VLF Remote Sensing of the Lower Ionosphere: Solar Flares, Electron Precipitation, Sprites, and Giant γ-ray Flares

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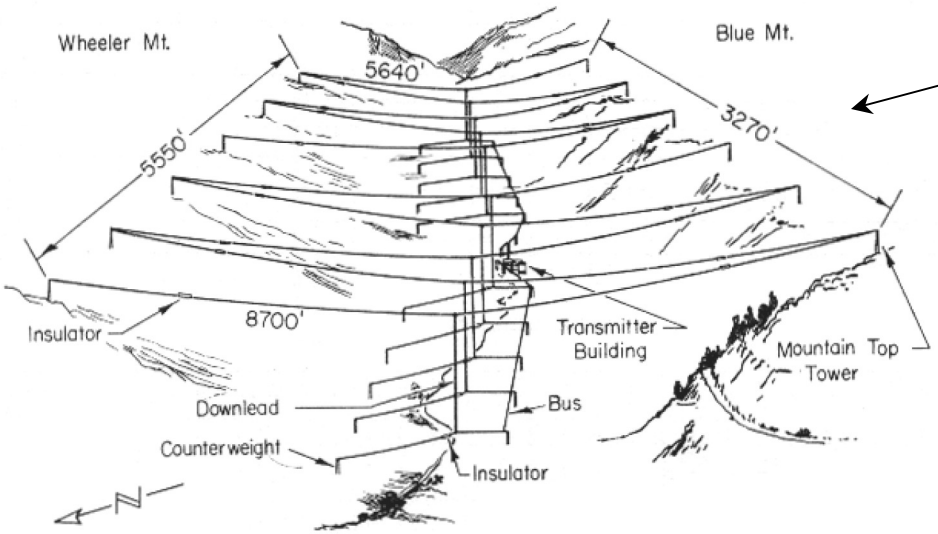
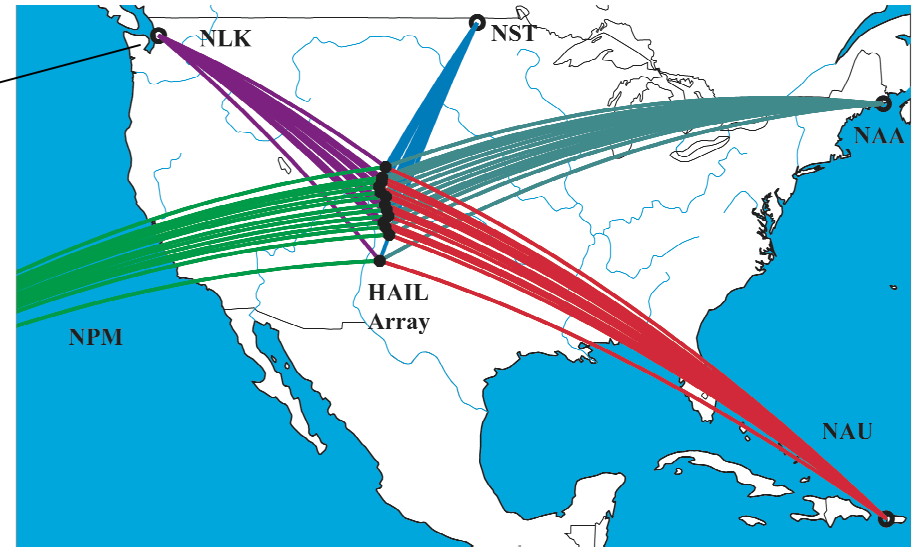
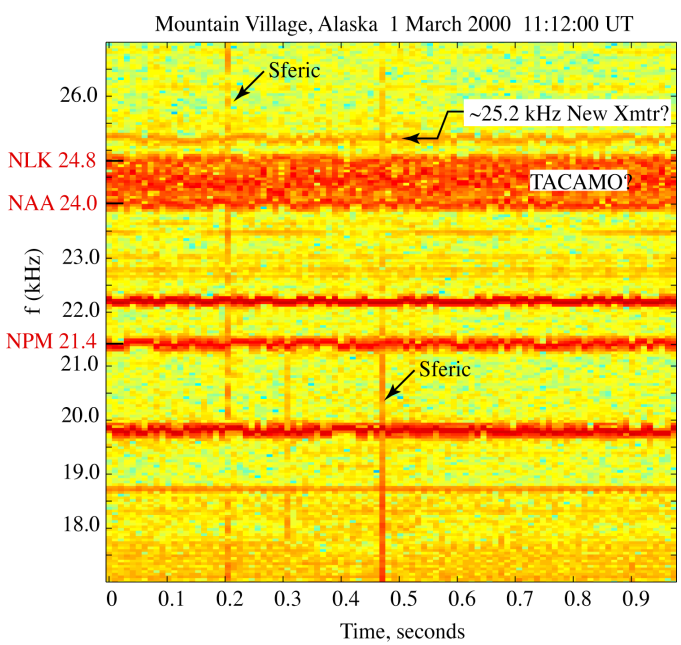
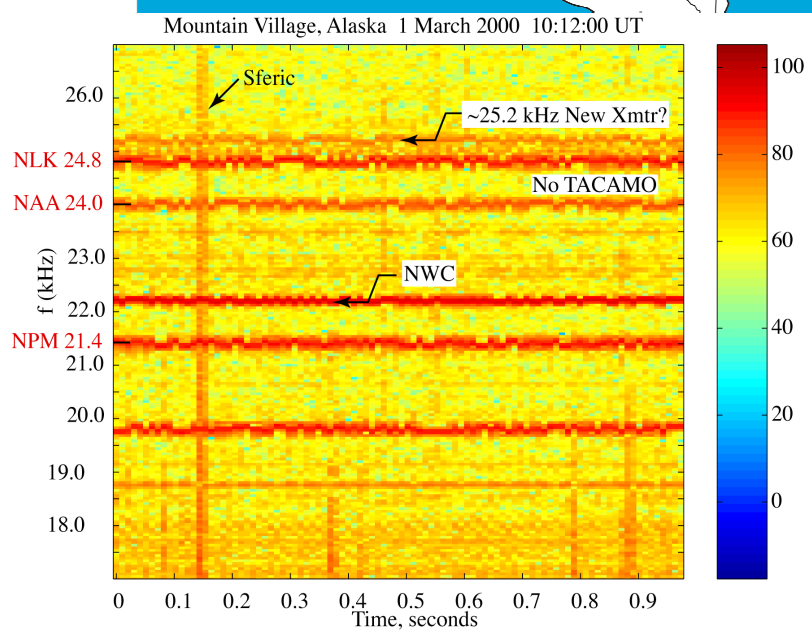
Subionospheric VLF Remote Sensing



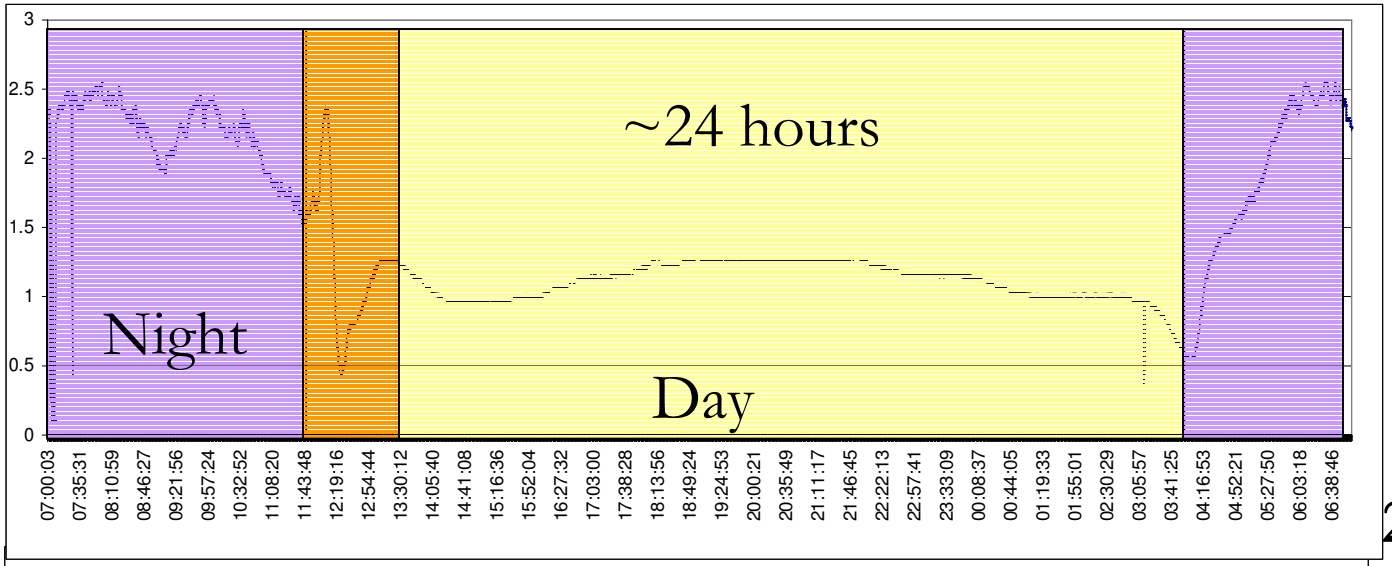






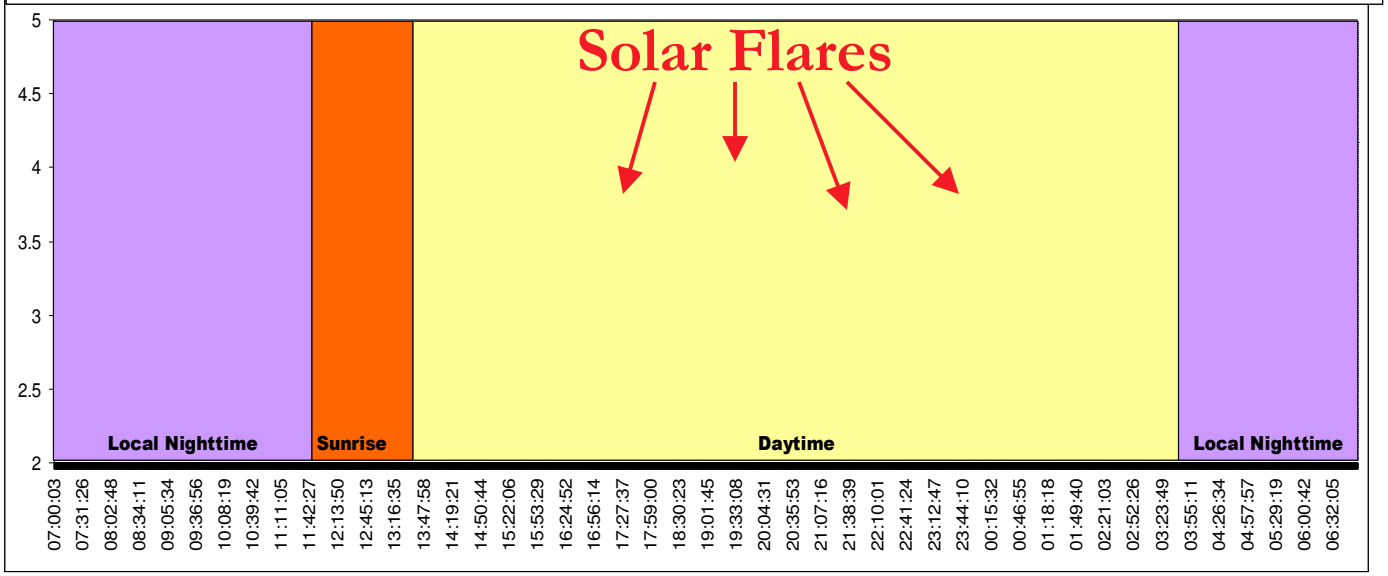
VLF Detection of Solar Flares

Quiet Day



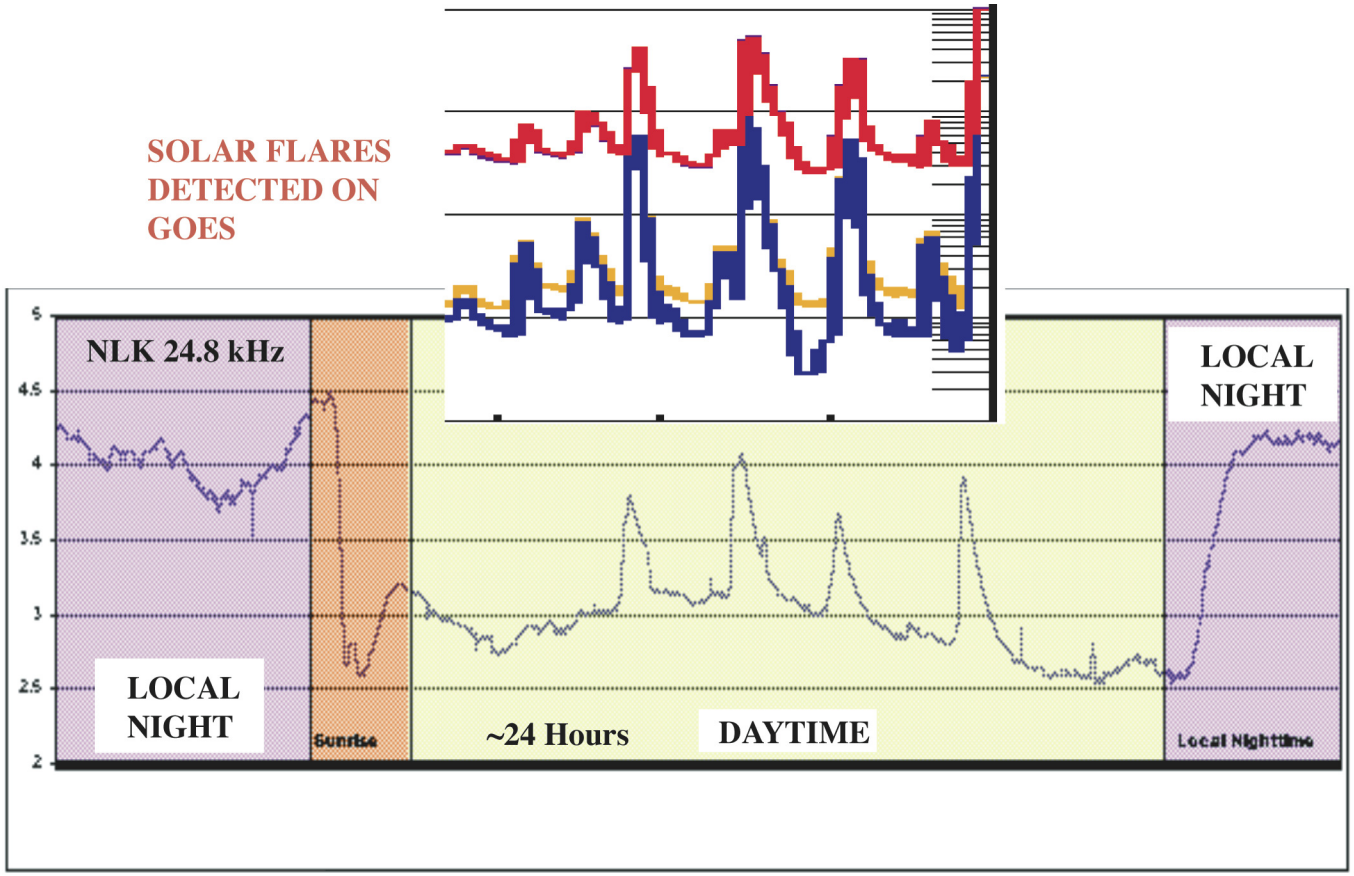
NLK
24.8 kHz

Active Day



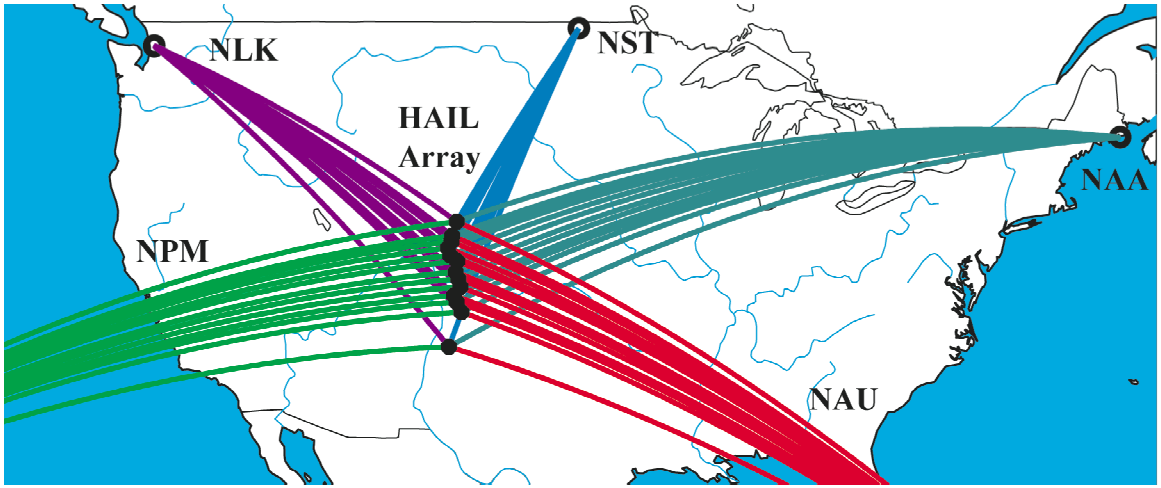
Source: Ray Mitchell

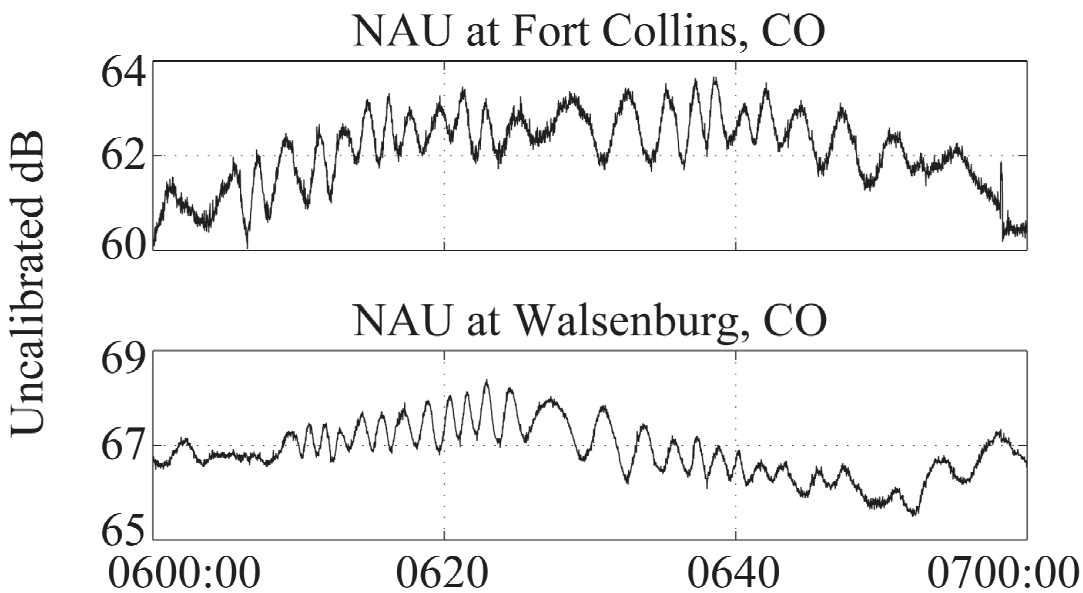
VLF Signatures of Solar Flares



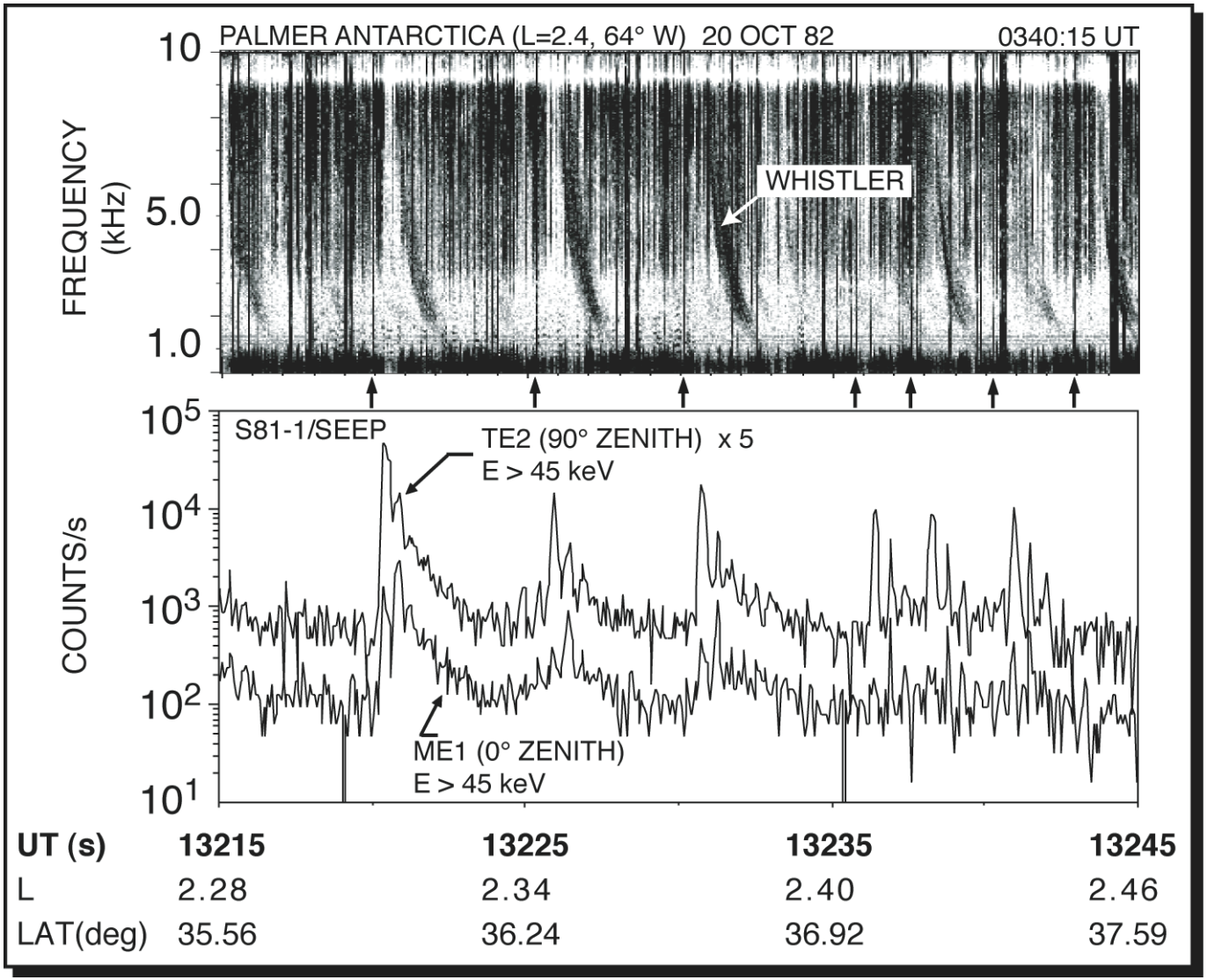
from Ray Mitchell

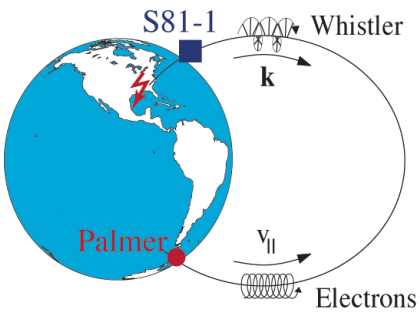
VLF Signatures of Gravity Waves



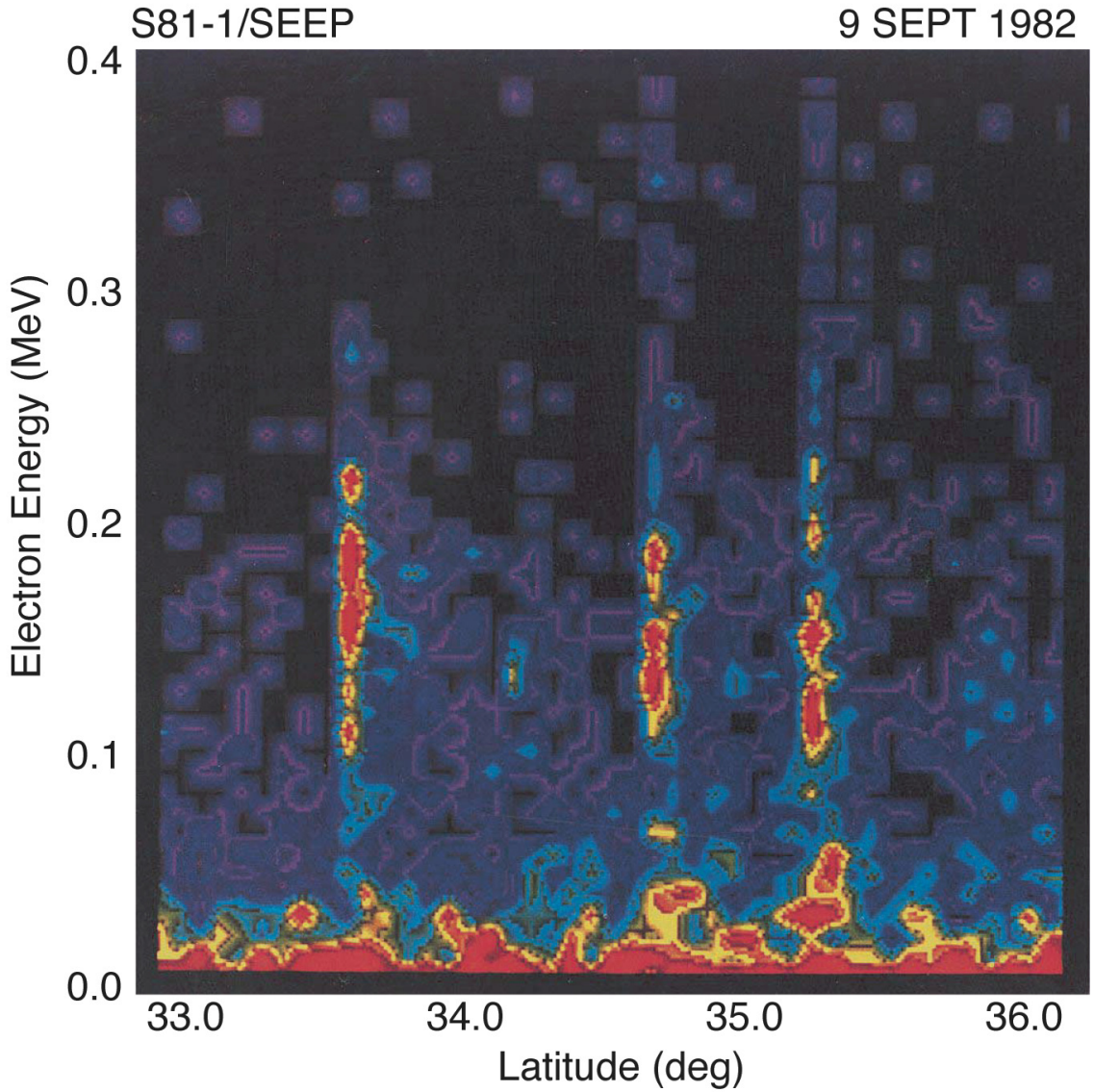


Lightning-induced Electron Precipitation (LEP) Bursts



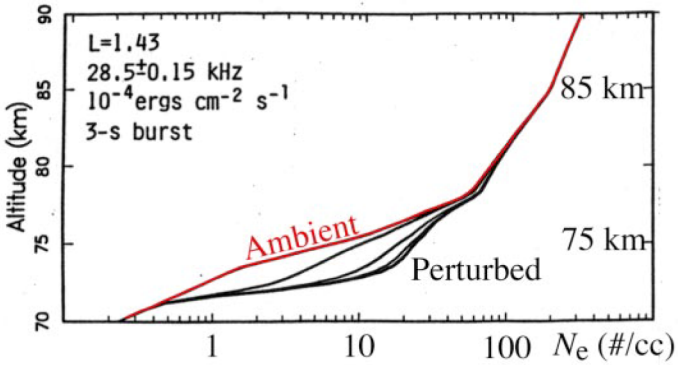


LEP Spectra [*Voss et al.*,1984]



Measurement Methods

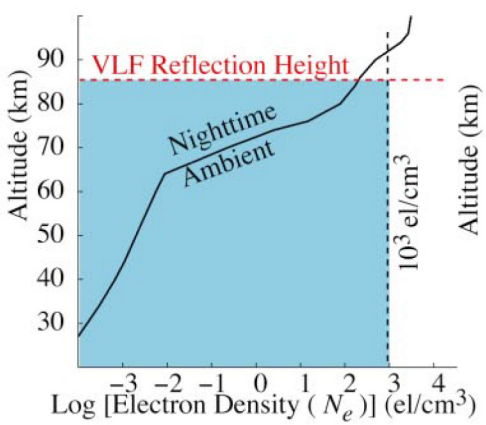
- Discrete wave-induced electron precipitation fluxes are relatively low(~10^3 to 10^4 times lower than typical auroral fluxes)
- Electron detectors currently in-orbit are designed for auroral fluxes and do not have sufficient sensitivity (geometric factor) or time resolution
  - One exception may be SAMPEX, which measures >500 keV electrons
- X-rays and optical emissions produced by precipitating electrons are relatively weak and difficult to detect
- Secondary ionization due to expected precipitation fluxes (10^{4} ergs/cm^2-s) is a small fraction of the relatively large ambient electron densities at *E*- (95-130 km altitude) and *F*-regions (160-400 km) of the ionosphere, so that detection by HF or VHF radars, ionosondes, and riometers is not feasible
- On the other hand, the *D*-region (~50-95 km) is mostly devoid of ambient electrons, especially at night, so that the relatively small additional secondary ionization produced by transmitter-induced precipitation fluxes constitutes a substantial (i.e., detectable) modification

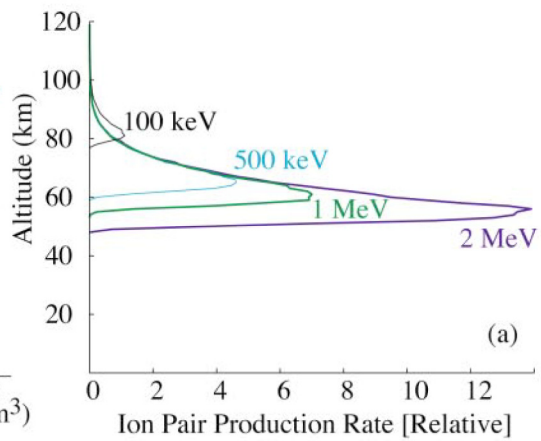


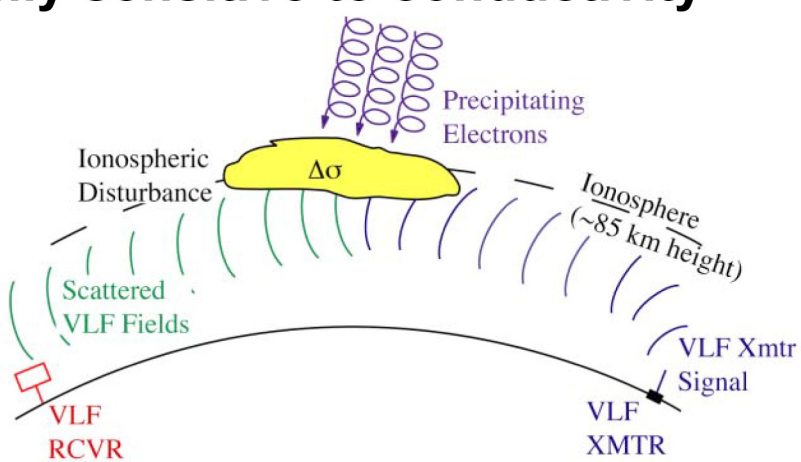
- Precipitating electrons must have >100 keV energy to penetrate down to *D*-region altitudes
- VLF radio remote sensing is the only technique suited for detection

VLF Remote Sensing of >100 keV Electron Precipitation

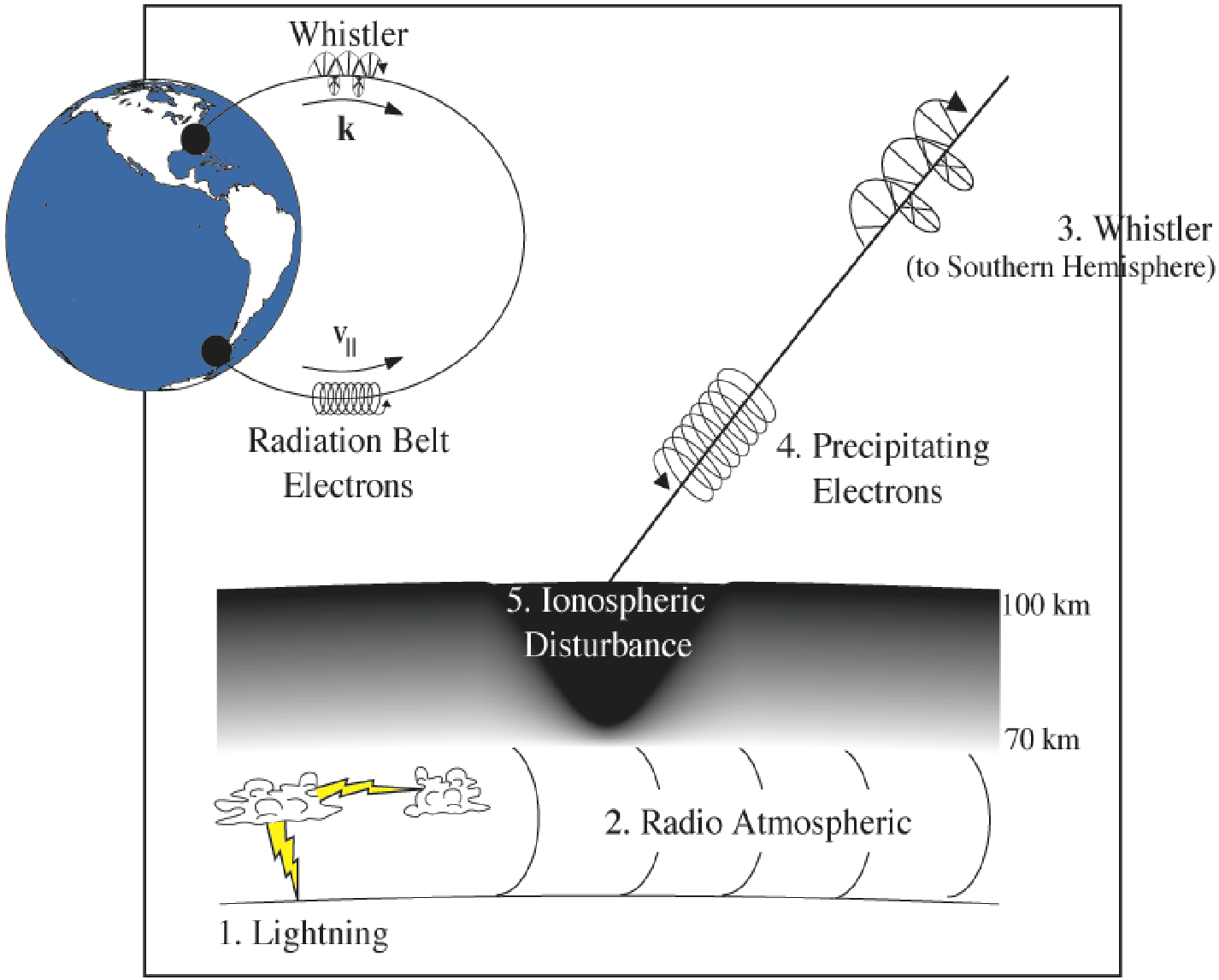
- The ambient nighttime electron densities in the *D*-region are typically ~1 to 10 el/cc
- Even the most powerful VHF or HF radars (e.g., Arecibo) cannot ëmeasuró the D-region at night, since they typically require >1000 el/cc for useful echoes
- Precipitating energetic electrons with >100 keV energy penetrate to altitudes <85 km, creating secondary ionization therein
  - The additional ionization produced is typically <100 el/cc
- The reflection height for VLF waves propagating in the Earth-ionosphere waveguide is ~85 km at night
- Amplitude/phase of VLF signal is highly sensitive to conductivity



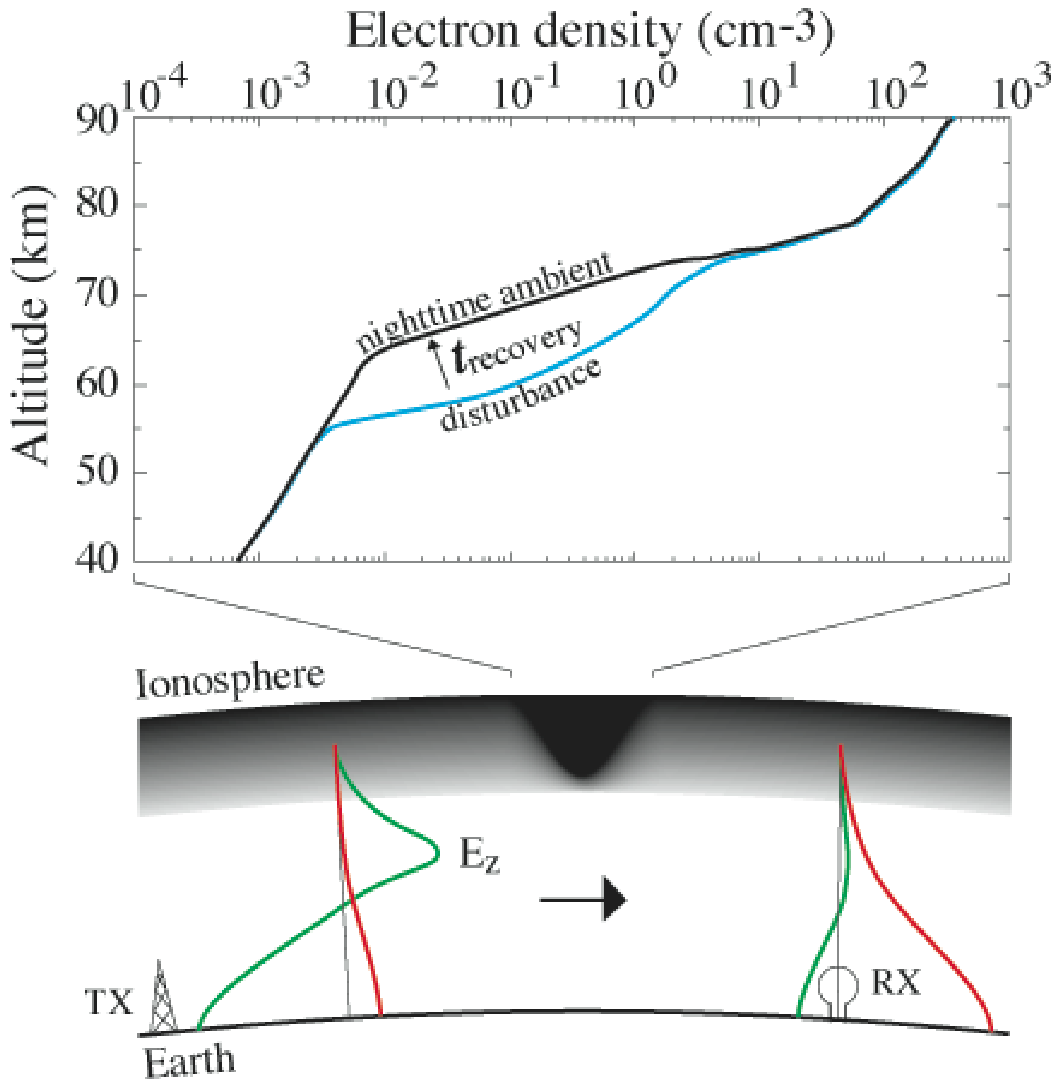




Lightning(Whistler)-Induced Electron Precipitation

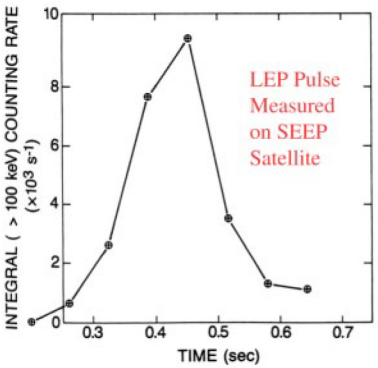


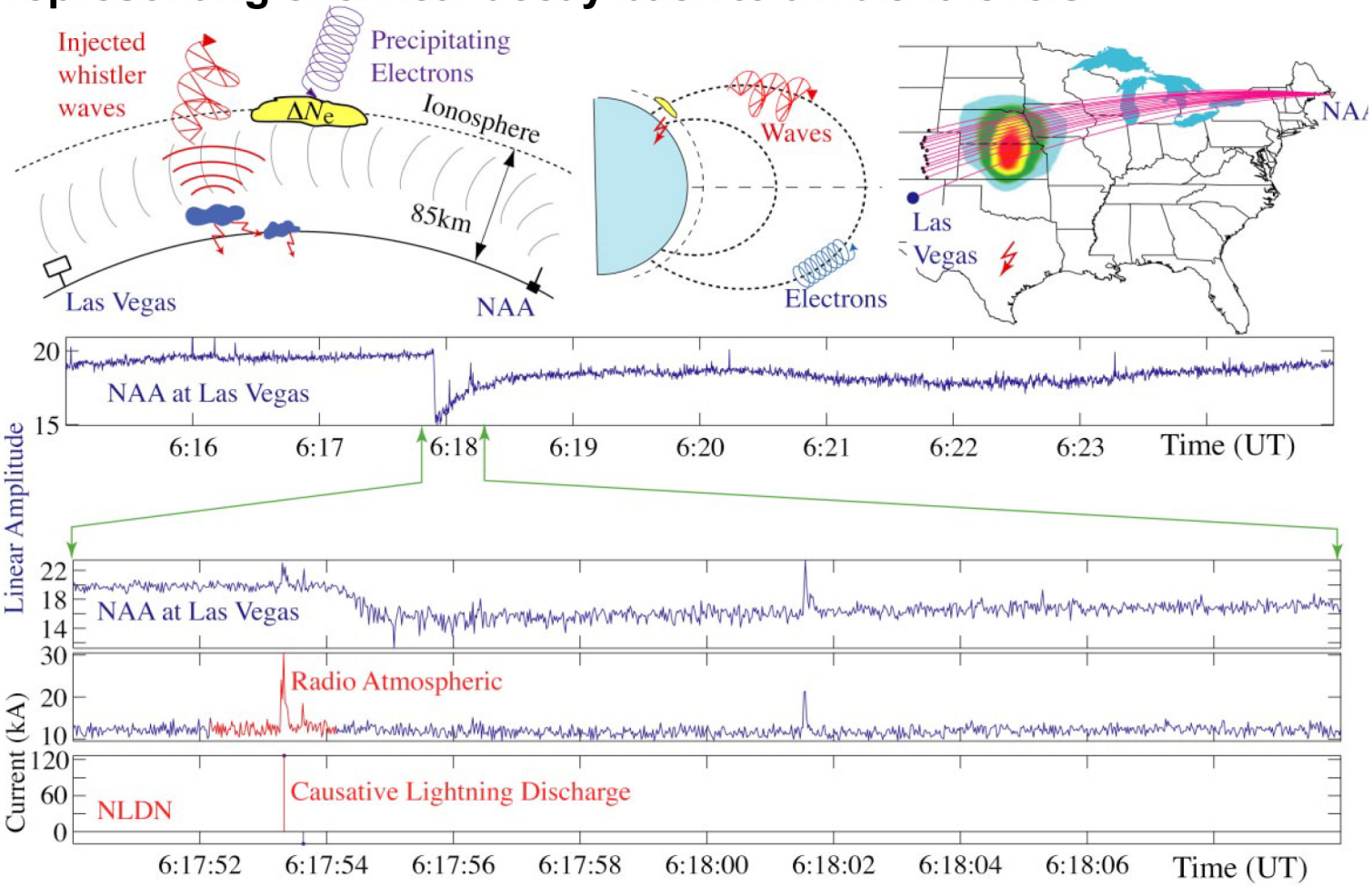
VLF Remote Sensing of Lower Ionospheric Disturbances



Lightning-induced Electron Precipitation (LEP) Bursts

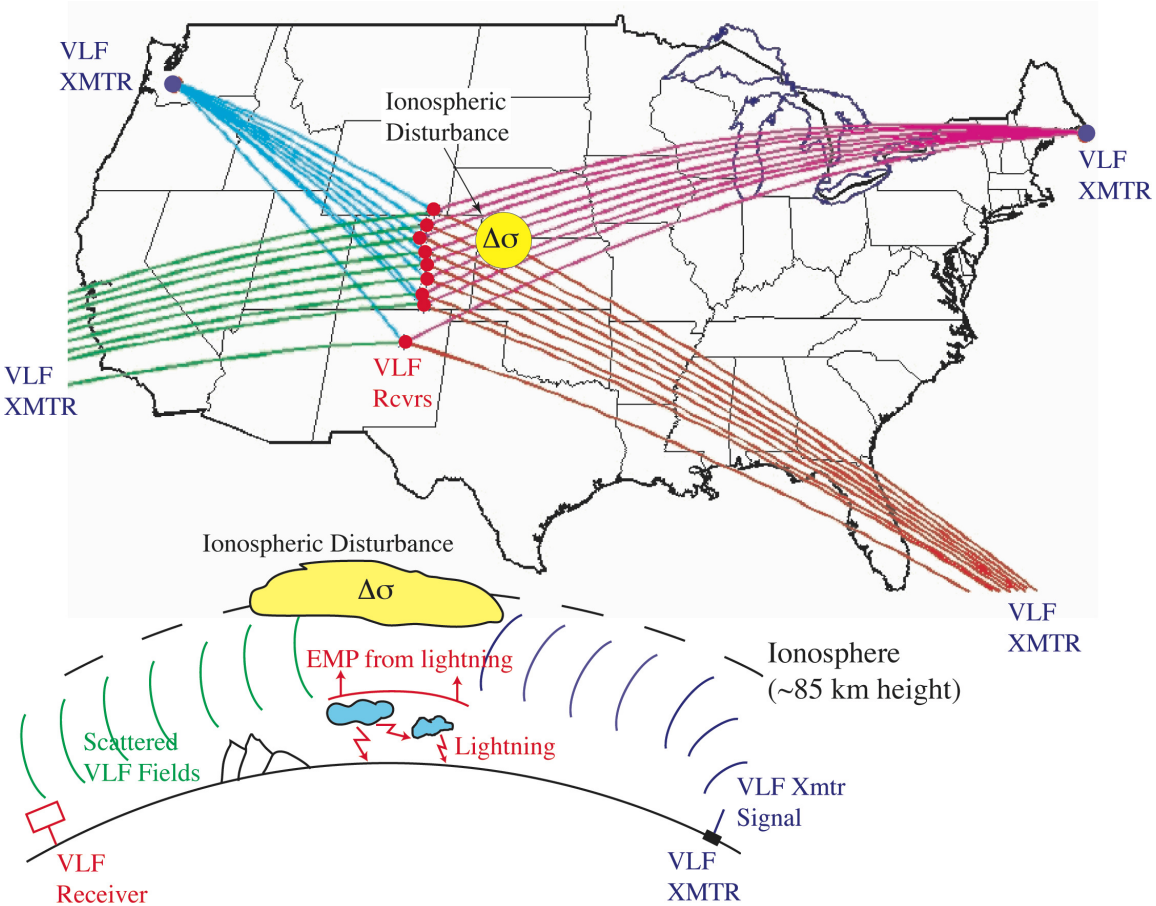
- Whistler waves launched by lightning commonly induce precipitation of <1 s bursts of >100 keV electrons, producing secondary ionization
- VLF signatures consist of rapid changes followed by 10-100 s recoveries, representing chemical decay back to ambient levels





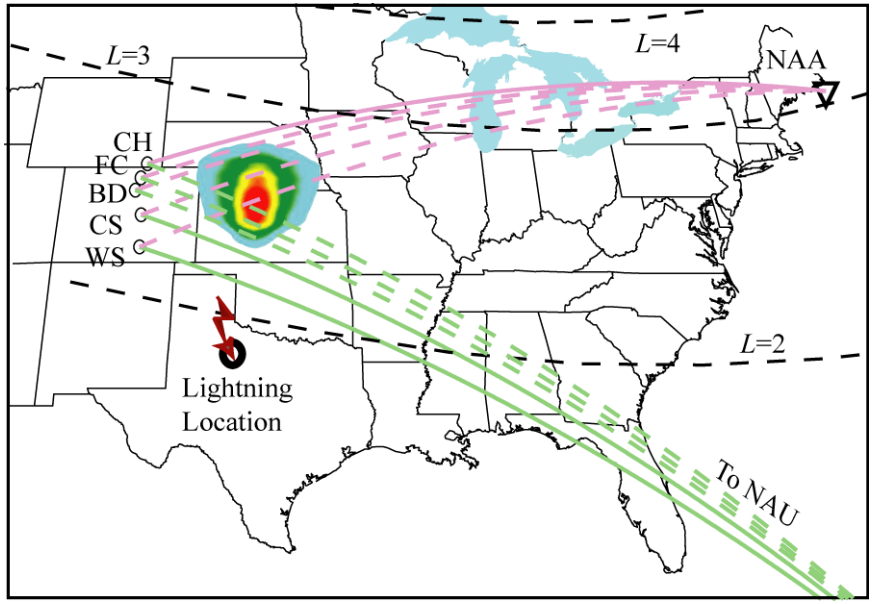
Holographic Imaging of the Lower Ionosphere

VLF receivers at 13 high schools
Provides excellent opportunities for outreach



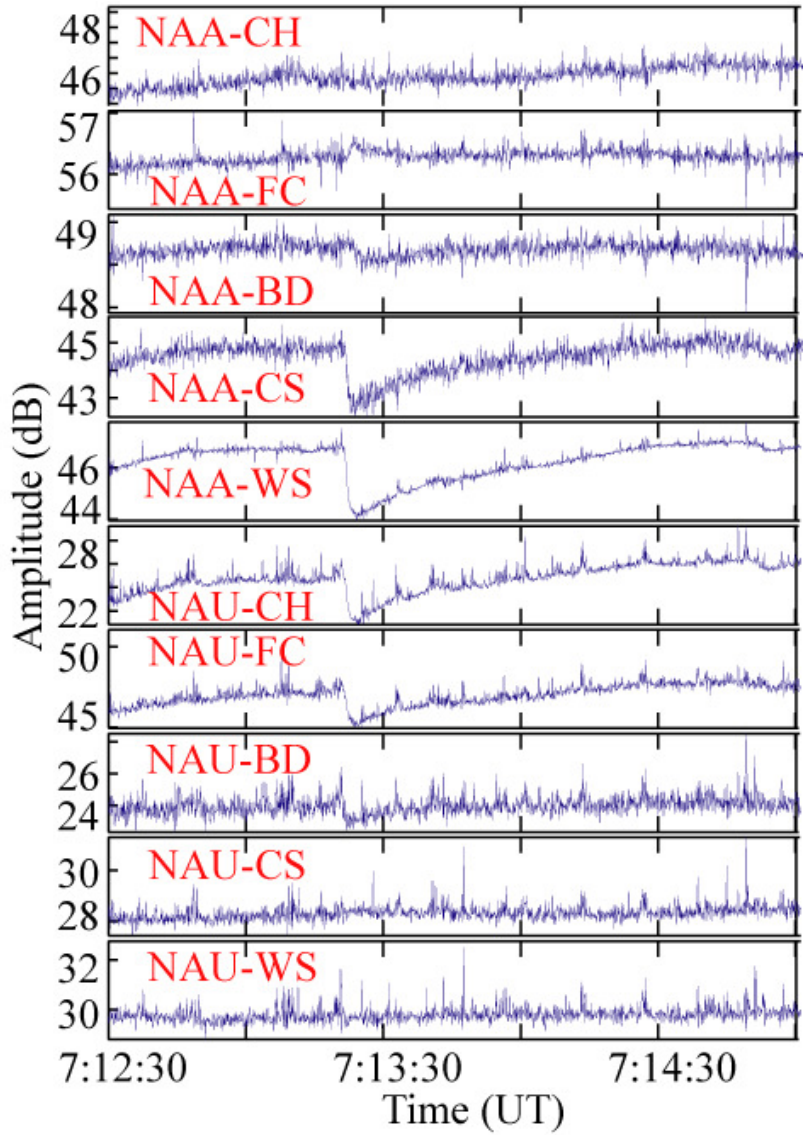
Subionospheric VLF Signatures of LEP Events

Theoretical Precipitation Region

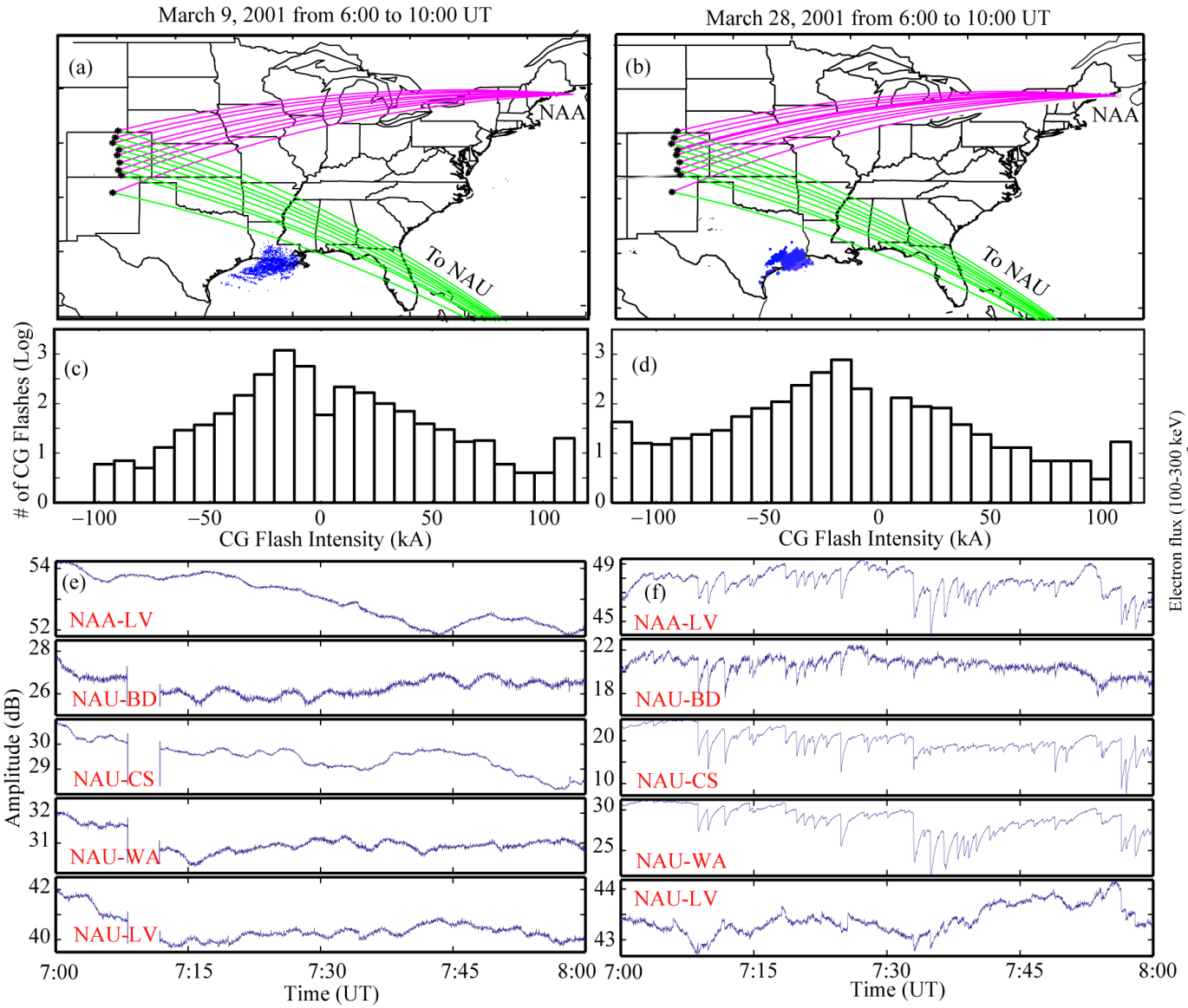


The HAIL array captures the full latitudinal extent of the LEP events.

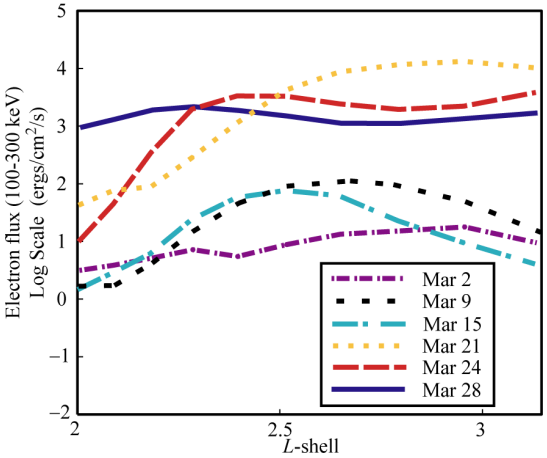
VLF Amplitude Data for 24 March 2001



Occurrence Rate of LEP Events



Dependence on geomagnetic conditions

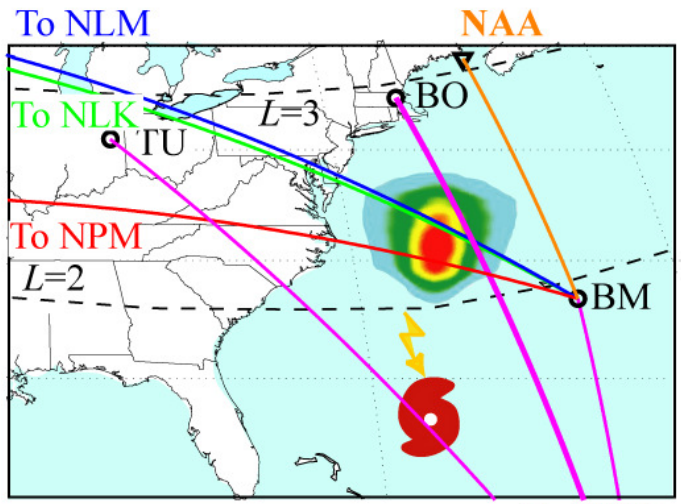


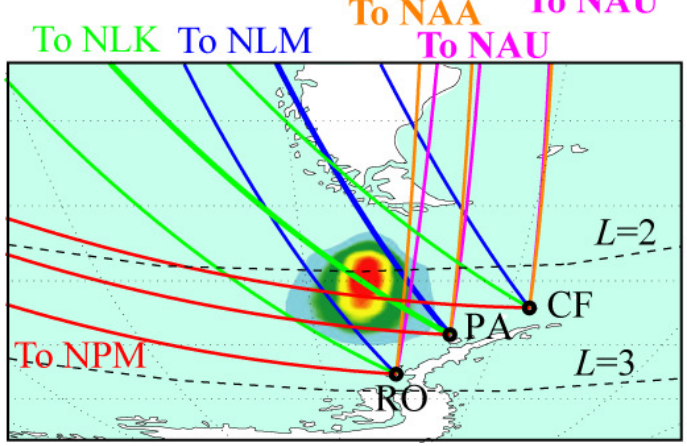
Courtesy of Dr. Dave Evans, NOAA.

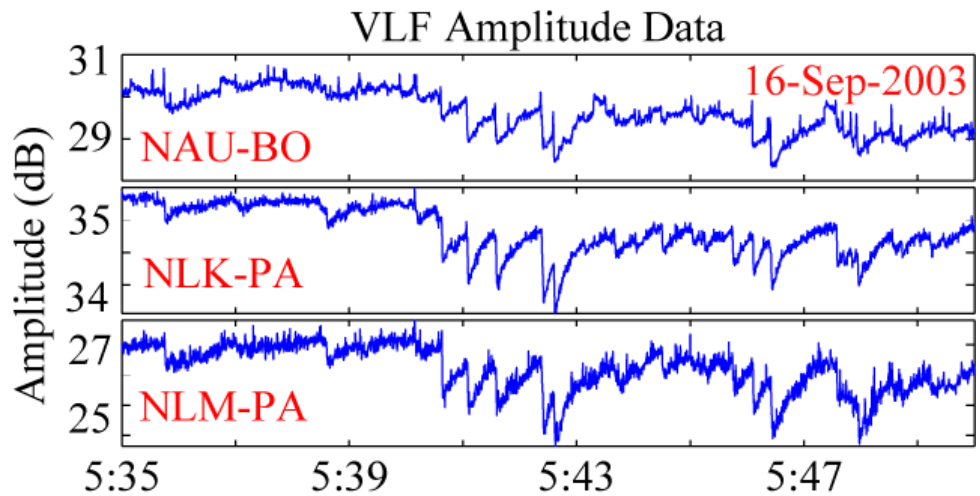
LEP Events Associated with Lightning in Hurricanes

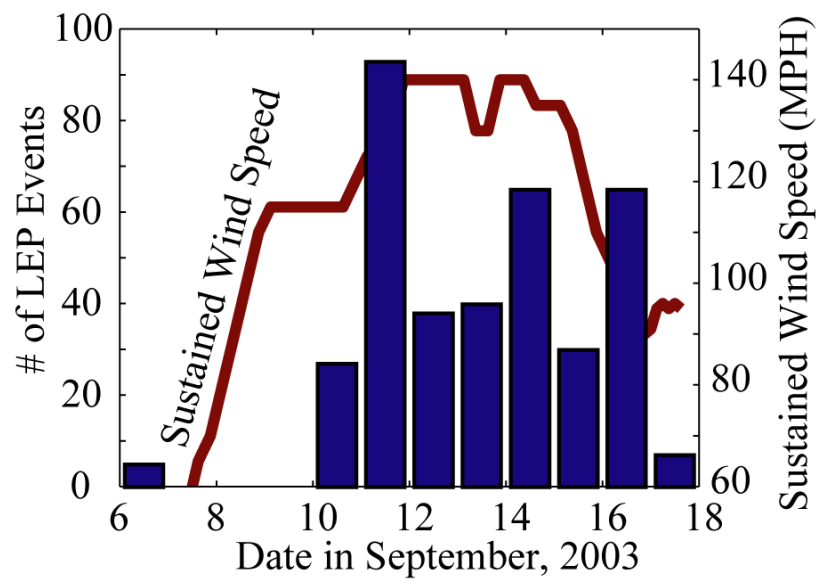
Hurricane Isabel

September 2003

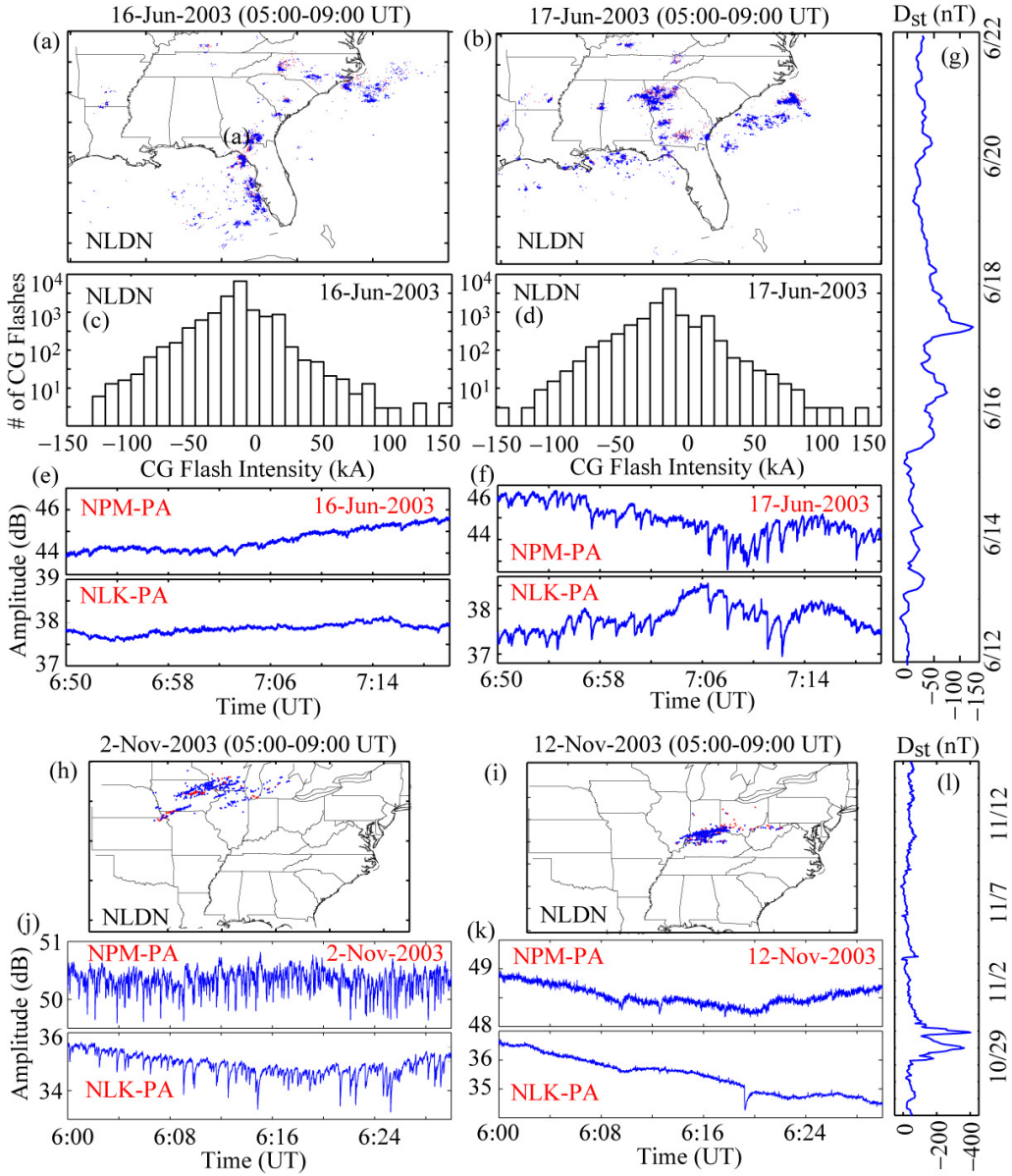






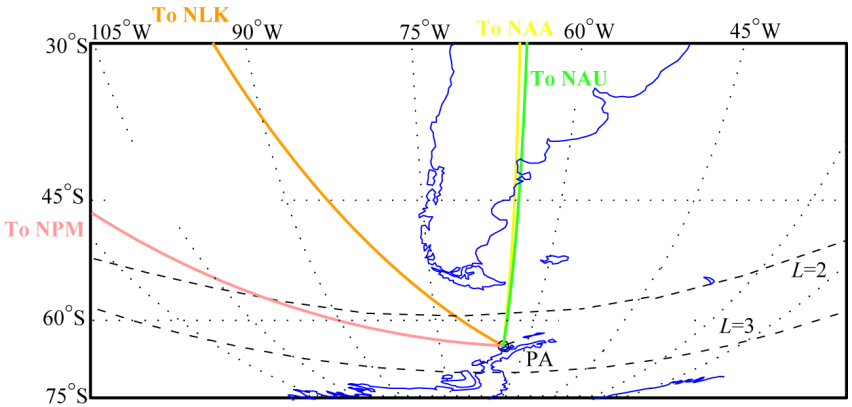


Occurrence Rate of LEP Events

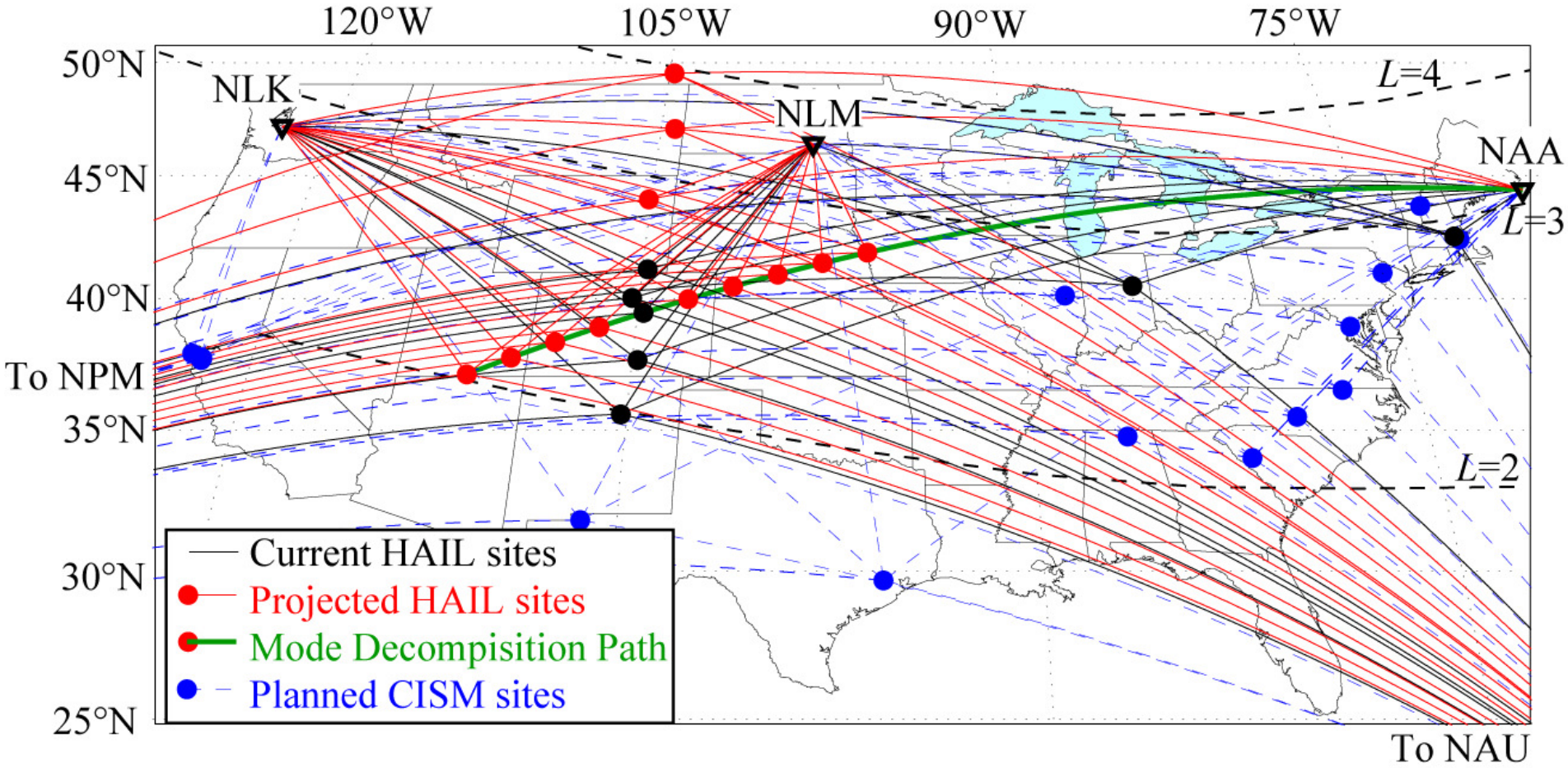


Variation in Occurrence Rates

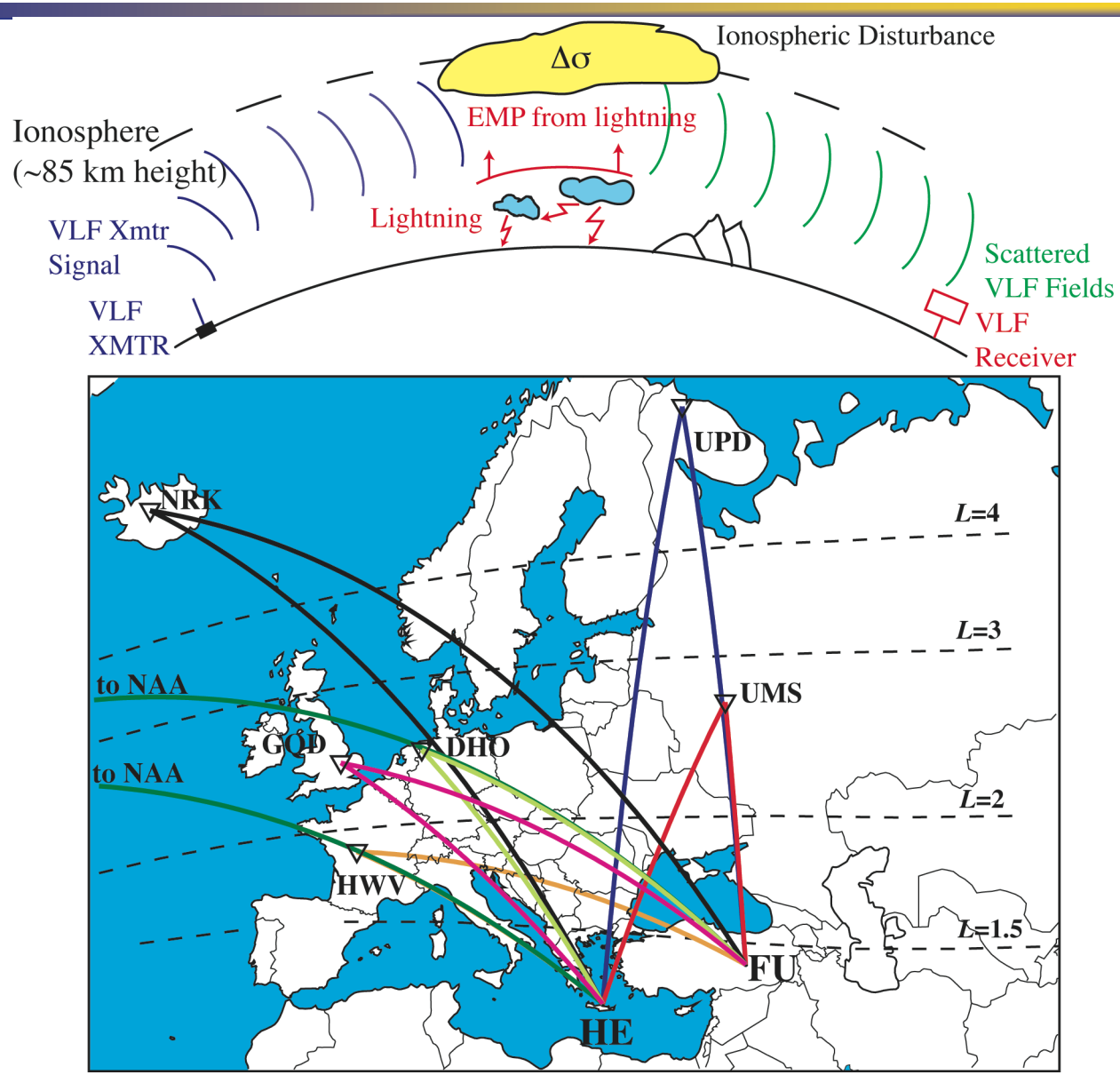
Conjugate Hemisphere



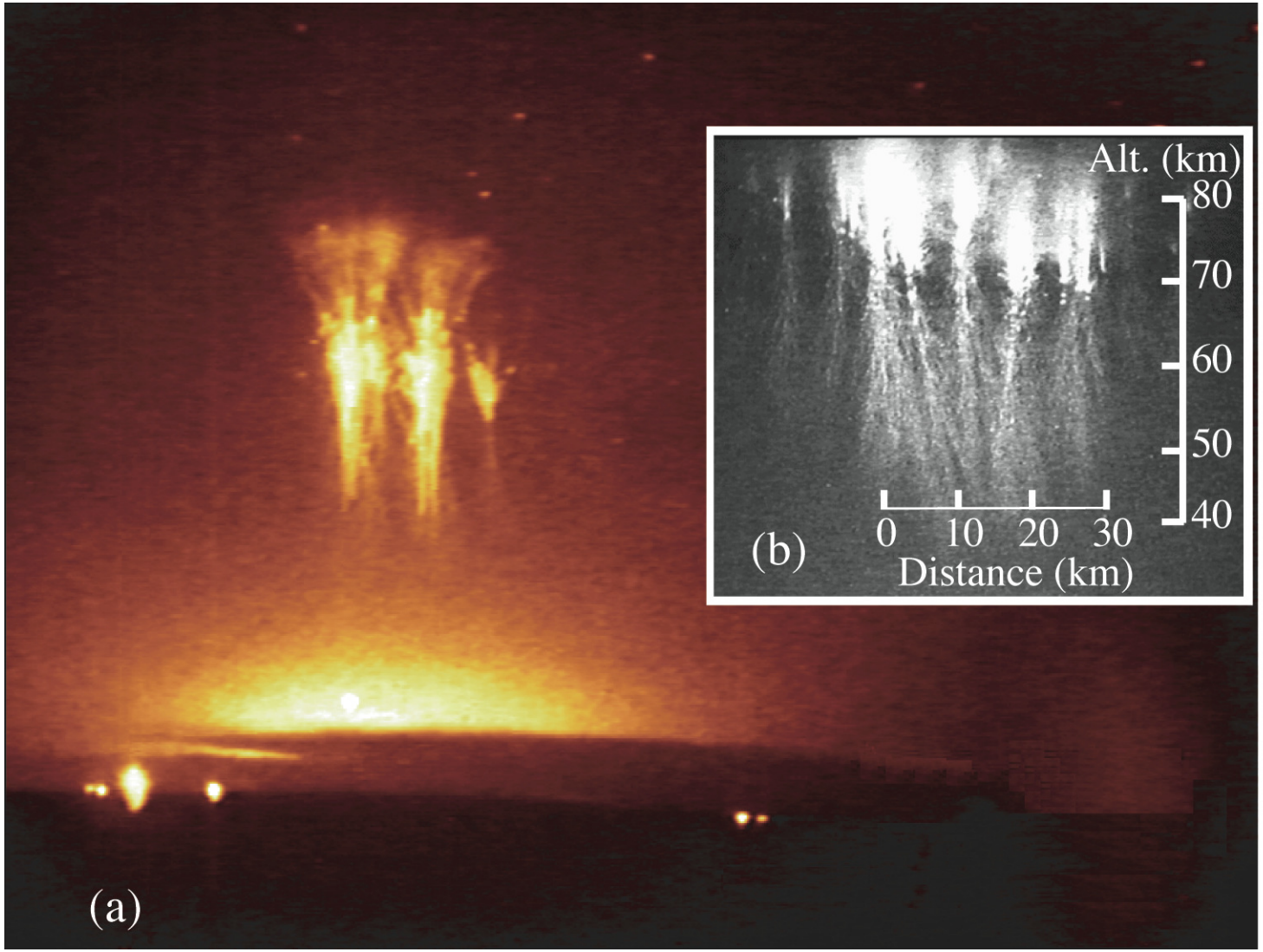
New HAIL Network



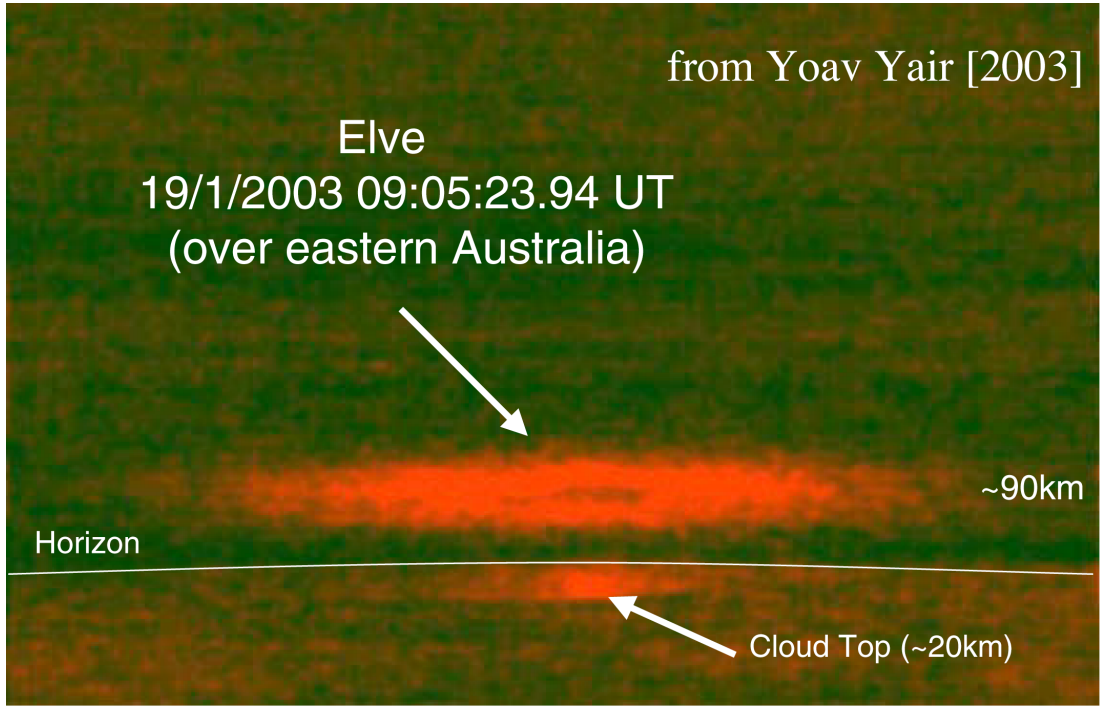
VLF Sensing of Ionospheric Disturbances over Europe

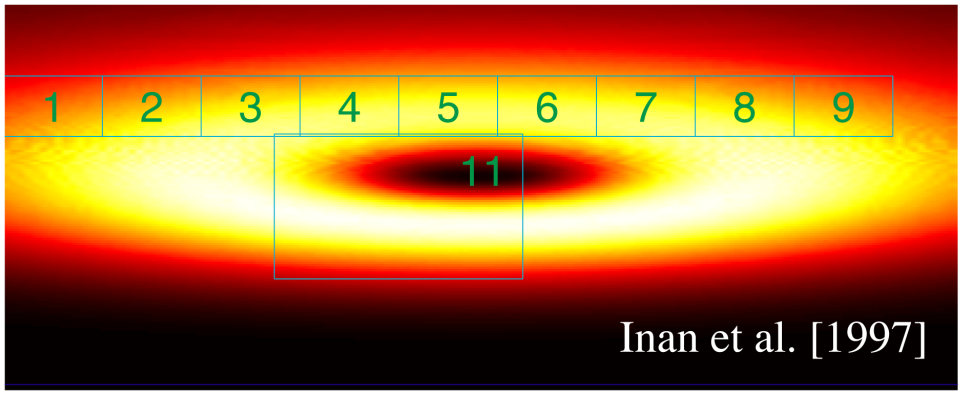


Sprites Above Thunderstorms

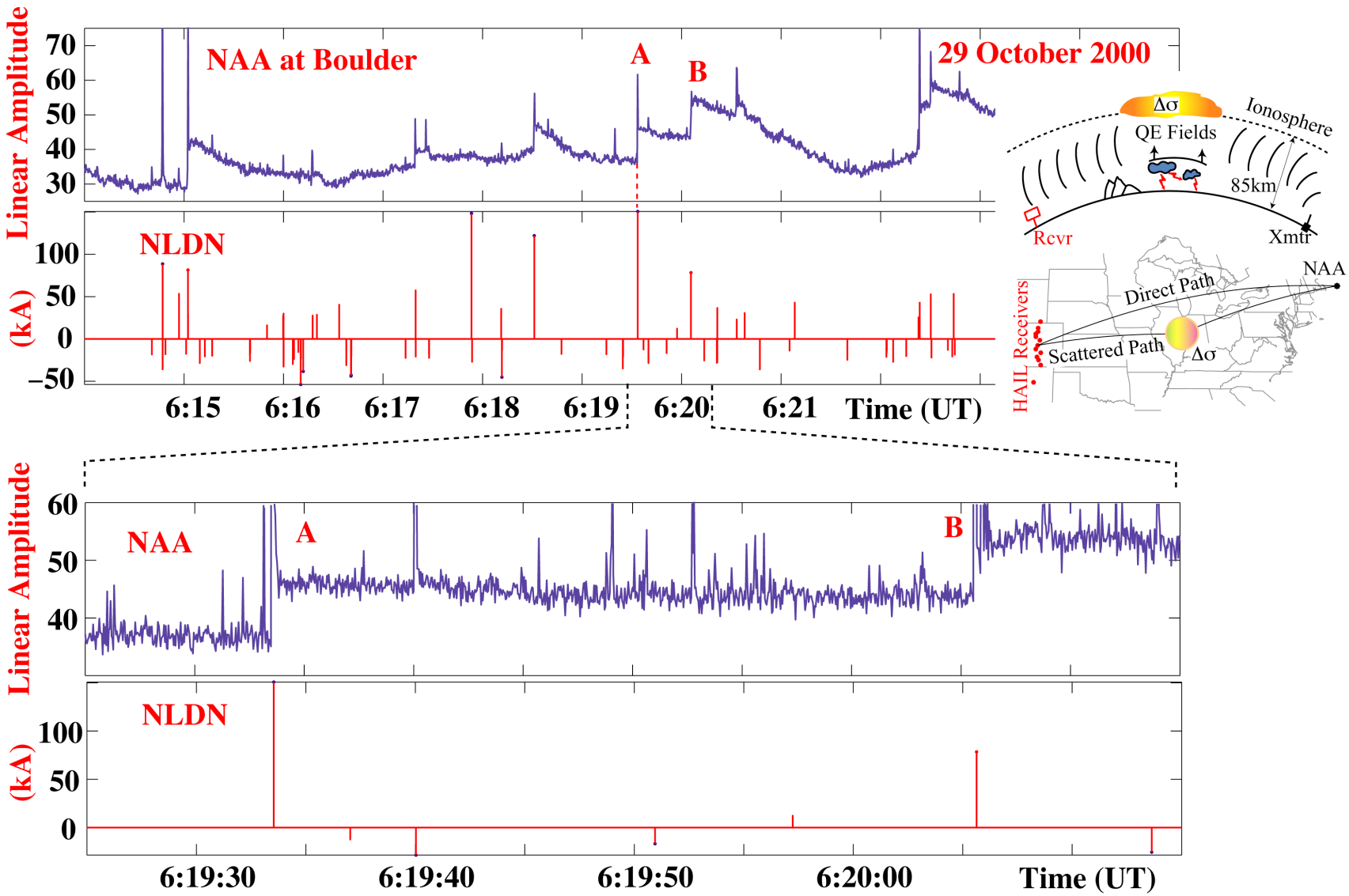


Elve Observed from Space

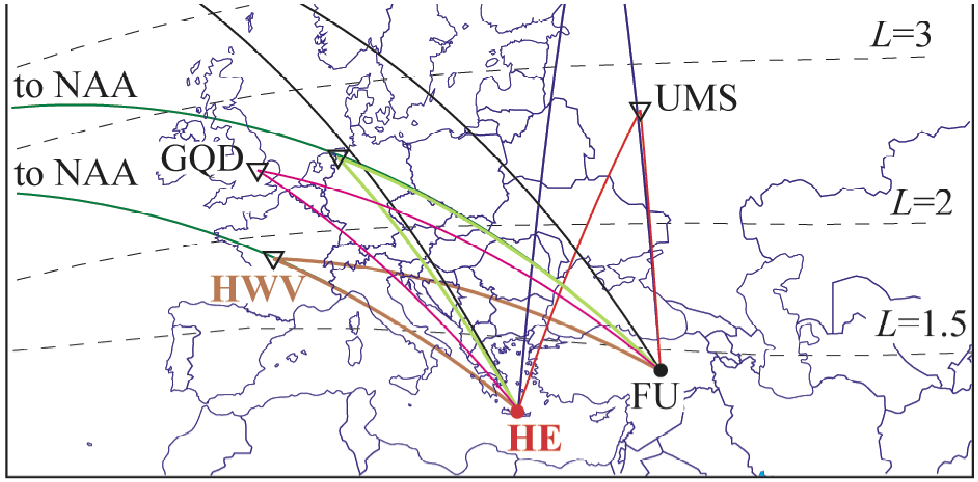




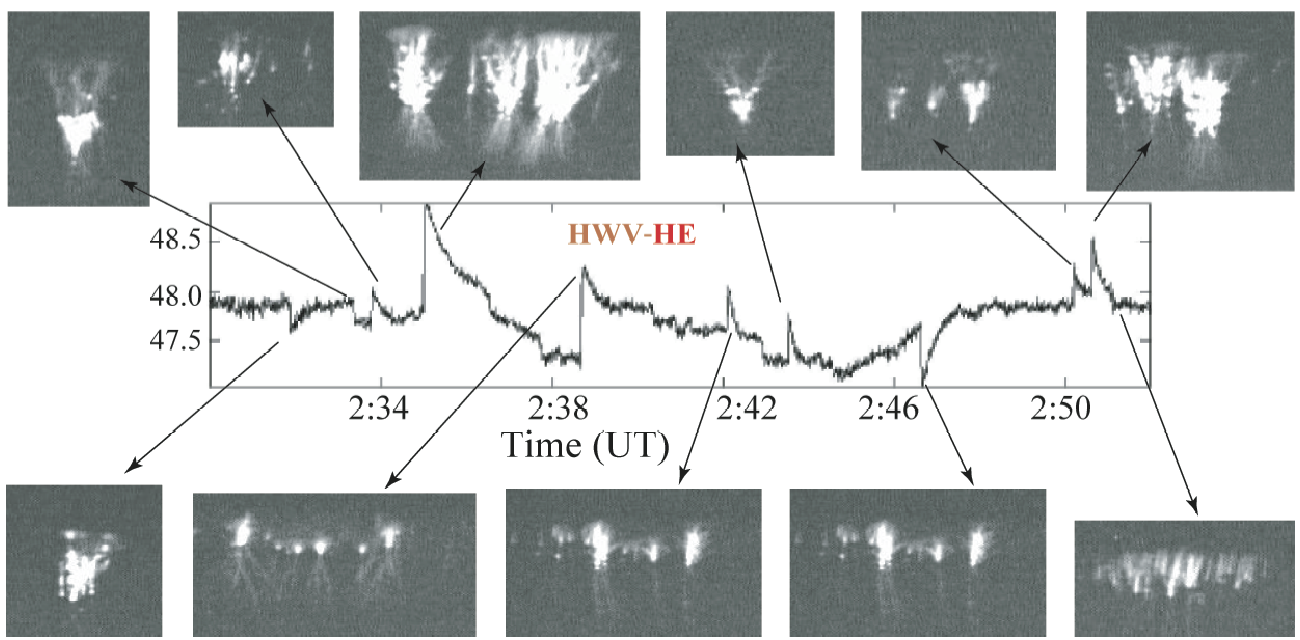
Early/fast VLF Events



Sprites and Early/fast VLF Events [*Haldoupis et al.*, 2005]

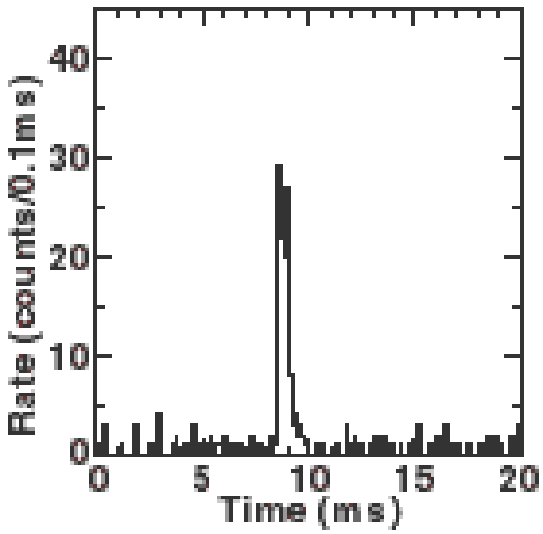


Sprites and Early/Fast VLF Events July 21, 2003; 0230-0252 UT



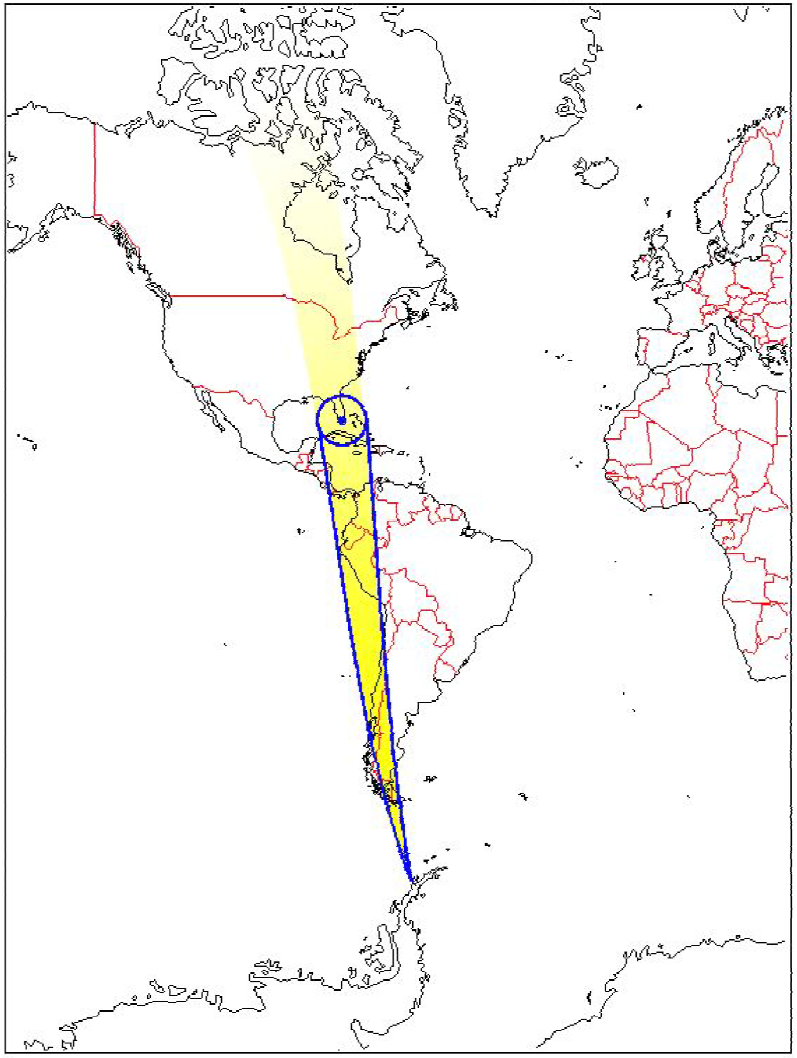
Discovery of TGFs by BATSE on CGRO:

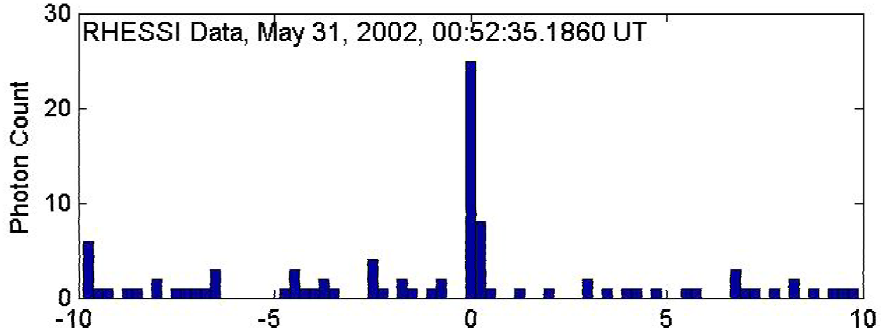
Flashes of duration ~ 1 ms
75 events discovered over 9 years
Hard spectra up to energies >> 300 keV
Correlation with thunderstorms

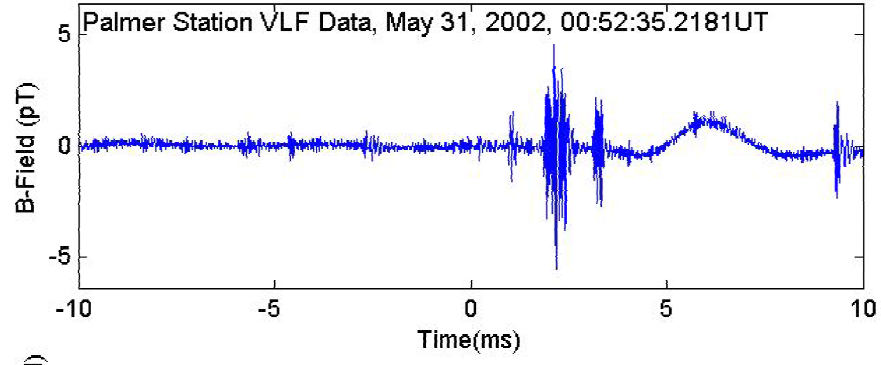


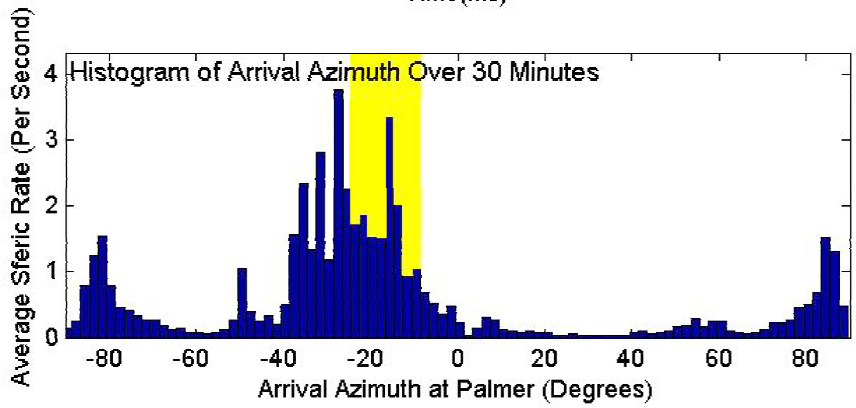
Terrestrial Gamma-ray Flashes and Radio Atmospherics

RHESSI Detection Footprint and Propagation Path



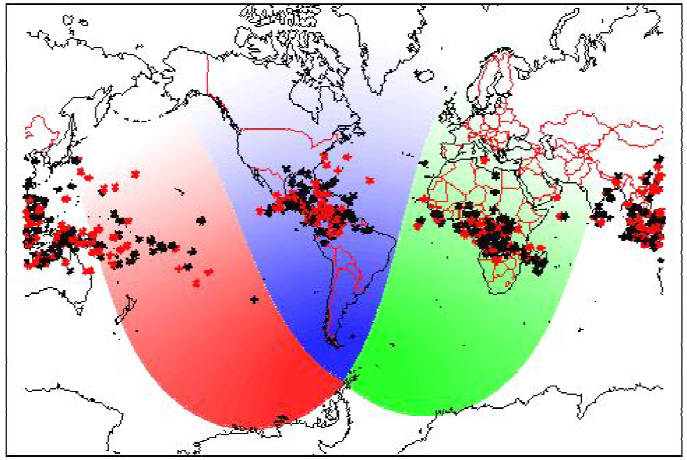




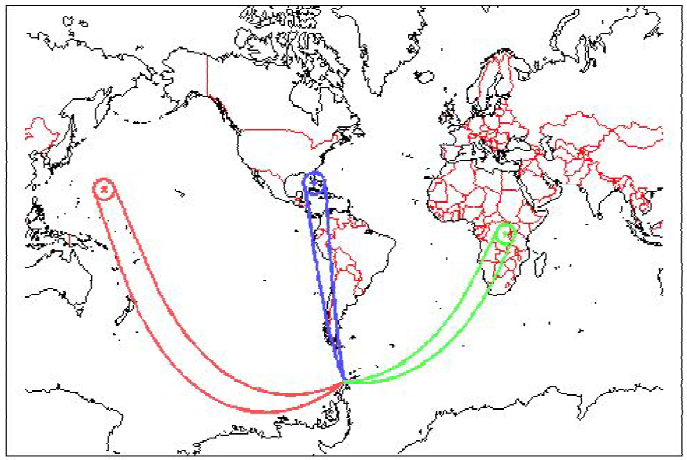


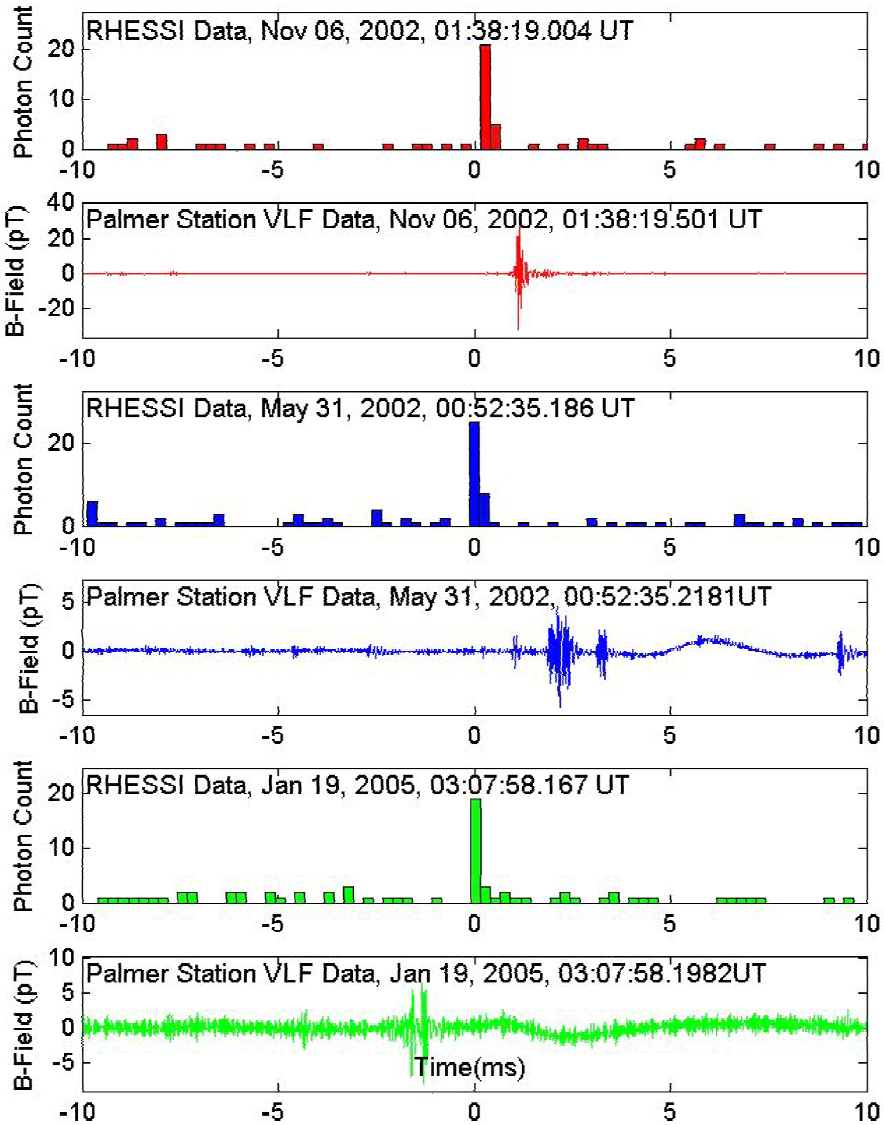
TGFs Time-correlated with Sferics (94%, 85%, 72%)

Global TGF Distribution and Sferic Detection Range at Palmer

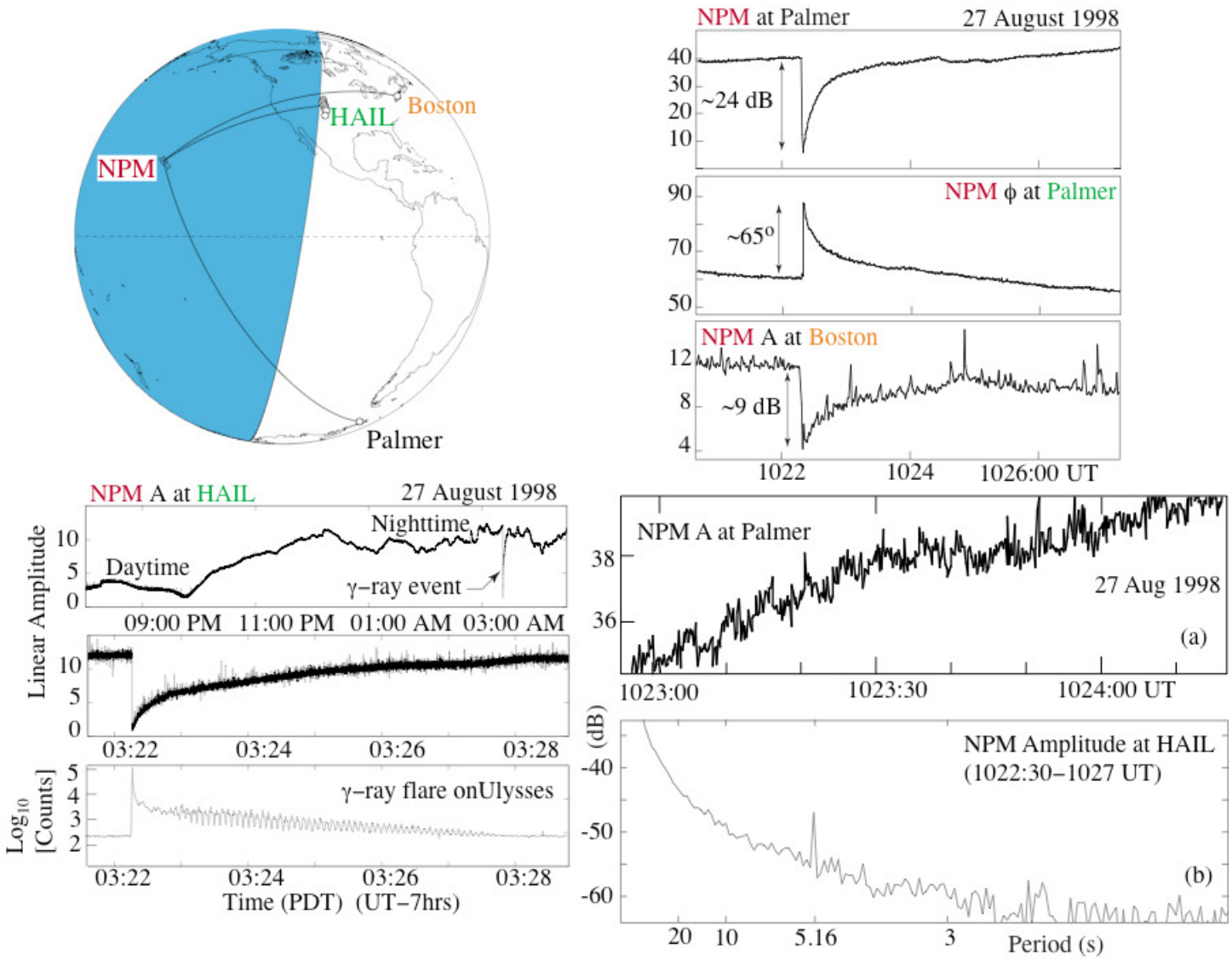


RHESSI Detection Footprint and Propagation Path

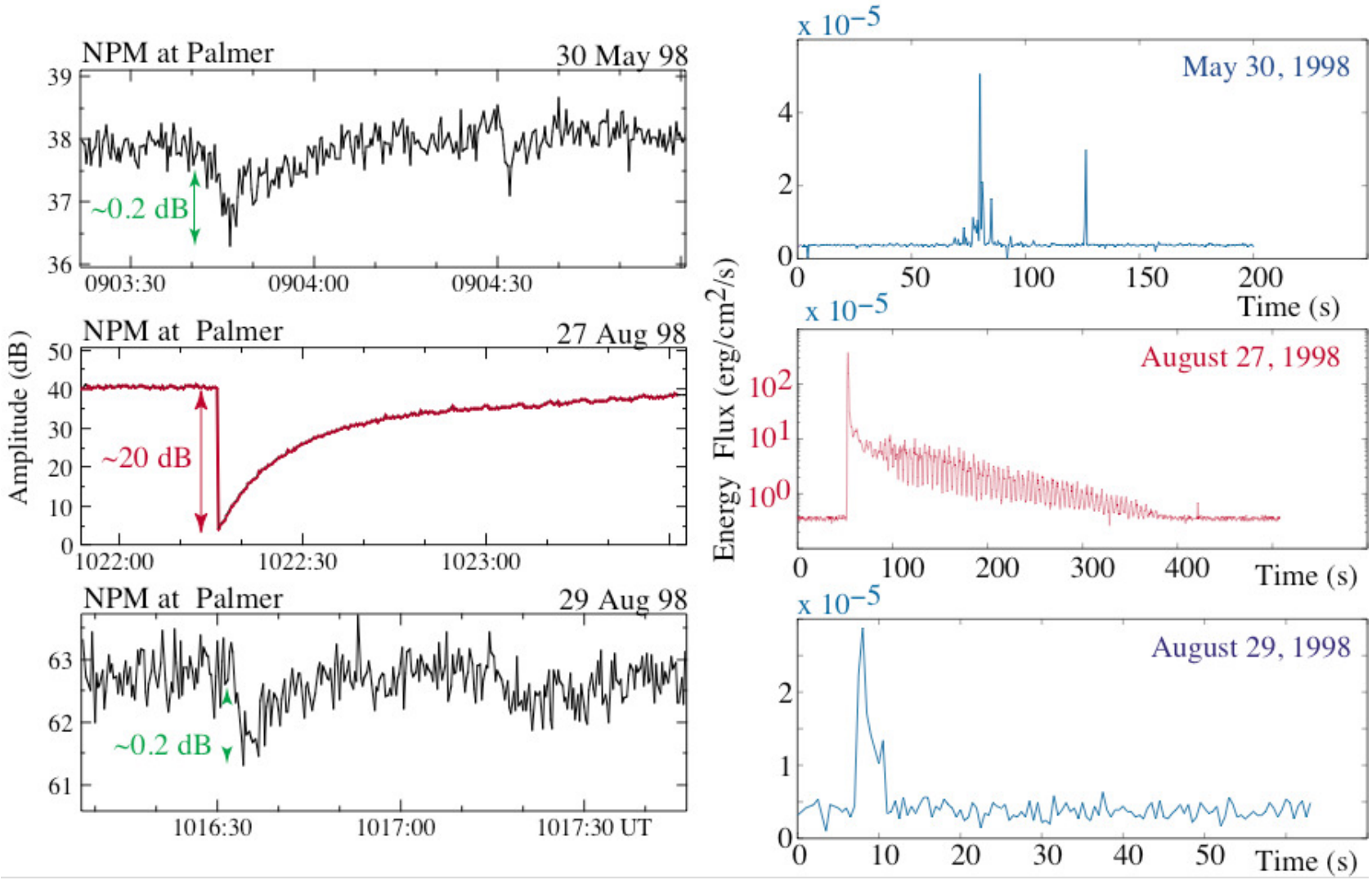




Disturbance of the Nighttime Ionosphere by SGR 1900+14

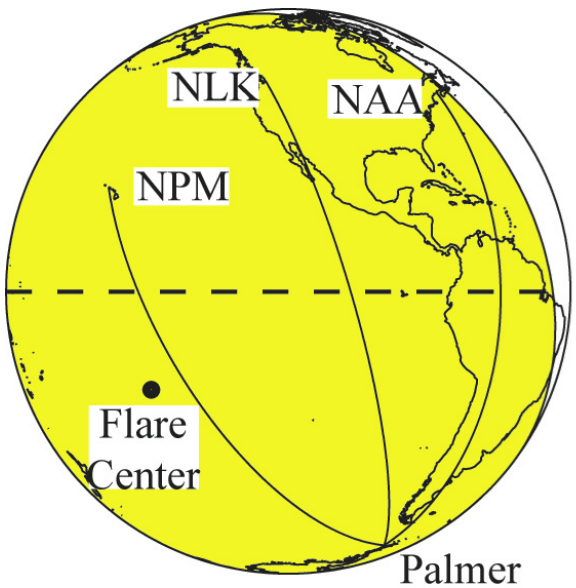


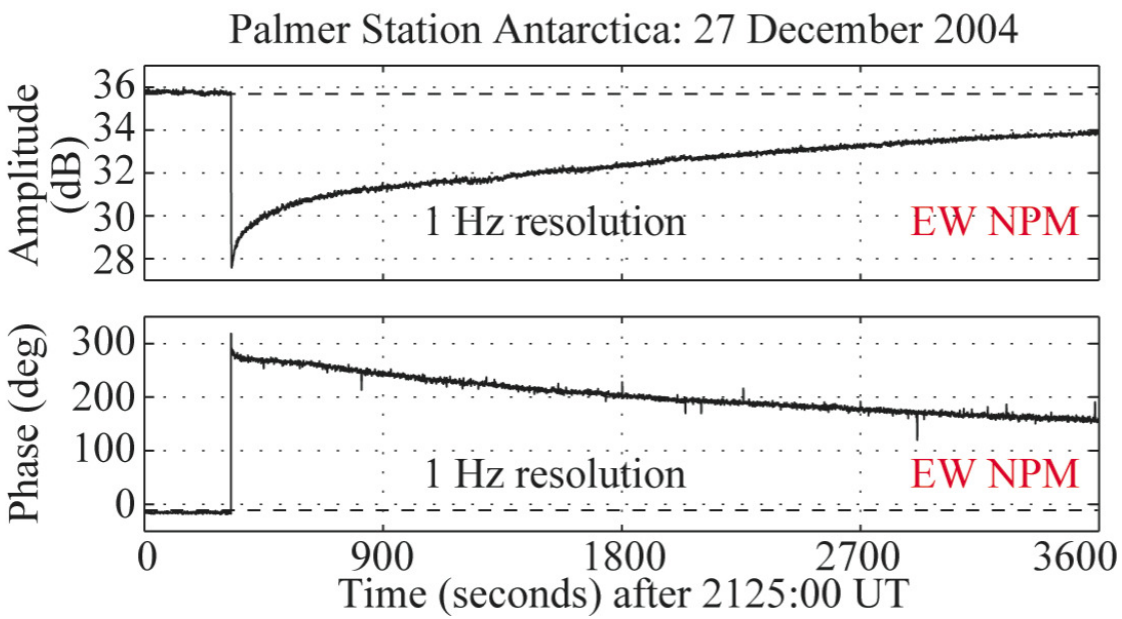
Repeated Disturbance of the Ionosphere by SGR 1900+14



VLF Detection of the Disturbance of the Daytime Lower Ionosphere

- Very large amplitude/phase perturbations on VLF signals, the great-circle propagation paths of which are illuminated by the Flare
- Flare center very near the sun; ionosphere was day-lit

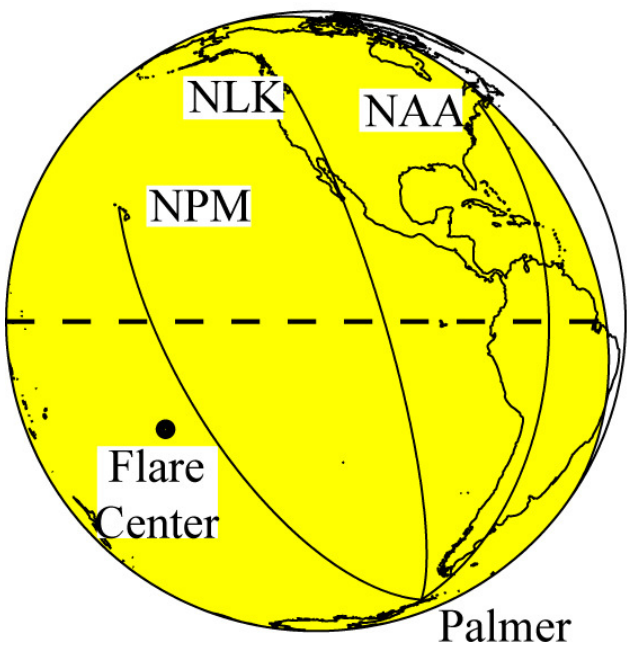


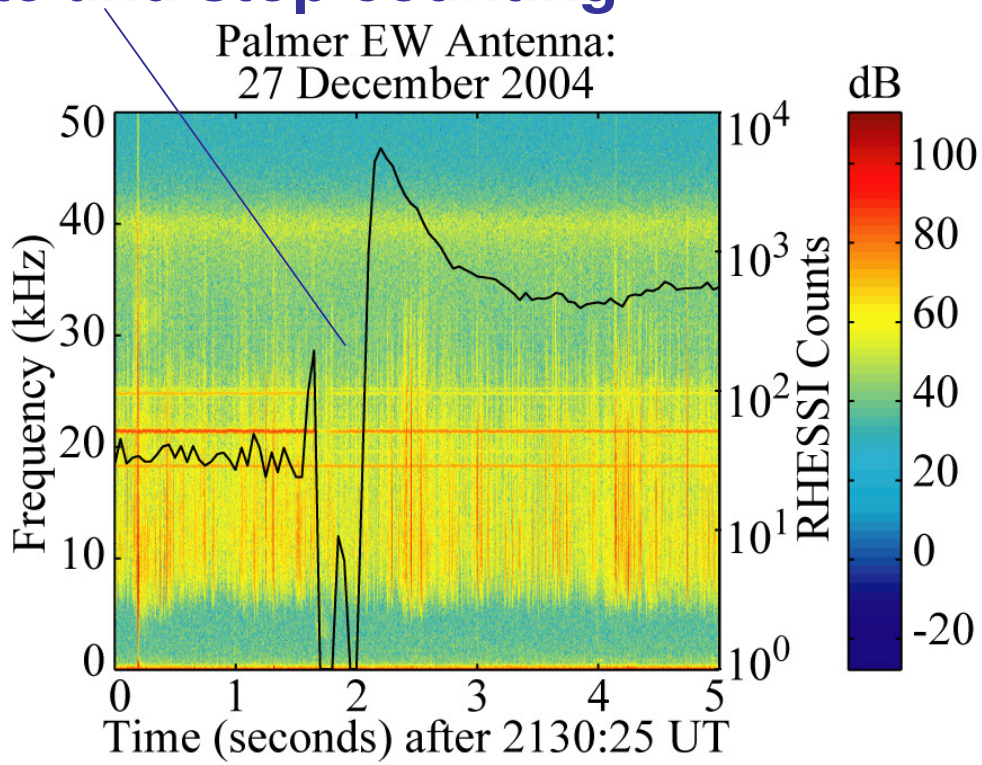


Event Setting and VLF Detection

Event onset clearly evident in broadband spectra, as amplitude reduction on all signals, including VLF transmitters and radio atmospherics

RHESSI Detectors saturate and stop counting



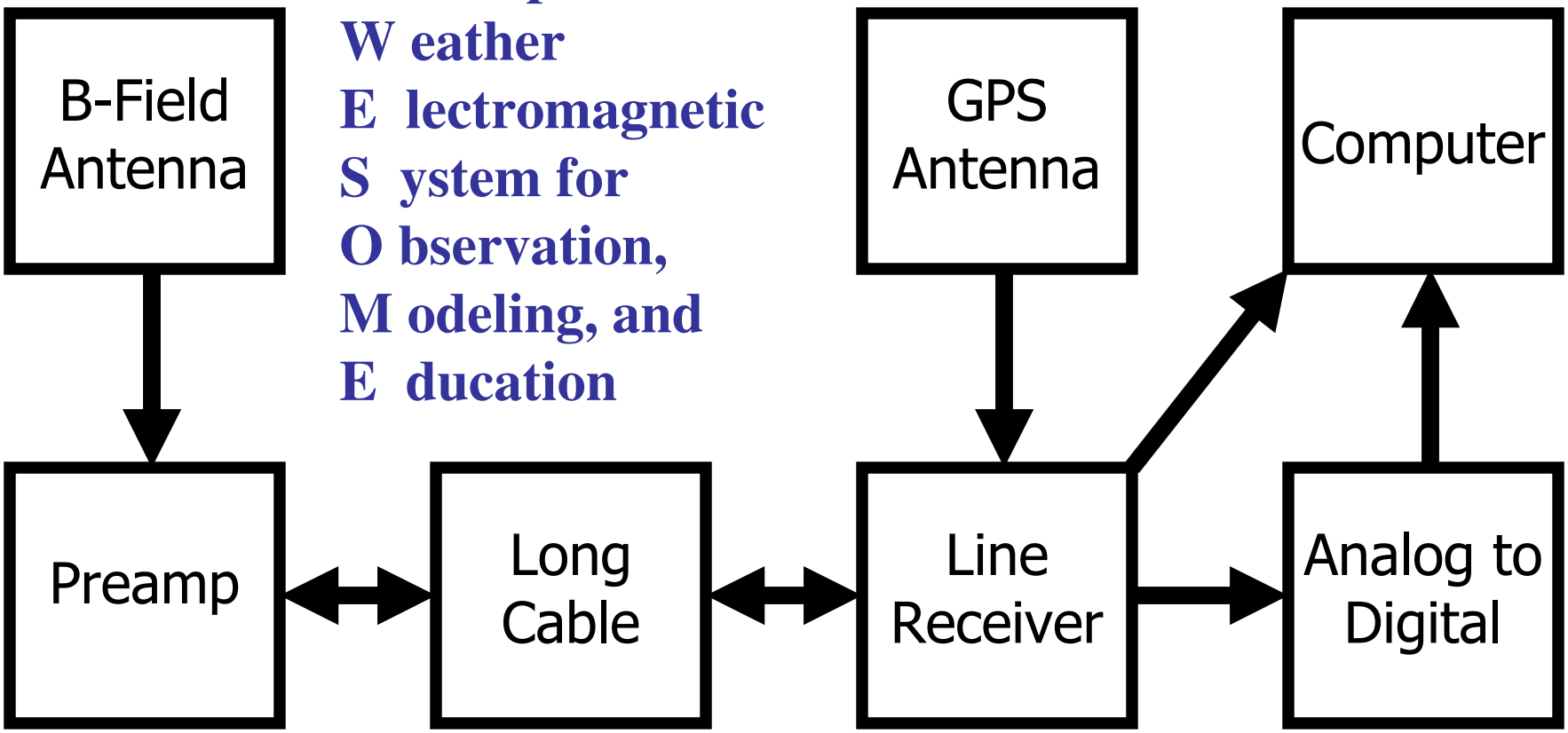


VLF Observations as Educational Outreach

- CISM Educational Outreach
- Professor Phil Scherrer
- High School Outreach
- Low Cost
- Easy to Use
- Dual use system
  - Daytime: monitor solar activity (*x*-ray flares)
  - Nighttime: monitor lightning-induced electron precipitation, gravity waves, sprites, etc.
- Science grade measurement, in terms of resolution, sensitivity, timing, and dynamic range

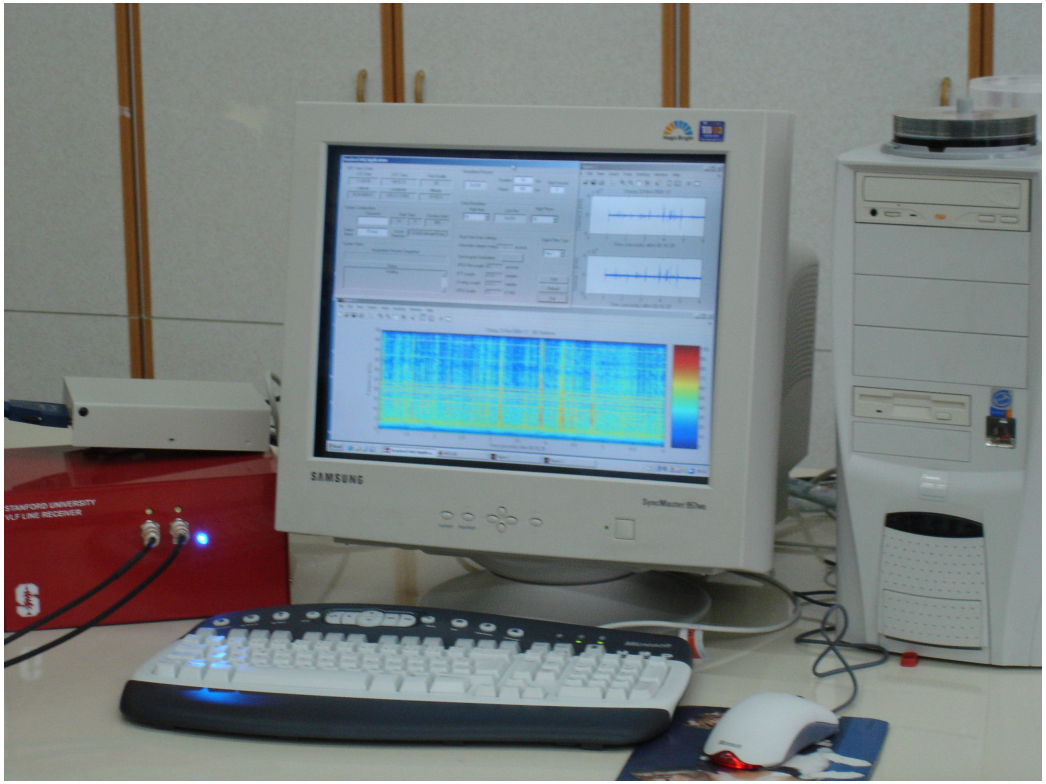
AWESOME
Receiver Overview

A tmospheric
W eather
E lectromagnetic
S ystem for
O bservation,
M odeling, and
E ducation



Antenna, Preamp, and Line Receiver

Computer, Line Receiver & A/D Card



- **National Instruments 6034E**
  - **Plugs into PCI slot; PCMCIA laptop version available**
  - **200 kS/second, 16-bit; 100 kHz sampling each channel**

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