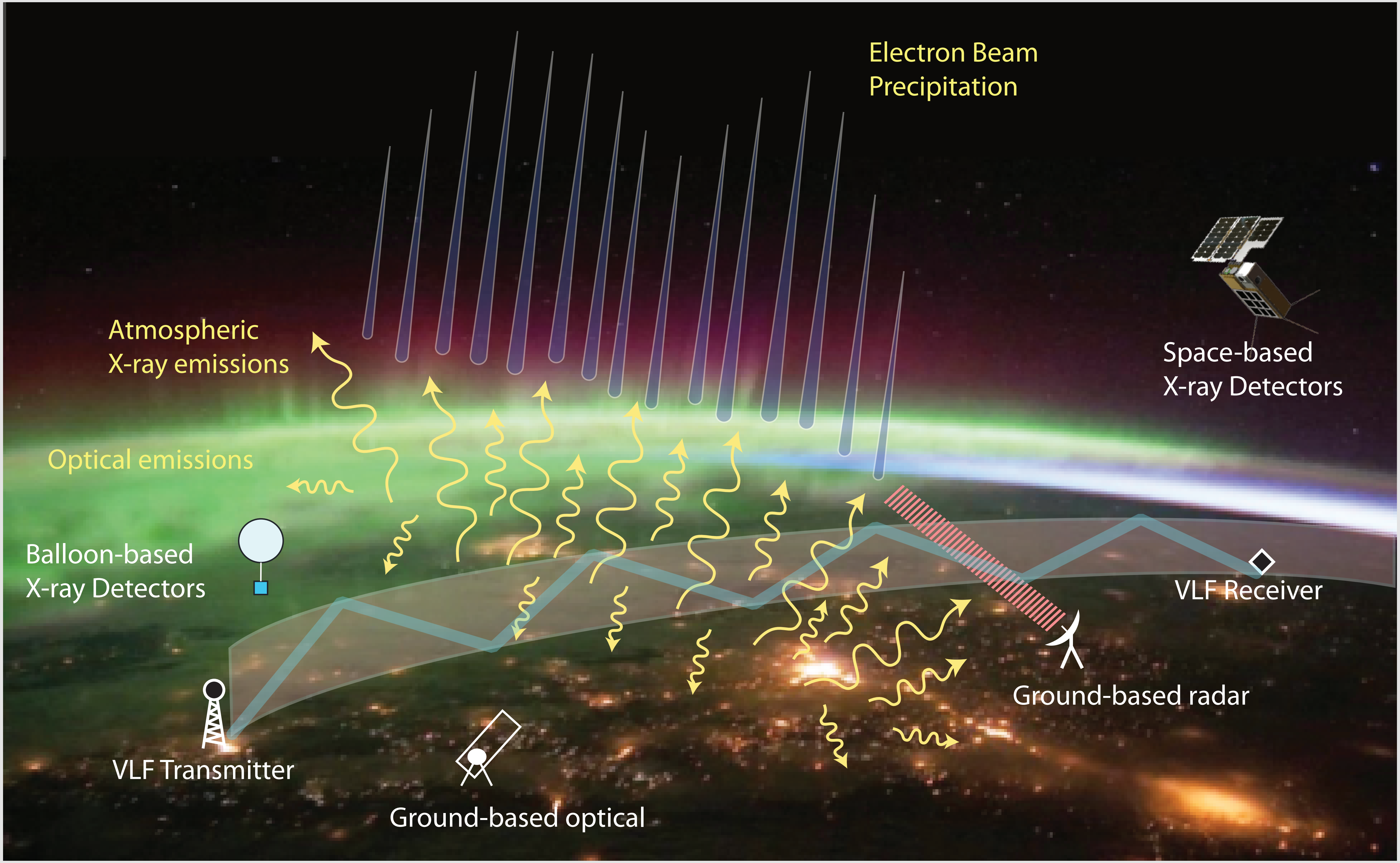
Diagnostic of Relativistic Electron Beam Injection in the Upper Atmosphere

Robert A. Marshall

With contributions from
Peter Porazik (PPPL),
Ennio Sanchez (SRI),
Antti Kero, (SGO),
Rasoul Kabirzadeh (Stanford)

Atmospheric Signatures of Beam Precipitation



Outline

1. **Overview of secondary effects of precipitation**
    1. Ionization, optical emissions, X-rays, chemistry
    2. Associated diagnostic methods
2. **Modeling framework to predict secondary signatures**
3. **Beam simulation results**
    1. Realistic beam parameters
    2. Modeling scenario
    3. Ionization signatures
    4. Optical signatures
    5. X-ray signatures
    6. Chemical response

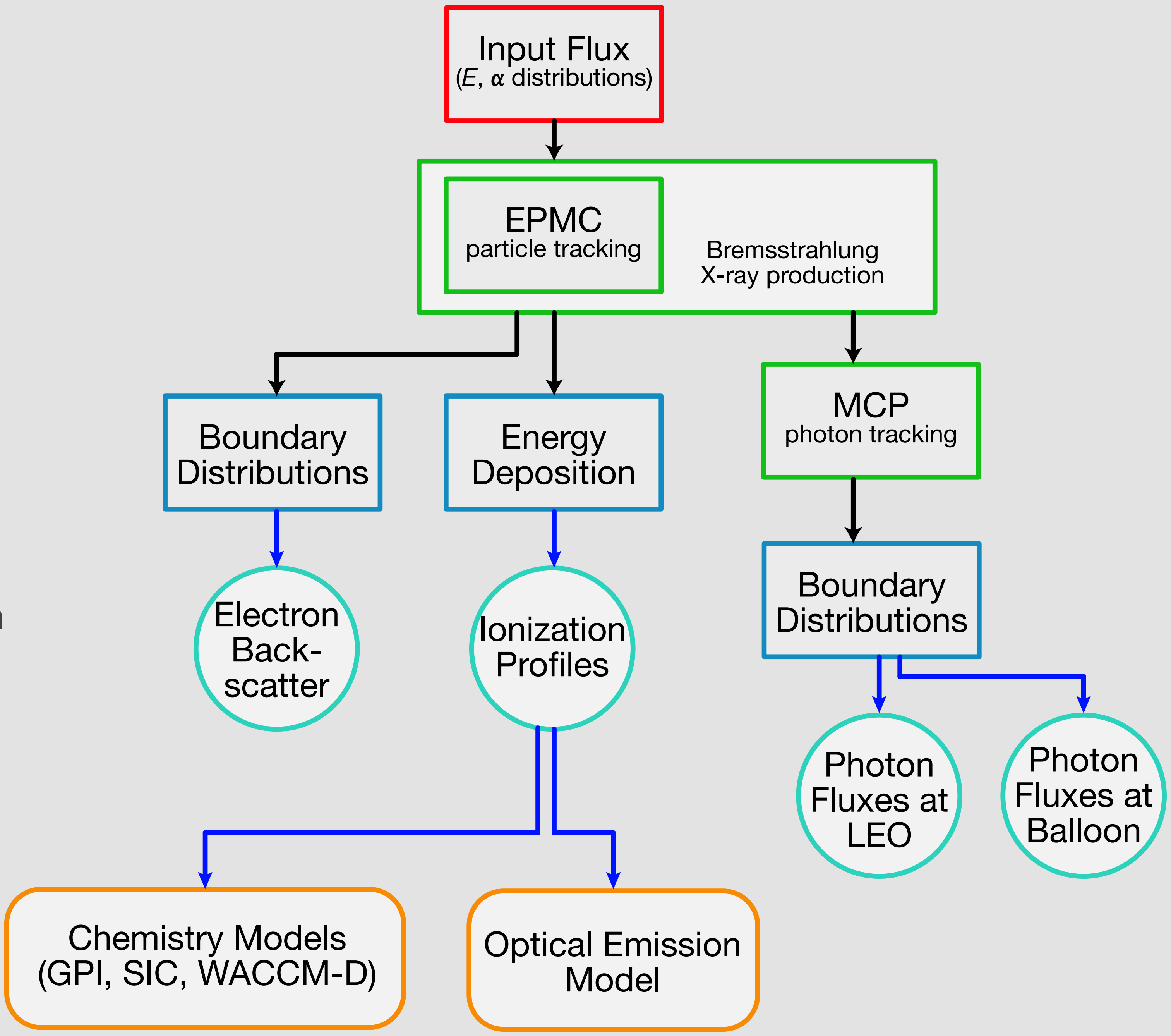
Atmospheric Effects and Diagnostics

- **Atmospheric Effects**
  - Ionization
  - Optical Emissions
  - X-ray emissions
  - Chemistry
  - Electrodynamics
- **Diagnostics**
  - Ground-based radar
  - Subionospheric VLF
  - Ground-based or space-based optical detectors
  - Space-based or balloon-based X-ray detectors
  - NOx emissions (optical)
  - TLEs?

Ionization → Ground-based radar; Ionization → Subionospheric VLF; Optical Emissions → Ground-based or space-based optical detectors; X-ray emissions → Space-based or balloon-based X-ray detectors; Chemistry → NOx emissions (optical); Electrodynamics → TLEs?

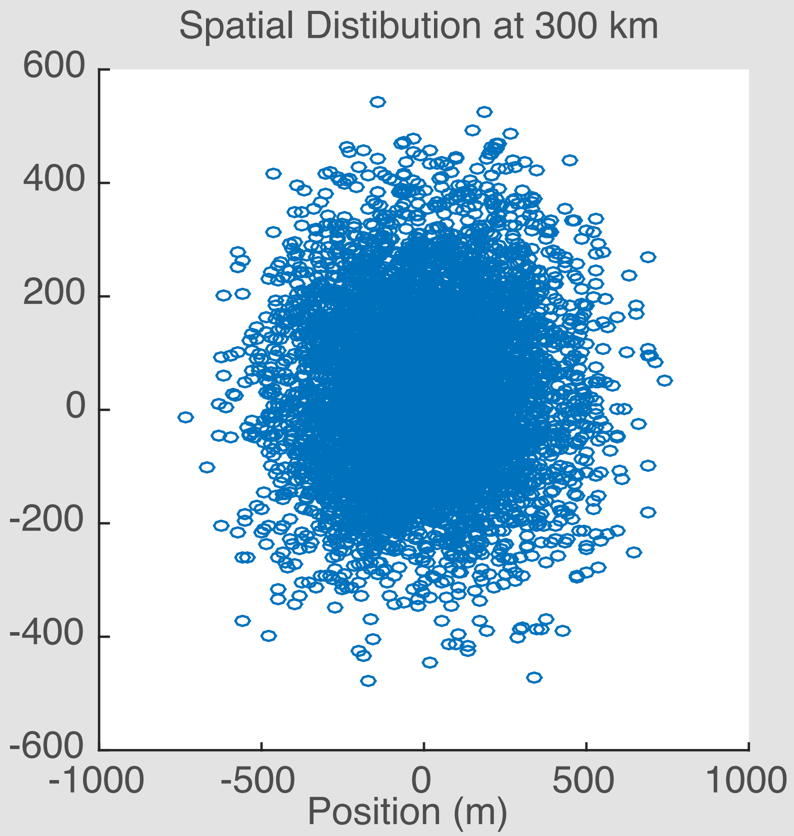
Atmospheric Effects: Forward Modeling

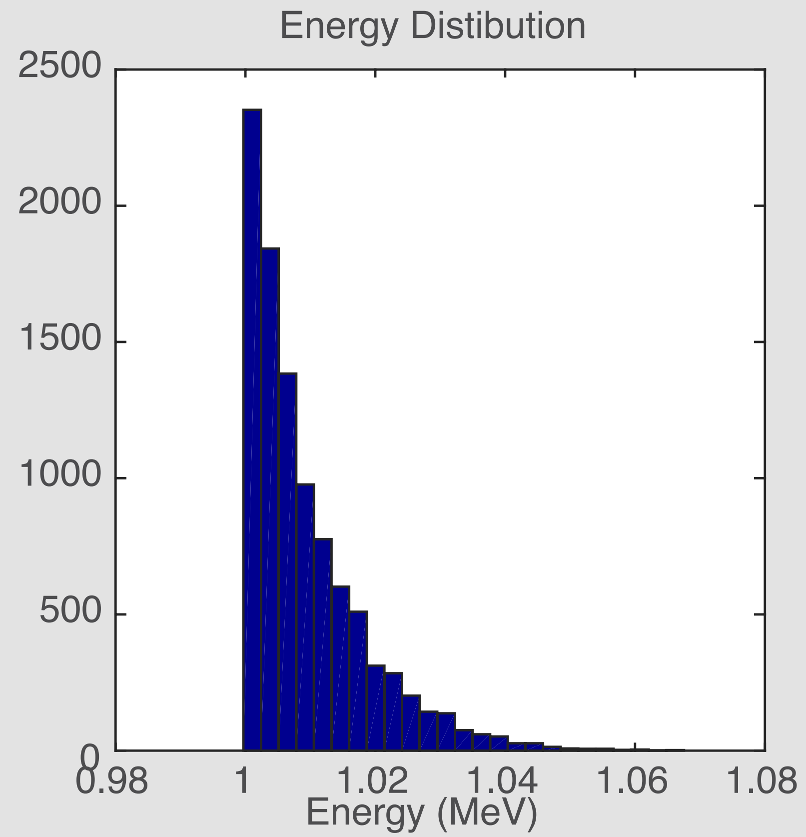
- **We use the Electron Precipitation Monte Carlo (EPMC) model framework**
  - Initial electron distribution propagated through atmosphere
  - Includes collisions, secondary ionization, energy loss, angular diffusion
  - Calculates bremsstrahlung photon production probabilistically
  - Photons separately propagated to determine observable fluxes
  - Energy deposition profiles used for secondary effects: ionization, optics, chemistry

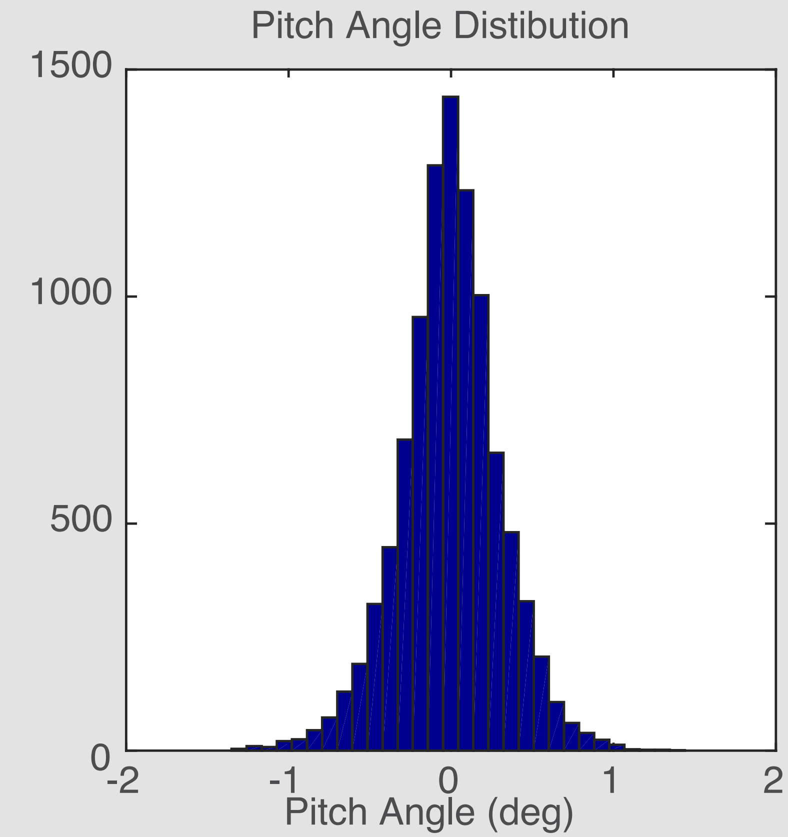


Input Electron Distributions

- We simulate a finite number of electrons, say 10^5 or 10^6
  - Energy, pitch angle, and spatial distribution given by PPPL simulation outputs
- These represent a larger number of total electrons; outputs scale linearly
  - 10 mA × 500 μs = 3 × 10^{13} total electrons in one pulse. At 1 MeV, that's 5 J per pulse







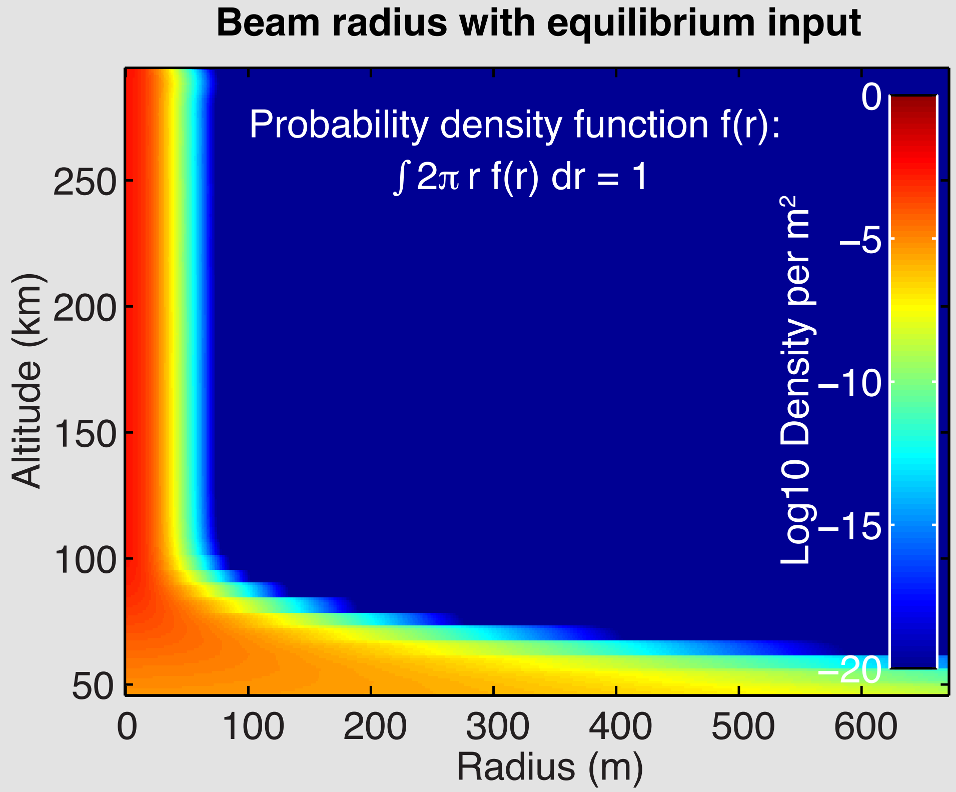
Tracking the beam radius

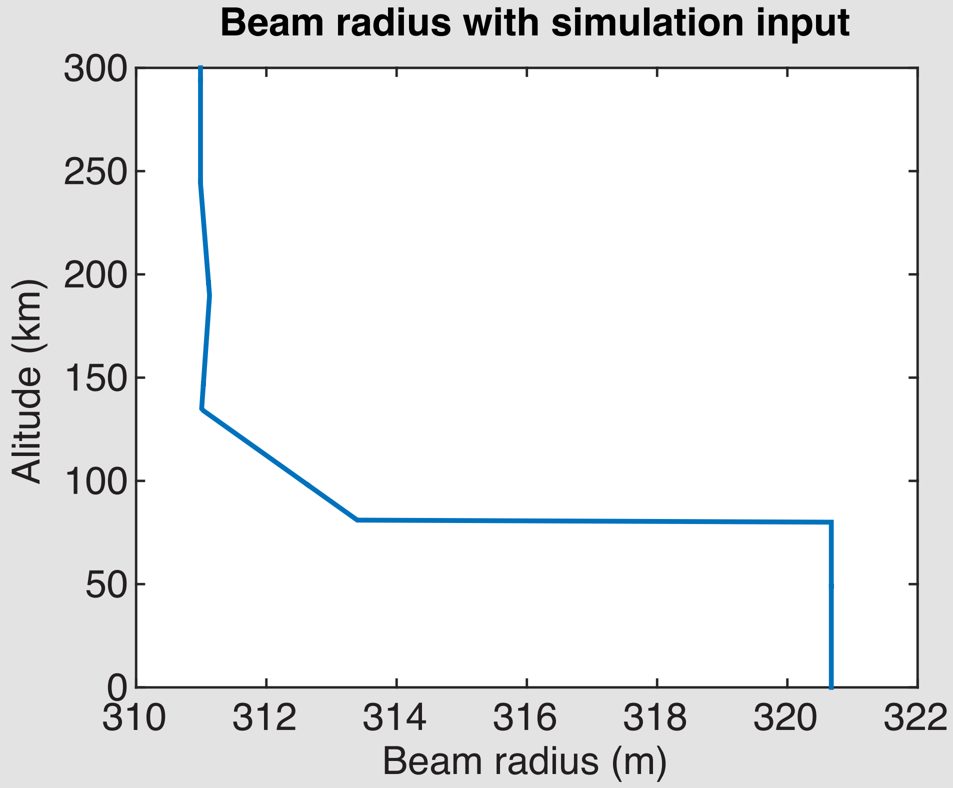
- We must assume or simulate an initial beam size / distribution at the top of the atmosphere
  - Assume: use the equilibrium radius, determined by beam energy, divergence, and properties of region (see Marshall et al, 2014)

Table 2. Beam Equilibrium Radius for Given Beam Electron Energies

Electron energy (MeV)	0.5	1	2	5	10	20
β	0.8630	0.9412	0.9791	0.9957	0.9988	0.9997
γ	1.98	2.96	4.92	10.79	20.59	40.17
Beam radius (m)	1.2	2.0	3.4	7.6	14.6	28.6

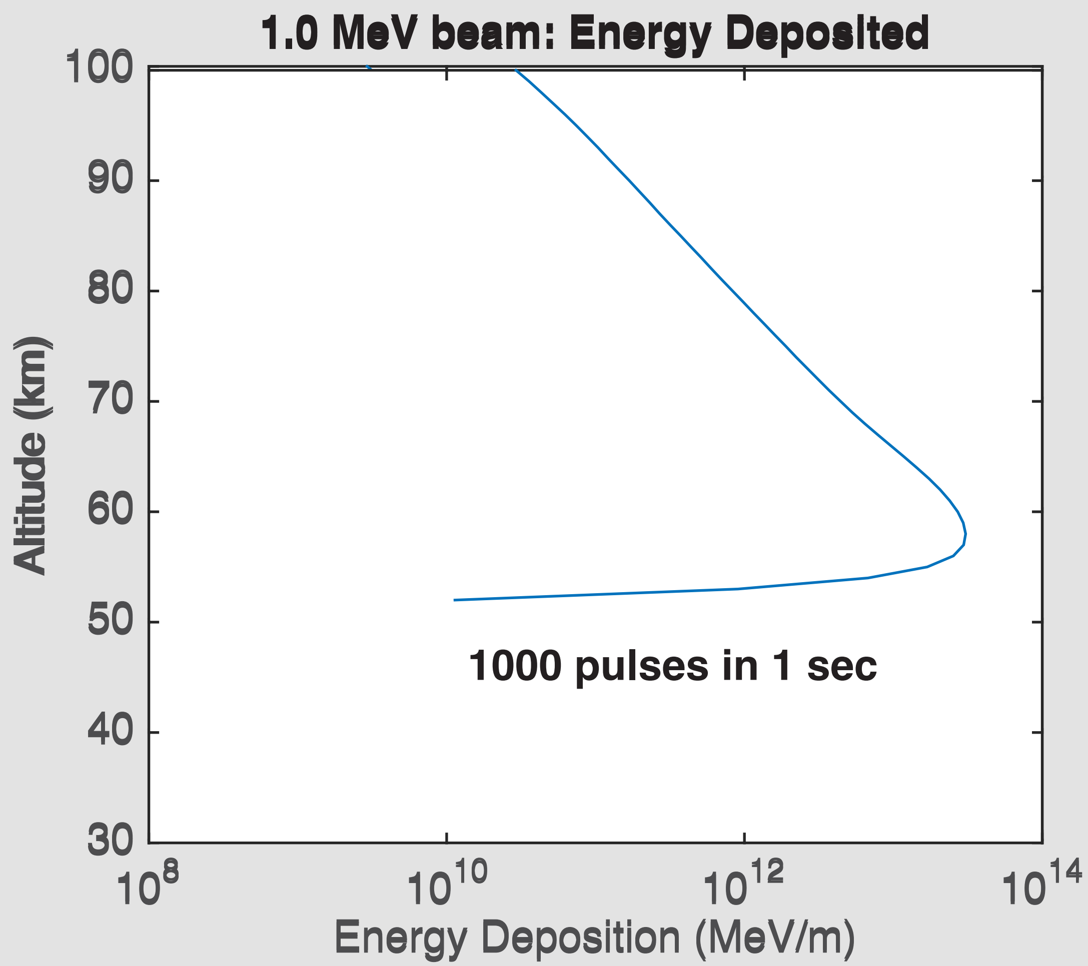
  - Simulate: determined by beam propagation simulations from PPPL (previous slide)
- During collisional interaction with the atmosphere, the distribution changes; need to track it to determine ionization density
  - We track electron distribution every 10 us and determine a beam radius

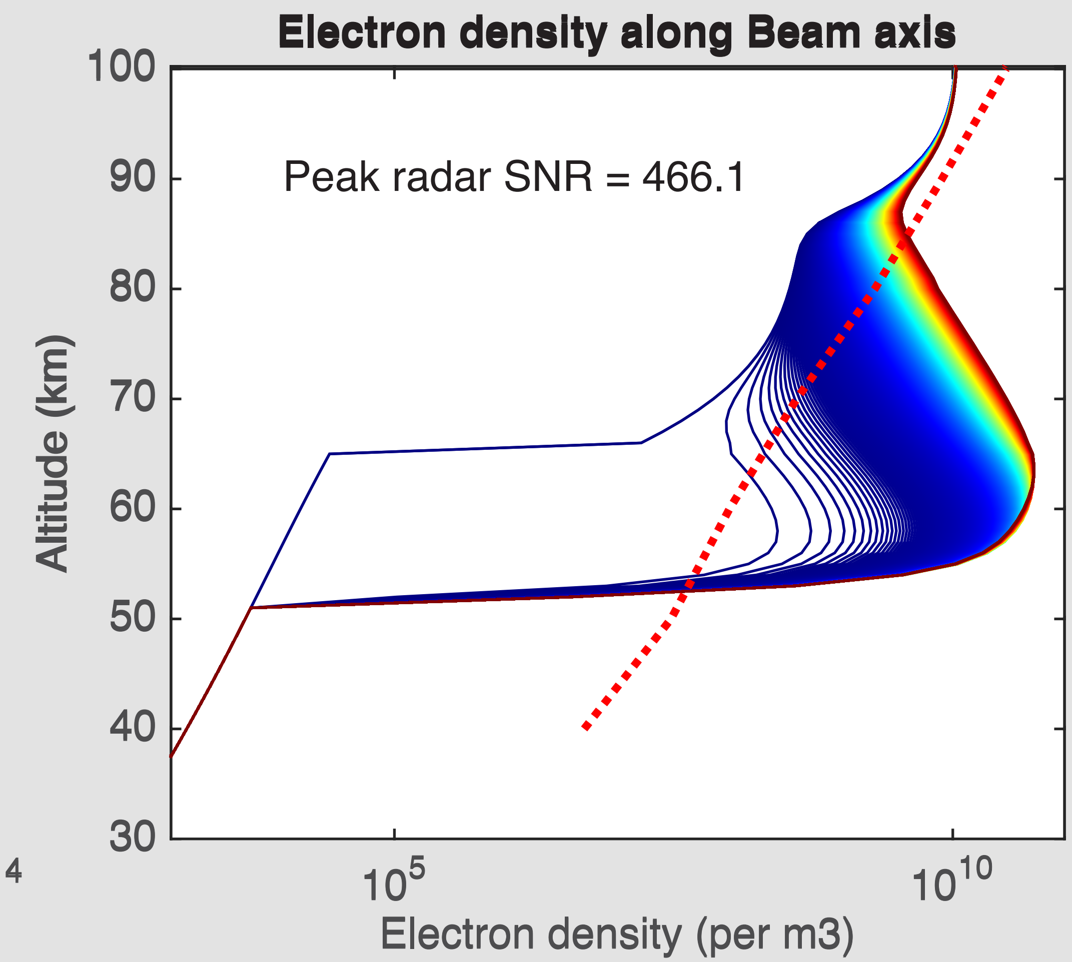




Energy Deposition and Electron density

- Given an input energy / pitch angle distribution, EPMC determines the energy deposition profiles for a single pulse. Ionization follows from 1 pair per 35 eV.
  - Use D-region ion chemistry models to determine electron density disturbance
    - Below uses 5-species GPI chemistry model [*Glukhov et al*, 1992; *Lehtinen and Inan*, 2009]
  - Wish to determine signatures in radar and VLF

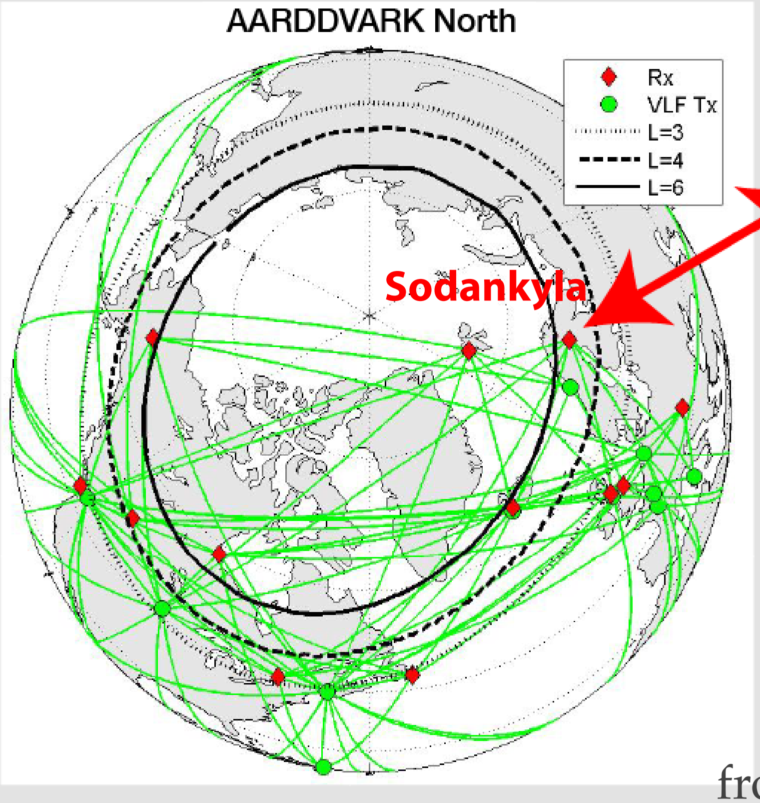


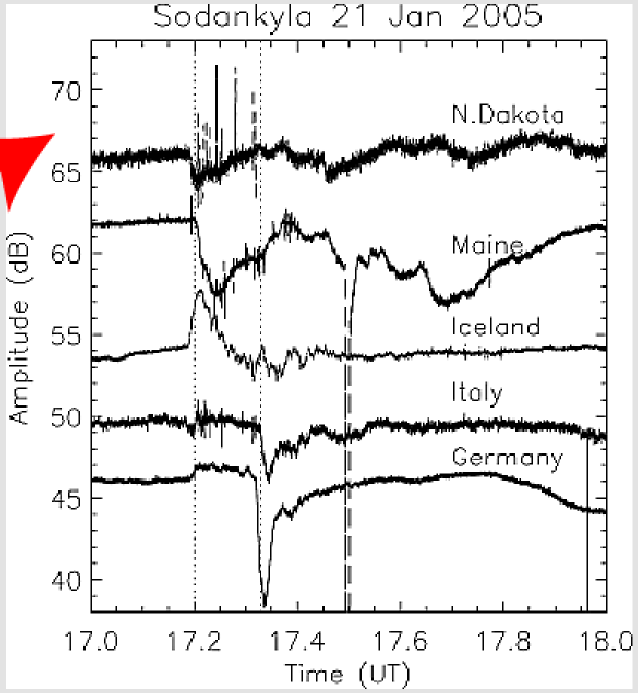


VLF subionospheric remote sensing (VLF-SRS)

- VLF transmitter signals, broadcast by US Navy and others, are very sensitive to variations in the D-region
  - Most operate in 15–40 kHz range; transmit ~100 kW – 2 MW
- Well-placed VLF receivers monitoring a range of transmitters can form a network of D-region remote sensing (e.g., AARDDVARK)

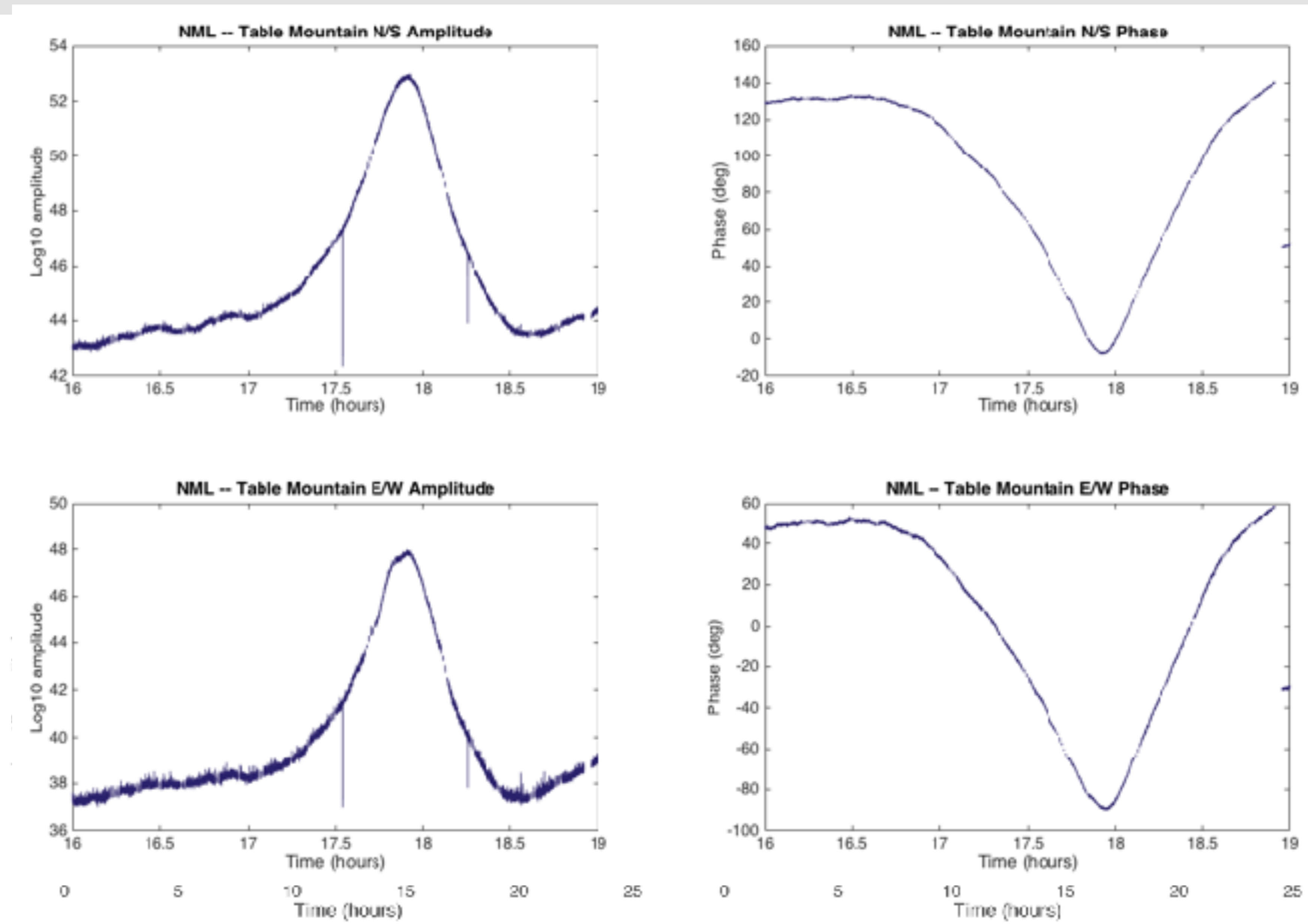
Table Mountain, Boulder, CO

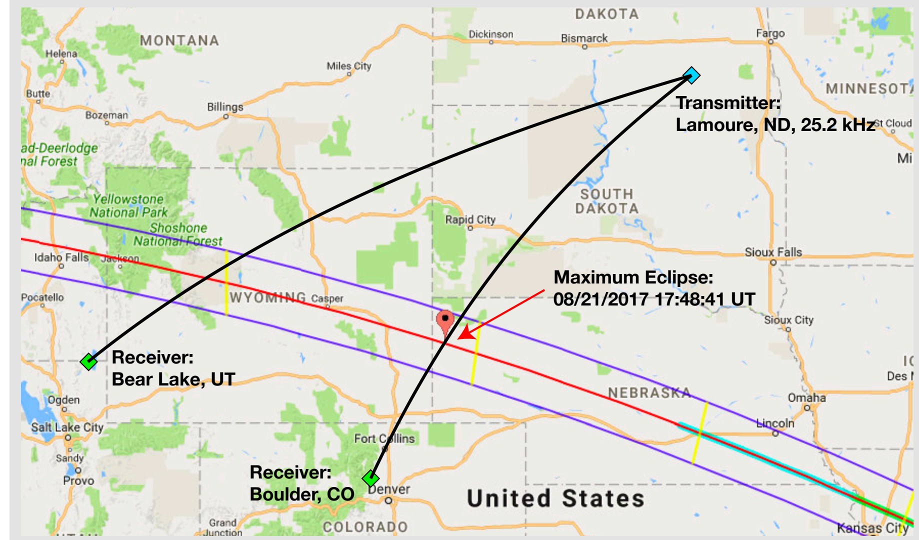




from *Clilverd et al* [2009]

Example data from Table Mountain

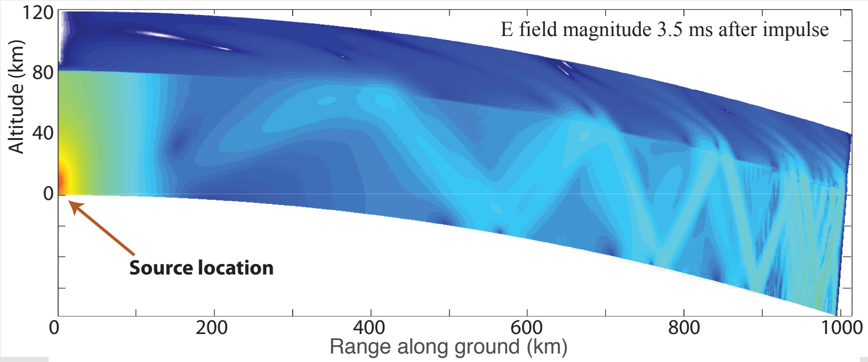


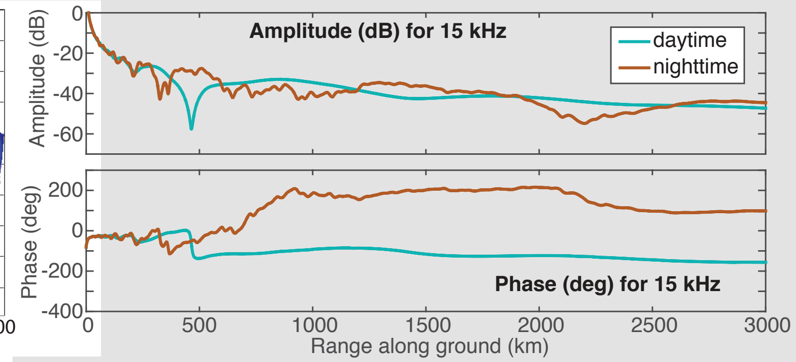


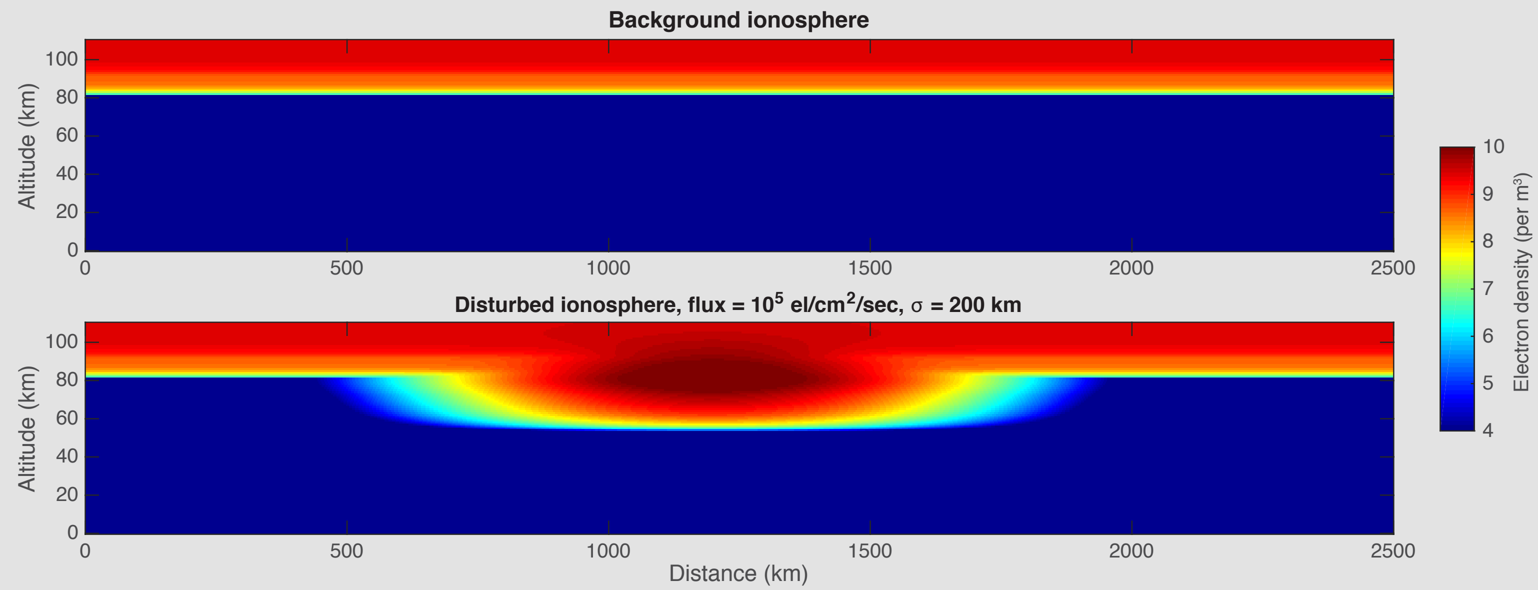
Rule of thumb: we can detect perturbations of ~0.1 dB amplitude, ~1 deg phase

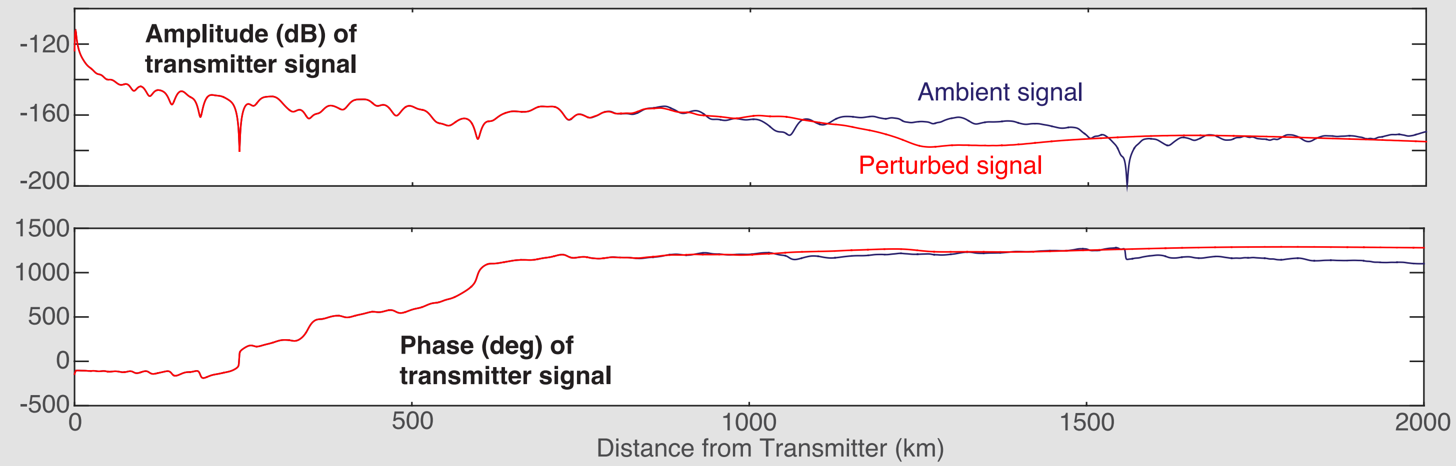
Modeling VLF signatures of Precipitation

- Electron density perturbations are used as input to 2D Finite-Difference Time-Domain (FDTD) model [Marshall, 2012, JGR]
    - FDTD model used to simulate amplitude and phase at locations along the ground for wide range of frequencies
    - Model with and without precipitation; subtract to determine perturbation
    - Use measure of “average” perturbation for correlation studies [Marshall and Snively, 2014; Kabirzadeh et al, 2017]



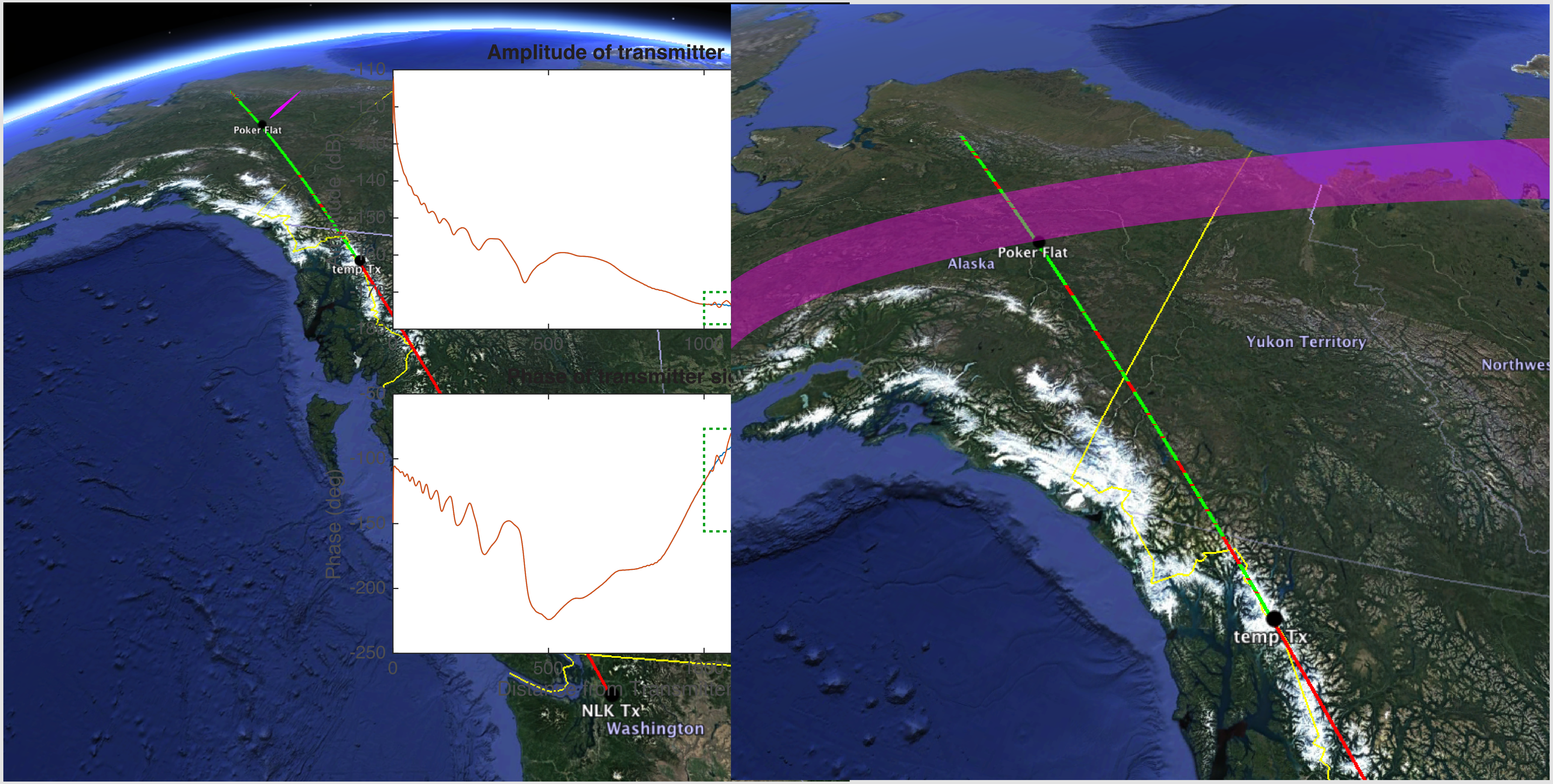






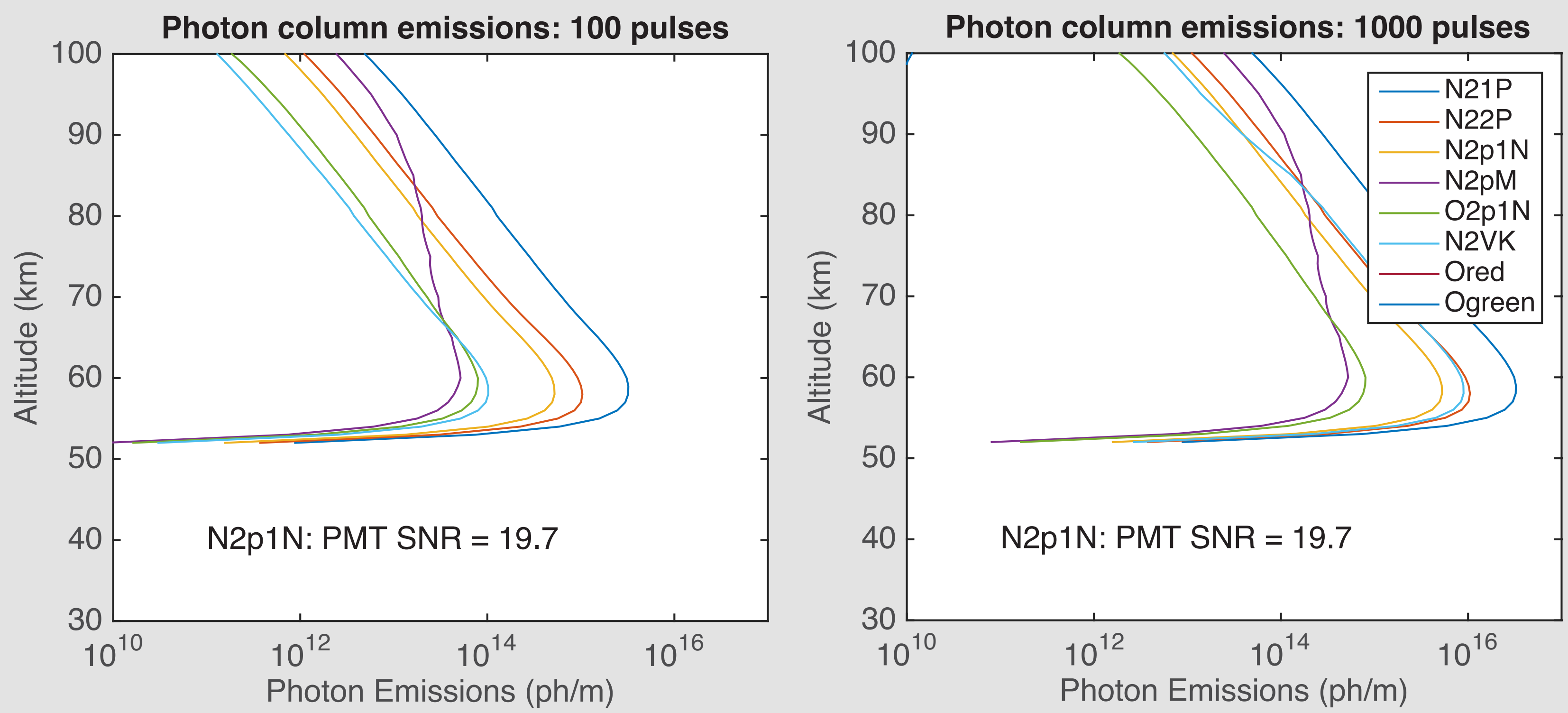
Beam VLF perturbation: first test

- Input the 1000 pulse / 1 sec electron density disturbance into the FDTD model as a "disturbed" ionosphere
- Compare simulated Amplitude / phase with ambient case



Optical emissions

- We use basic auroral optical physics [Vallance Jones, 1974] to calculate optical emission rates given ionization rates
  - Include quenching, cascading, lifetimes
- Ionization rates result of photon emission rates for each band of interest; integrate over total pulse duration to get total photons



- Next, propagate photons in 4π steradians and include atmospheric transmission as function of wavelength; determine photon flux (ph/m^2) reaching ground location

Optical sanity check

- **For 100 J injected into the atmosphere:**
  - Emitted as N_2 1st positive photons: ~**2.2 J**
  - N_2 2nd positive: ~**1.1 J**
  - N_2 Vegard-Kaplan: ~**1.0 J**
  - N_2^+ Meinel: ~**0.1 J**
  - N_2^+ 1N: ~**0.6 J**
  - O_2^+ 1N: ~**0.06 J**
  - O green line: ~**0.7 uJ**
  - O red line: ~**0.3 nJ**
- Total optical emissions = **~5% of injected energy, consistent with auroral estimates of energy partitioning** [e.g., Vallance Jones, 1974]

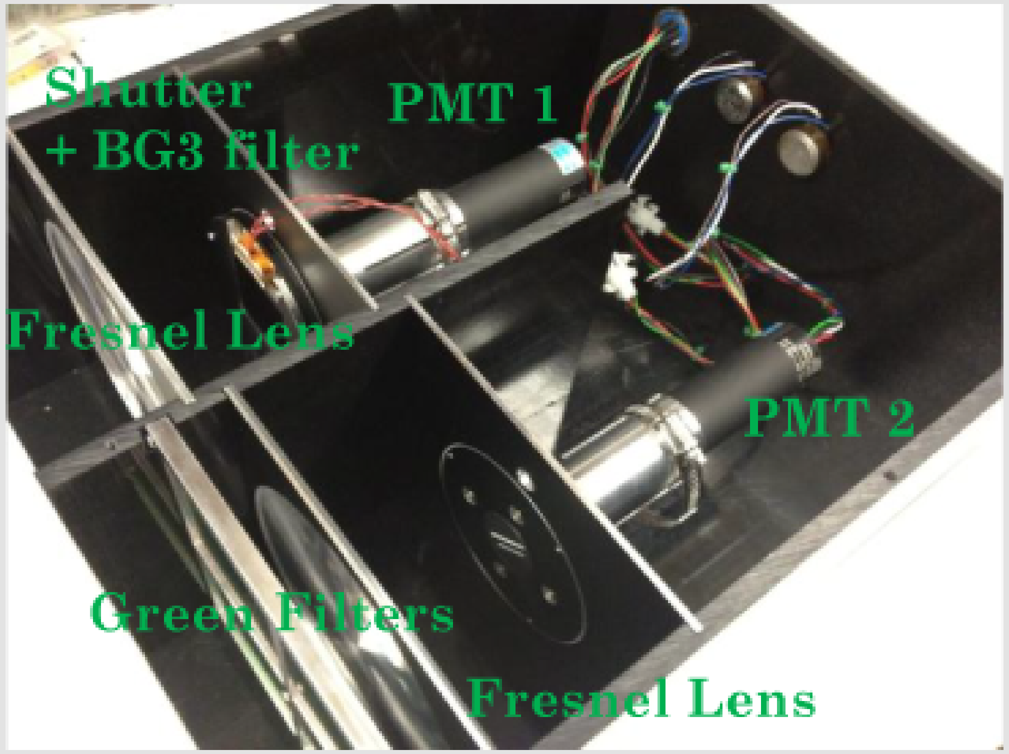
- For 100 J injected, **1.2×10^{18} photons** are emitted in N_2^+ 1N band system (0.6 J)
- When accounting for spreading over $4\pi r^2$, from each altitude, and considering atmospheric attenuation, **1.2×10^7 photons/m^2** reach the ground
- Now, we can use any detection system we want to determine expected signal
  - Example: filter covering 380 to 392 nm –> **factor of 0.27**
  - 2" lens aperture –> **6×10^4 photons hit the lens**

Optical Detection: PMT or All-sky

- Integrate photon flux to ground; use instrument parameters to estimate expected signal and SNR
- **Difficulty**: isolating RB precipitation from aurora!

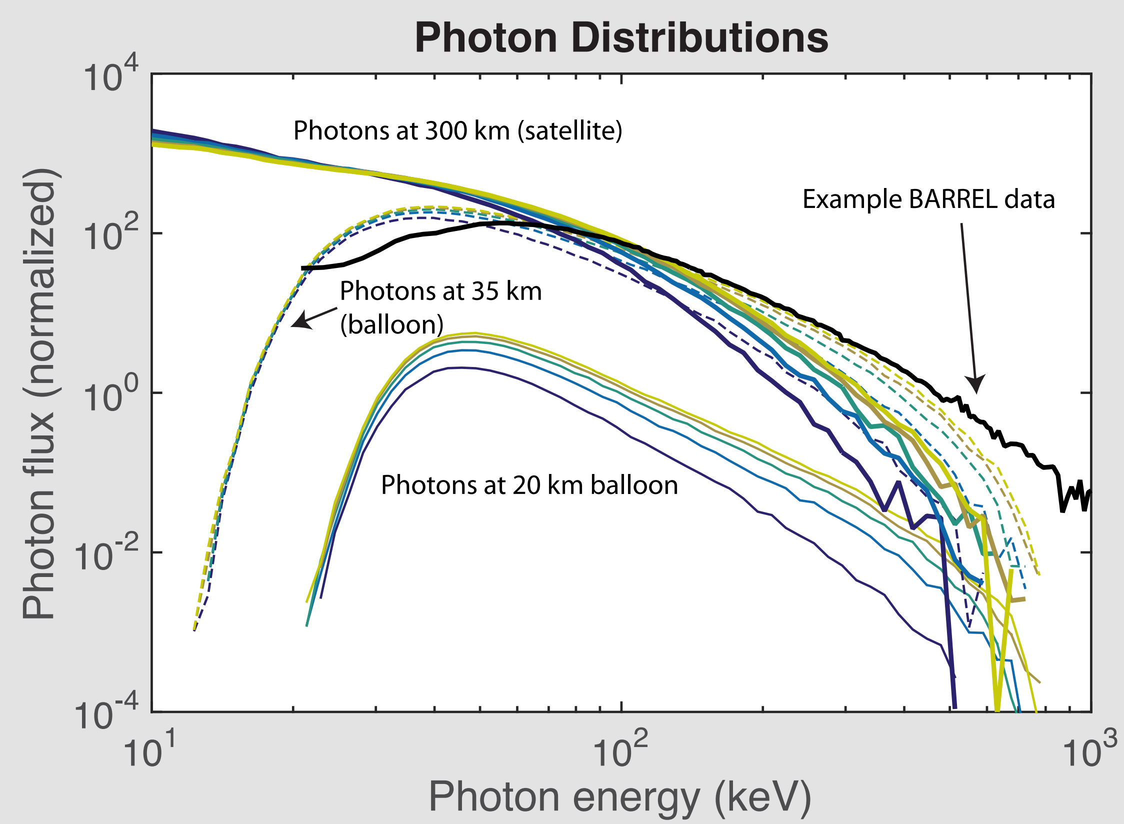
- **PMT SNR: ~20**
  - independent of number of pulses, because we assume 1 kHz sampling
  - Integration in time will help, of course
- **All-sky SNR: ~50**
  - assuming 0.5 second integration
  - 500 J injected over 0.5 seconds; 70% detector QE; shot-noise limited

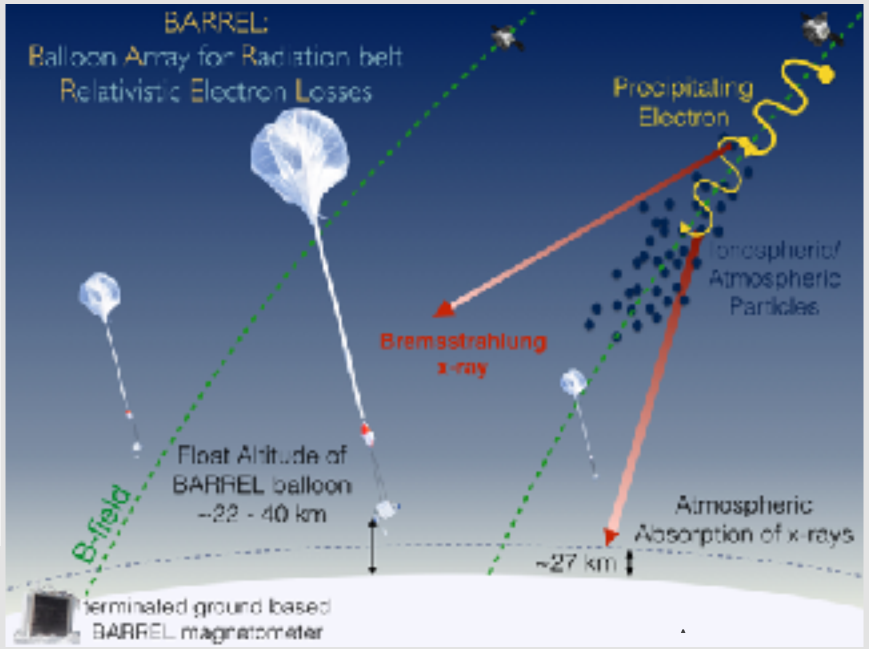
PMT features:
f/0.5 lens
6″ aperture
10 nm filter
28 mm PMT



X-ray emissions by bremsstrahlung

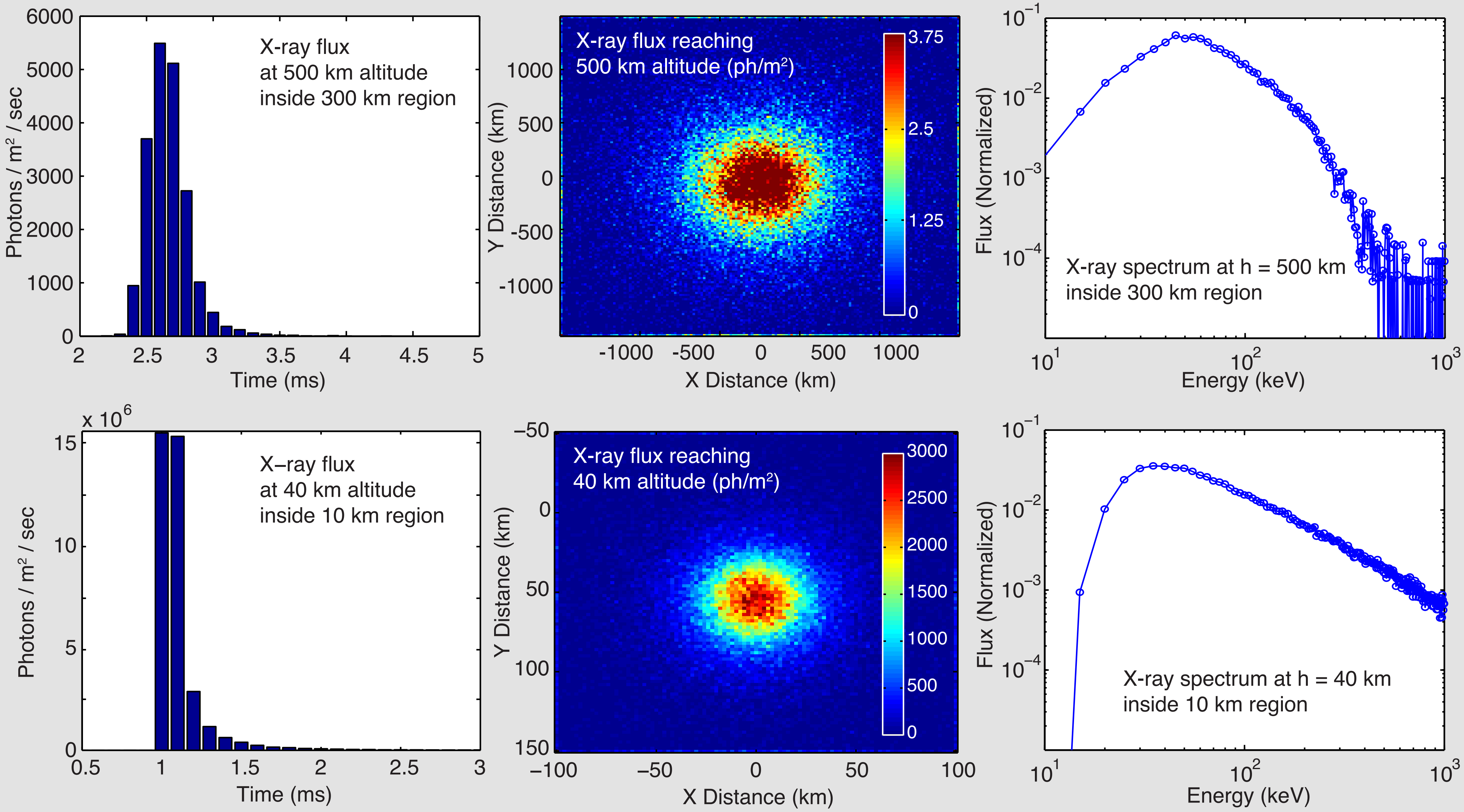
- At each time step of the electron propagation, bremsstrahlung photons are produced probabilistically
  - Given statistically-determined energy and direction relative to parent electron
- Photons are propagated in atmosphere, and we consider Compton scattering, photoelectron production, and pair production
- Ultimately, energy spectrum of photons is collected at observing locations (balloon or satellite)





X-ray fluxes from a beam input

5 MeV beam, 10 mA, 500 us, 3 x 10[13] total electrons, field-aligned

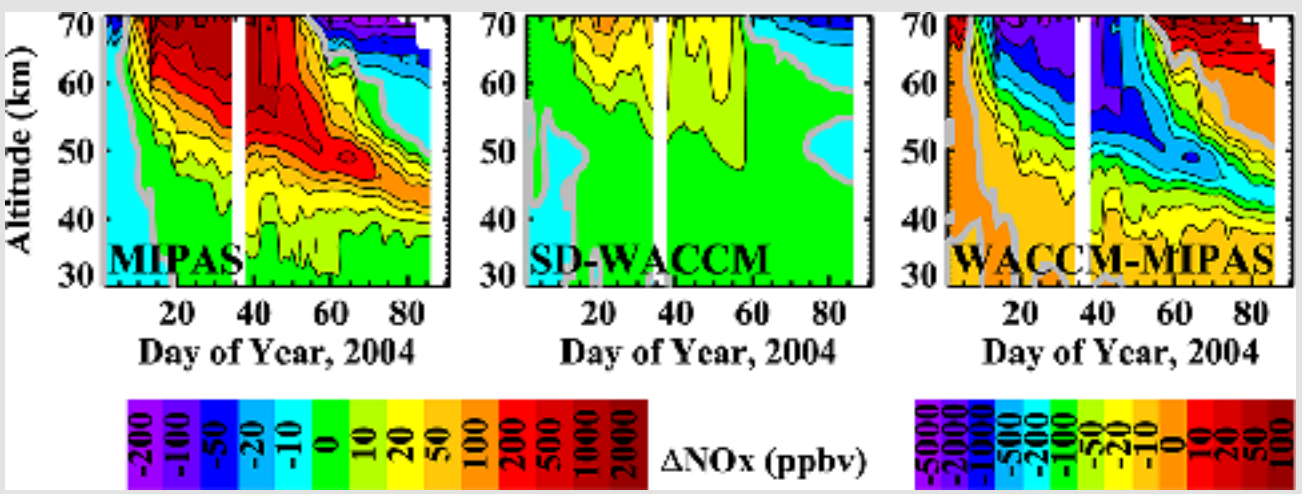


Expect lower photon flux by factor of ~5 or more for 1 MeV electrons

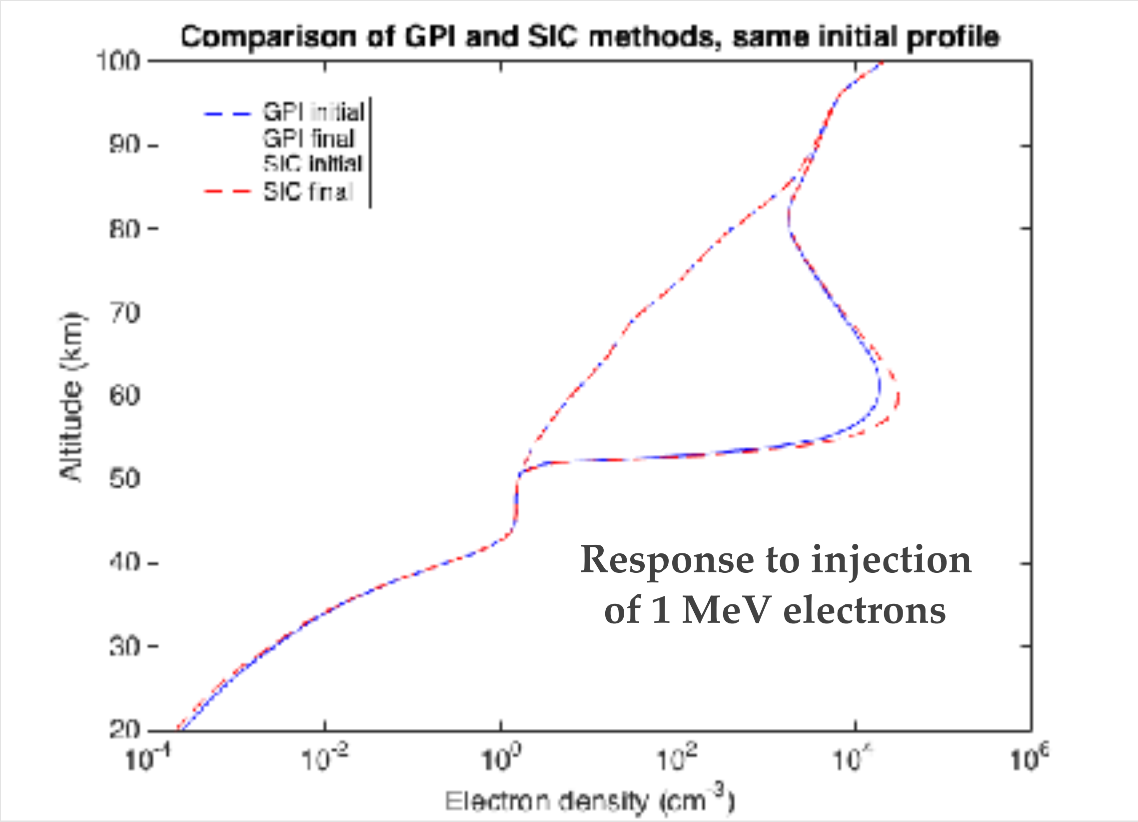
Chemical Effects in the Atmosphere

- Chemical effects in atmosphere include NOx / HOx production and Ox destruction
  - NOx descends to stratosphere and causes further Ox destruction
- Precipitating fluxes / spectra important to quantify chemical effects
- Model / data discrepancy likely caused by incorrect flux / spectrum input

	About	Advantages	Disadvantages
GPI	Stanford; 5 or 6 species; Matlab code	Matlab code; time evolution; fast	only 1D; no detailed minor species (NOx, etc)
SIC	Sodankyla; hundreds of species	time evolution; fast; hundreds of species and reactions	only 1D; availability*
WACCM-D	NCAR	3D+time; horizontal transport;	slower (still pretty fast though!); fewer species / reactions than SIC

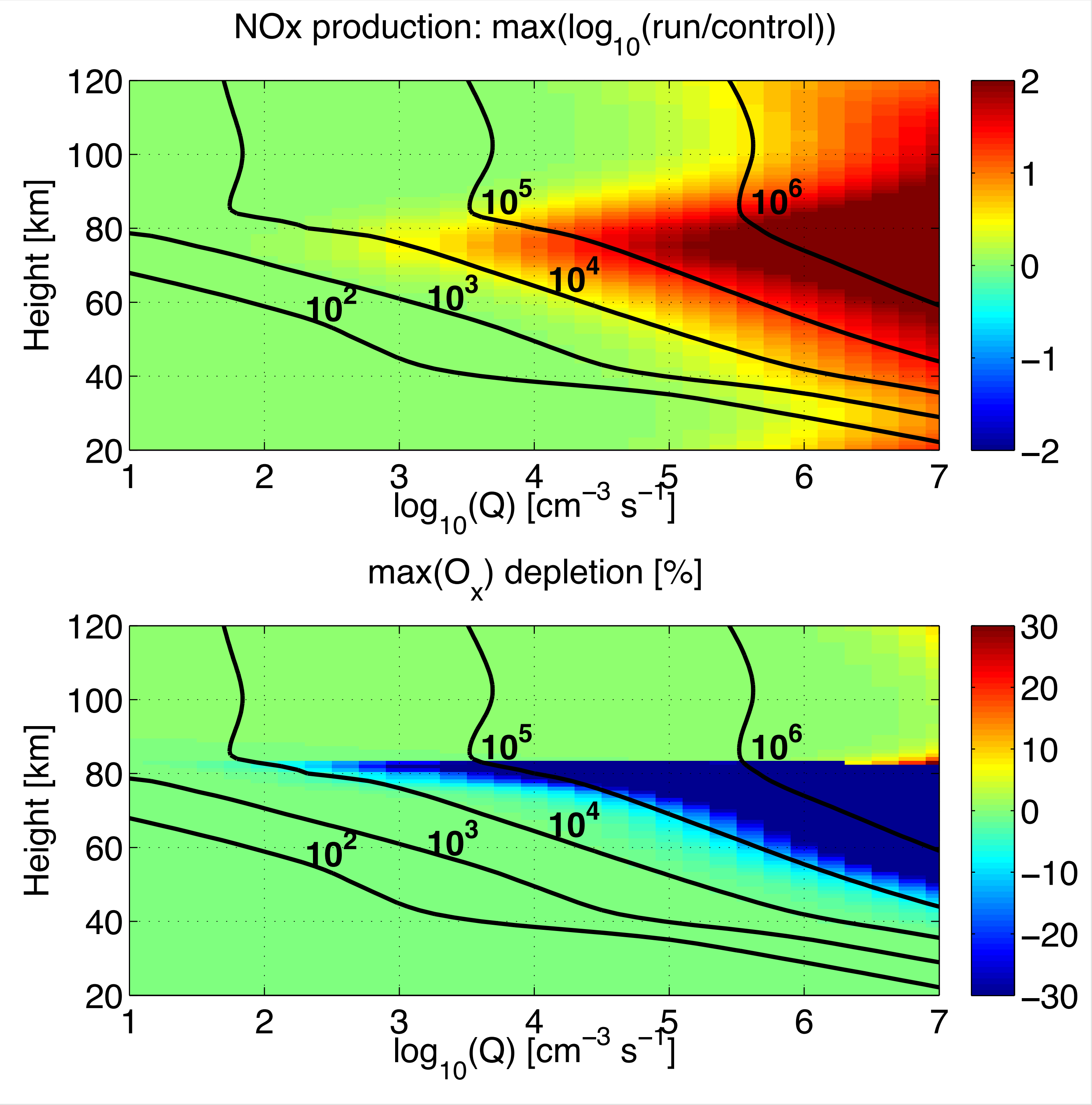


from *Randall et al* [2016]



Chemistry modeling

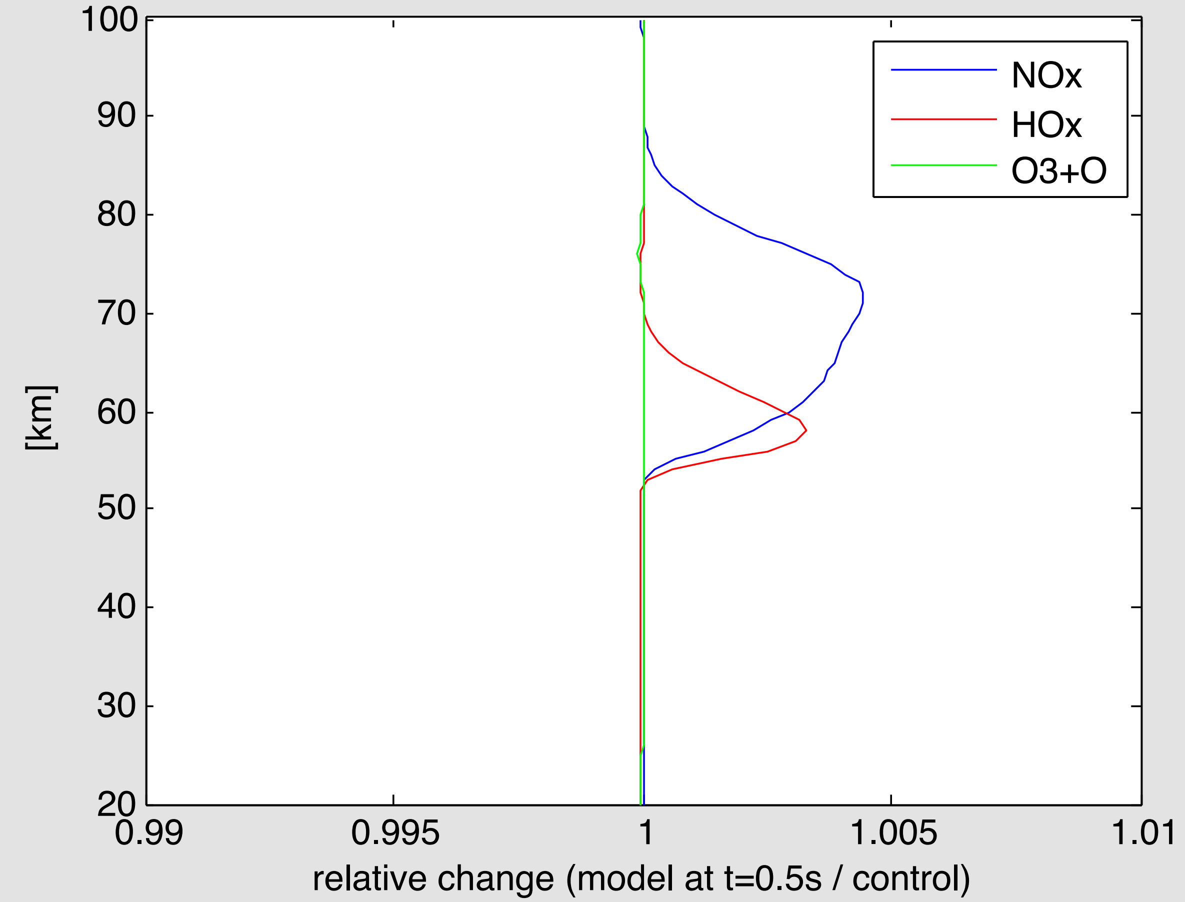
- Lookup table generated using SIC model:
  - provides NOx and Ox enhancements at each altitude, for range of ionization rates
  - Generated for nighttime, winter atmosphere over Poker Flat, Alaska (~65 N, 147 W), site of PFISR radar
  - Results depend on background profiles and duration of forcing (30 minutes here)



work conducted by Antti Kero, SGO

Chemistry Effects of 100 pulses in 0.5 sec

- Simulate 100 pulses of 5 J each, every 5 ms* (earlier they were every 1 ms)
  - For chemical effects, timing at this scale is not important; total ionization is key
- NOx and HOx enhancements are relatively small (0.5% increase)
- Ox effects are negligible
- Note effects increase roughly linearly with total ionization
  - More pulses, more energy –> more chemistry

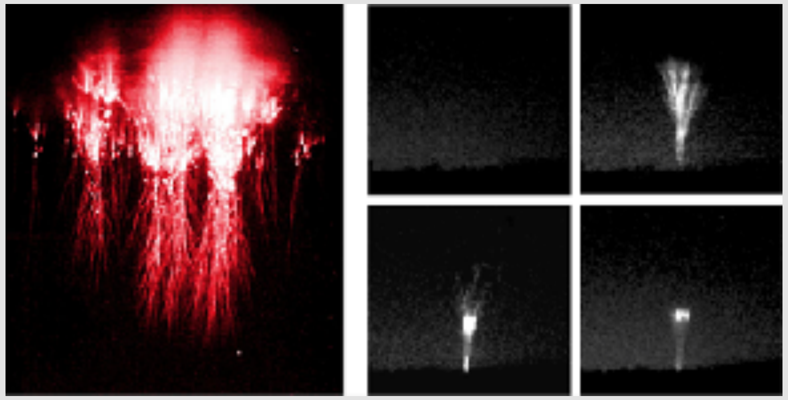


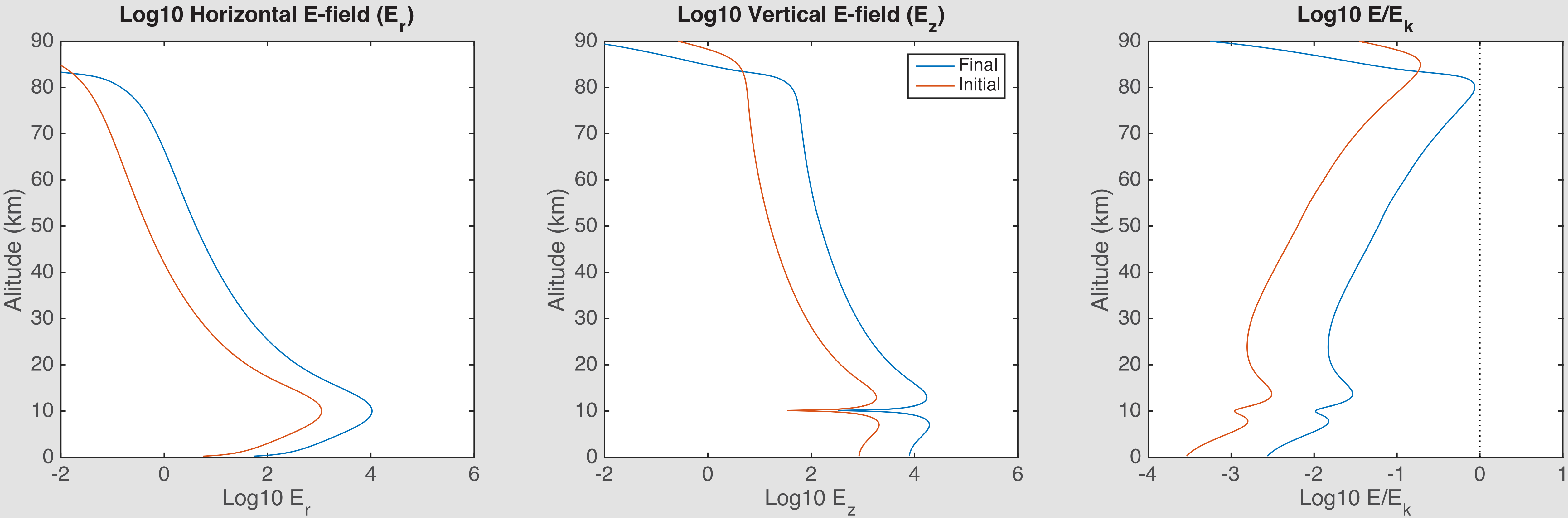
Overall: chemical effects of pulse train likely to be negligible

(For Active Experiments, this is likely good news)

Quasi-Electrostatic field effects

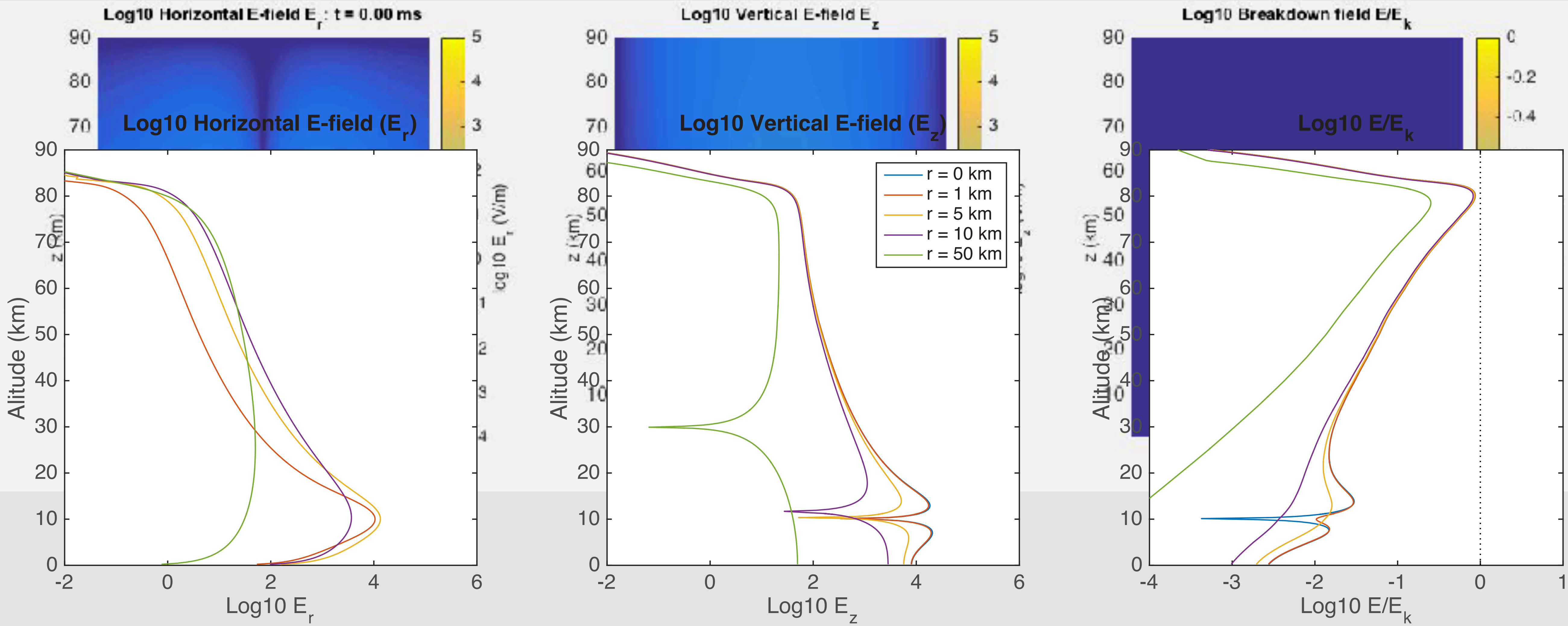
- Thunderstorm charge distributions produce electric fields that extend to the base of the ionosphere
- The breakdown field E_k scales with the neutral density N, and $N \sim e^{-h/H}$
- when $E > E_k$, breakdown occurs – sprites!





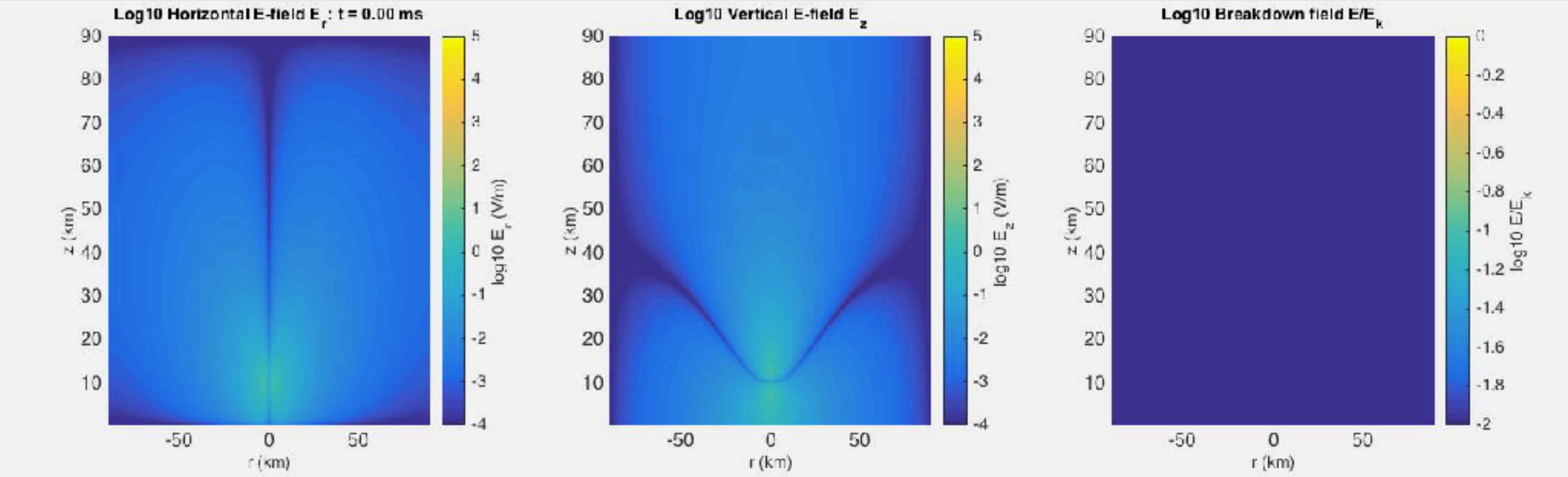
QES calculation

- We use the 2D version of the QES field model of Kabirzadeh et al [2015]
- Consider initial charges of -50 C located at 5 km altitude and +50 C at 10 km
- Suddenly remove 50 C from 10 km altitude: a large positive cloud-to-ground
  - 500 C-km is just below the threshold for sprite initiation [Cummer et al, 2000]

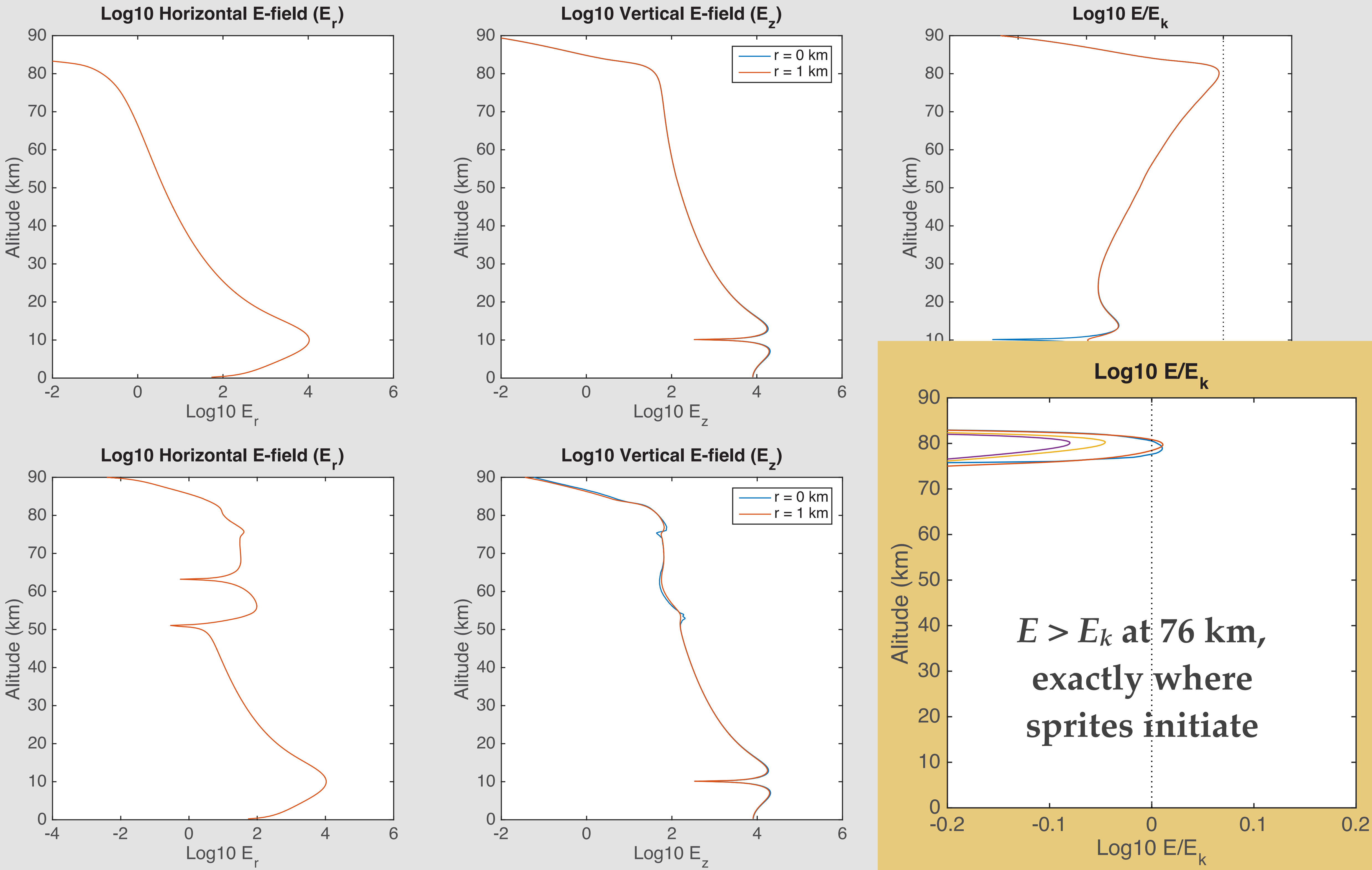


QES after beam injection

- Neubert and Gilchrist [2004] first postulated that a beam injection could help trigger sprites
- We repeat our QES simulation with a column of enhanced electron density, 300 m in diameter with Gaussian distribution, given by Monte Carlo / chemistry simulation



QES after beam injection



Summary

- **Explored atmospheric effects and diagnostics of 1 MeV electron beam injection**
  - train of 100 or 1000 pulses, every 1 ms; 500 us x 10 mA in each pulse
- **Ionization effects** suggest easy detection by ground-based radar (PFISR)
  - Possible detection by subionospheric VLF, but 3D modeling necessary
- **Optical emissions** (N2+ 1N lines) visible by photometer or all-sky camera
- X-ray fluxes likely too weak – simply not enough total energy injected
- Chemical effects negligible
- **Electrodynamics** suggest the ability to enhance fields above thunderstorms and **trigger sprites**
  - Timing of the experiment likely difficult!

- Models ready to explore different scenarios (energy, pulse sequence, etc.)