Terrestrial Gamma Ray Flashes and VLF Radio Atmospherics

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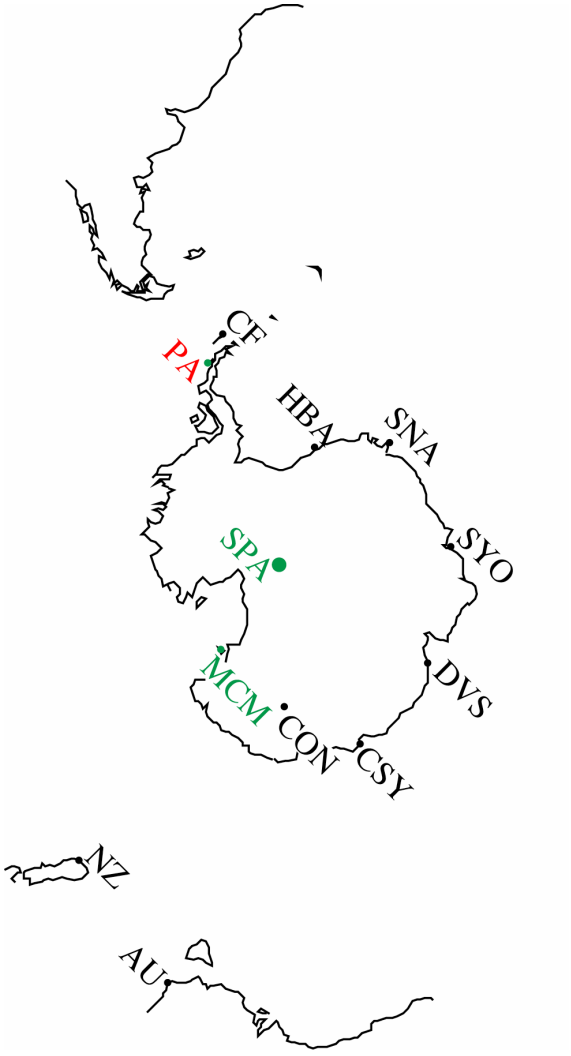
Outline

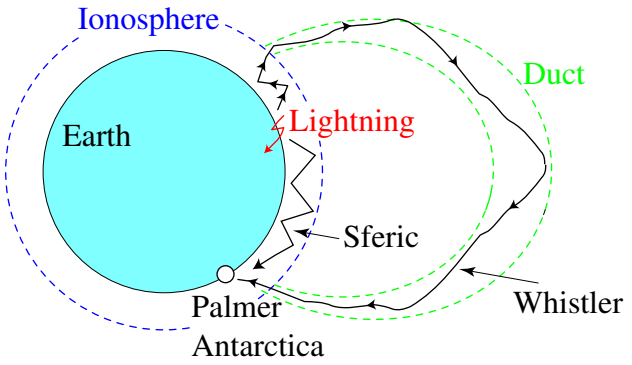
- TGF Background
- Stanford Data Collection
- Direction Finding Technique
- Data, Analysis, and Results
  - Good TGF-sferic matches
  - Poor matches
- Summary and conclusions

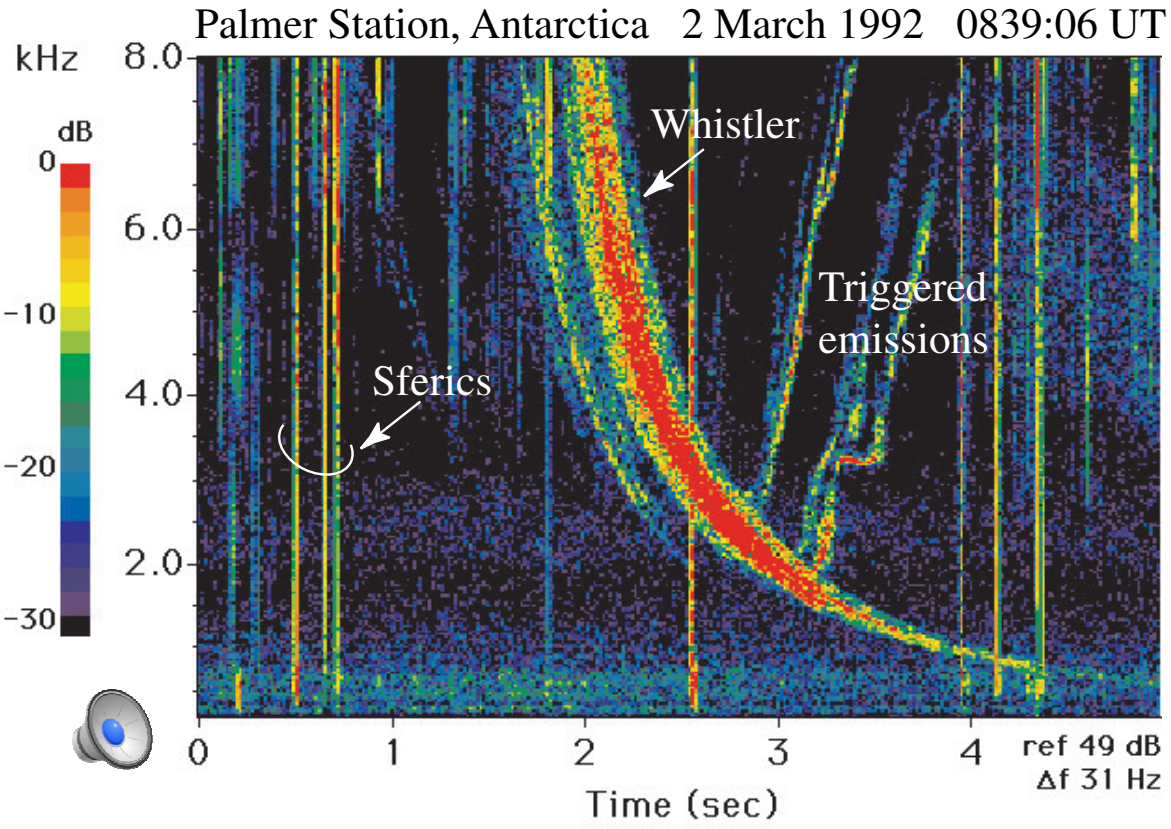
Stanford Program at Palmer Station, Antarctica



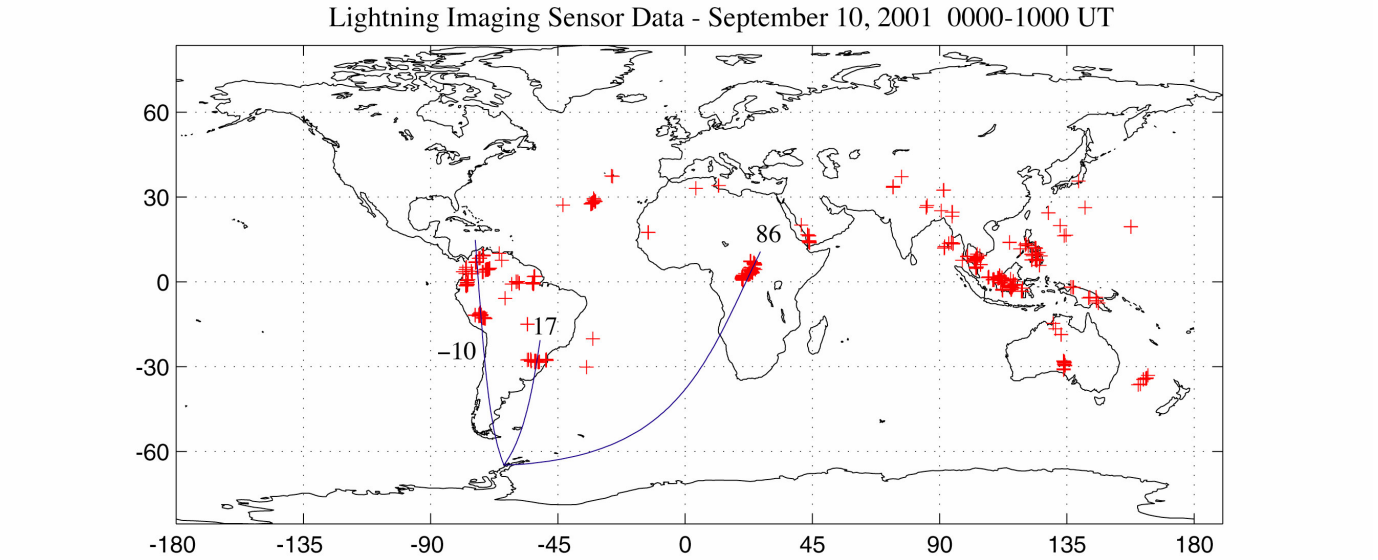
Lightning-generated Whistlers

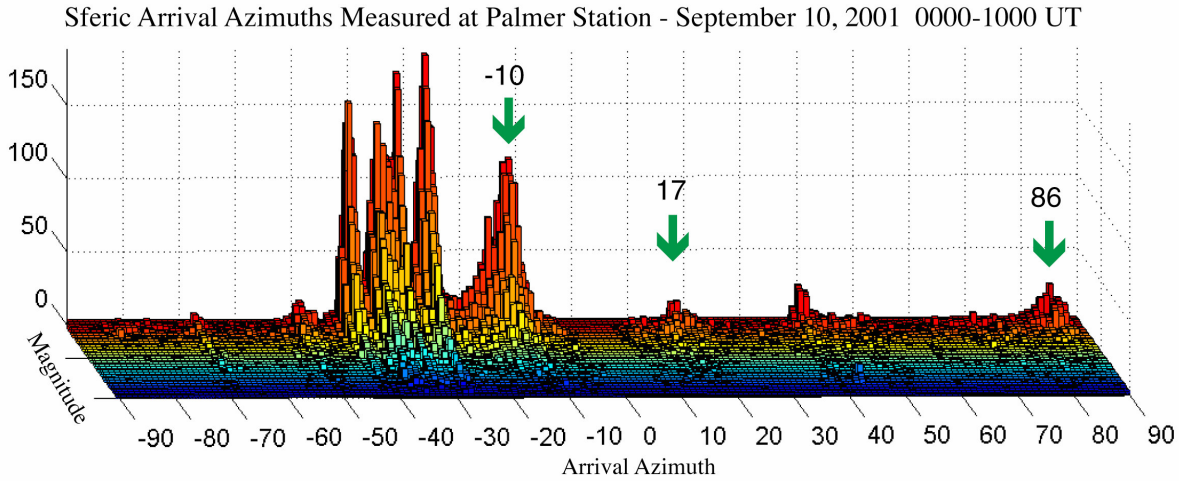
- **Very Low Frequency (VLF) waves launched by lightning propagate in the Earth-ionosphere waveguide *(v_p=c)***
- **Wave energy also couples upward to the radiation belts, propagating along filamentary "ducts" of enhanced ionization**
- **The magnetospheric plasma is a dispersive slow wave medium *(v_p=0.01 c)***
- **Signal arriving at the conjugate region sounds like a "whistler"**





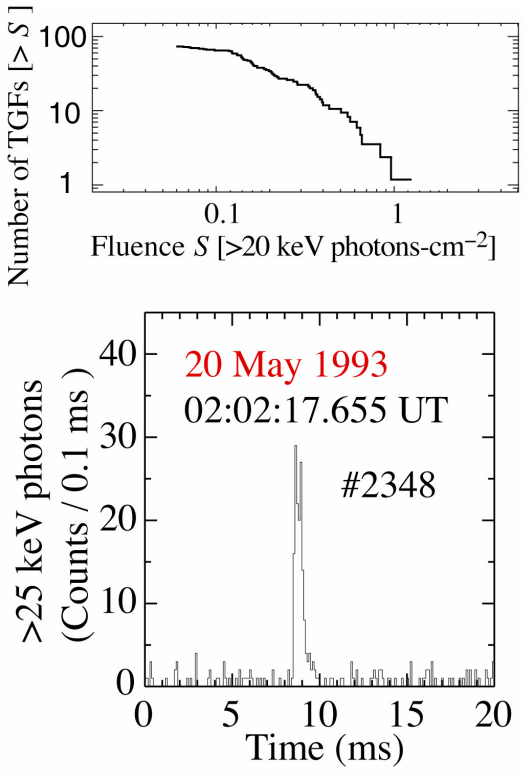
Global Lightning Observations

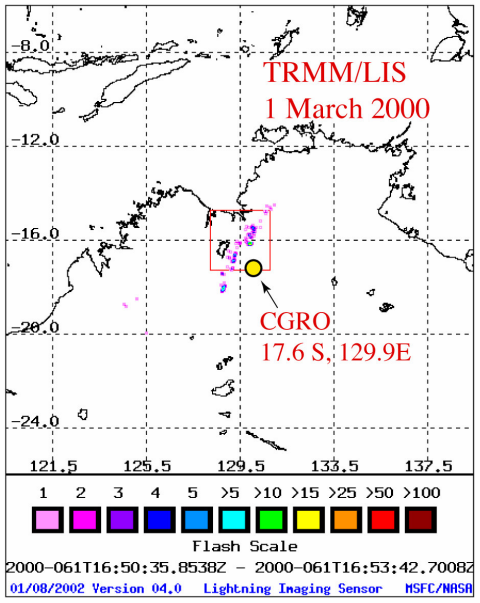


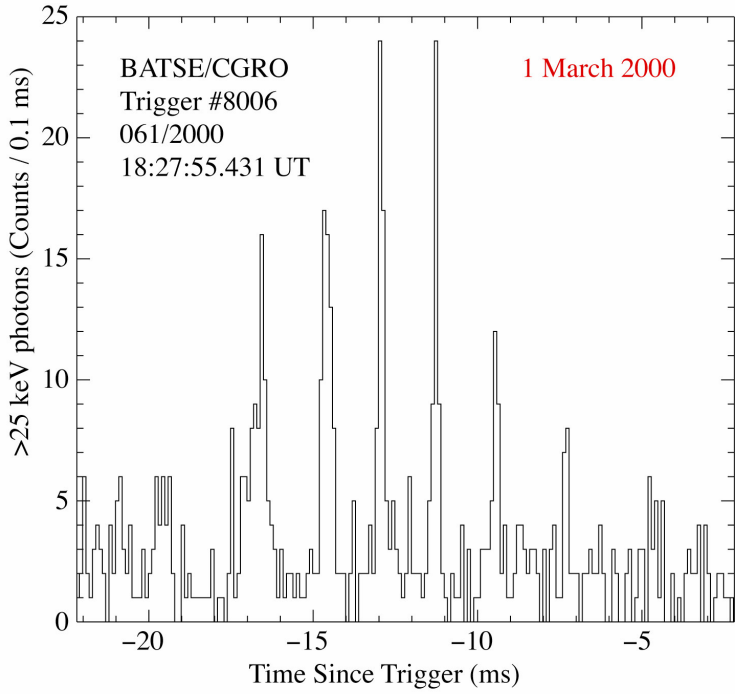


Terrestrial γ-ray Flashes

- **A sequence of seven flashes were observed**
- **Rather different from the typical single flash**







GEOPHYSICAL RESEARCH LETTERS, VOL. 23, NO. 9, PAGES 1017-1020, MAY 1, 1996

On the association of terrestrial gamma-ray bursts with lightning and implications for sprites

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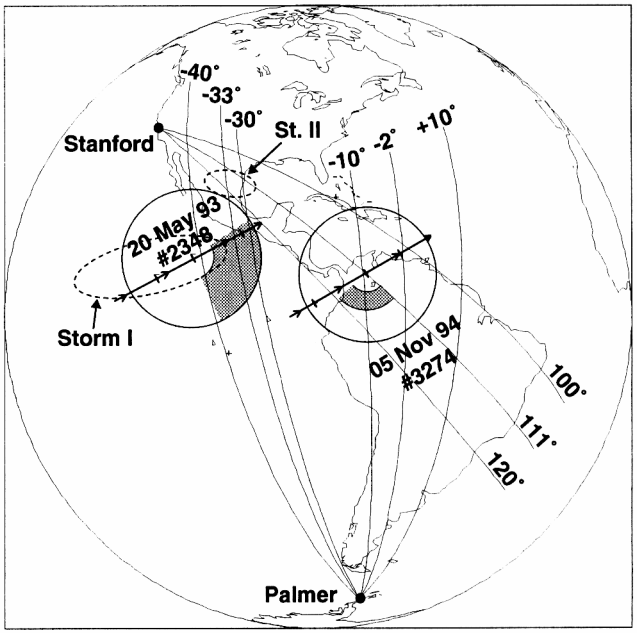
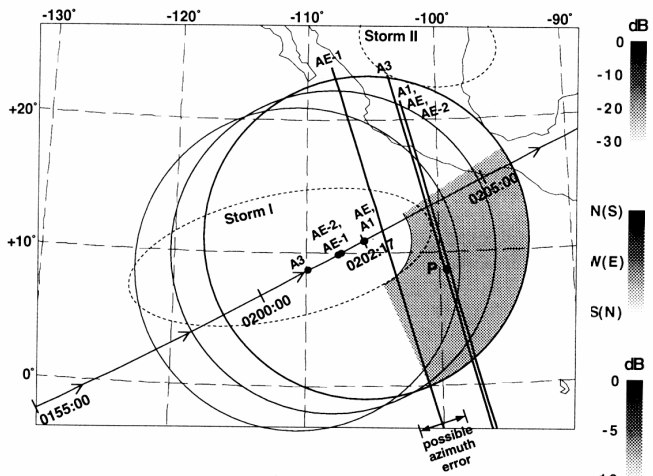
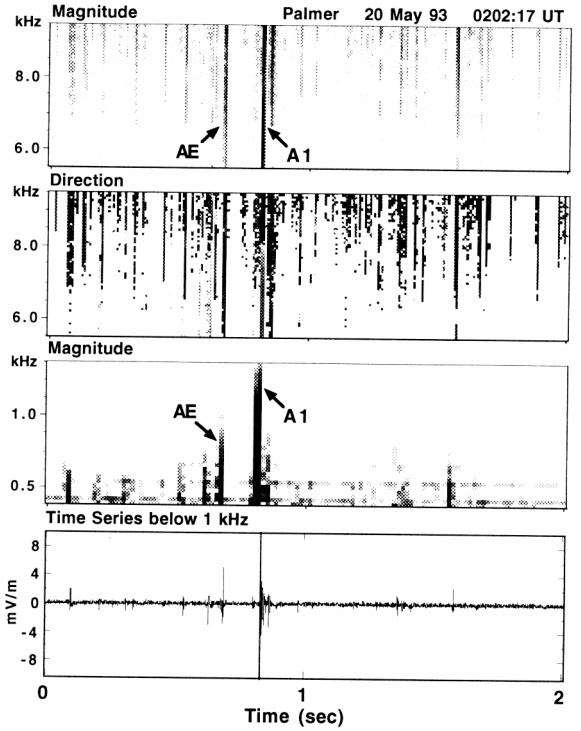
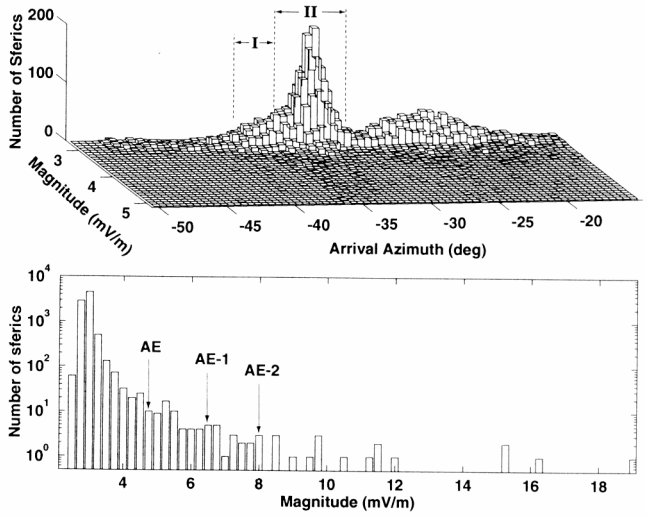
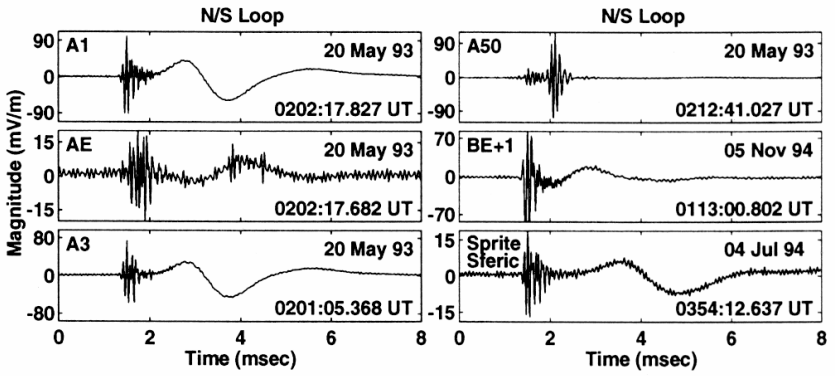
NASA Marshall Space Flight Center, Huntsville, Alabama



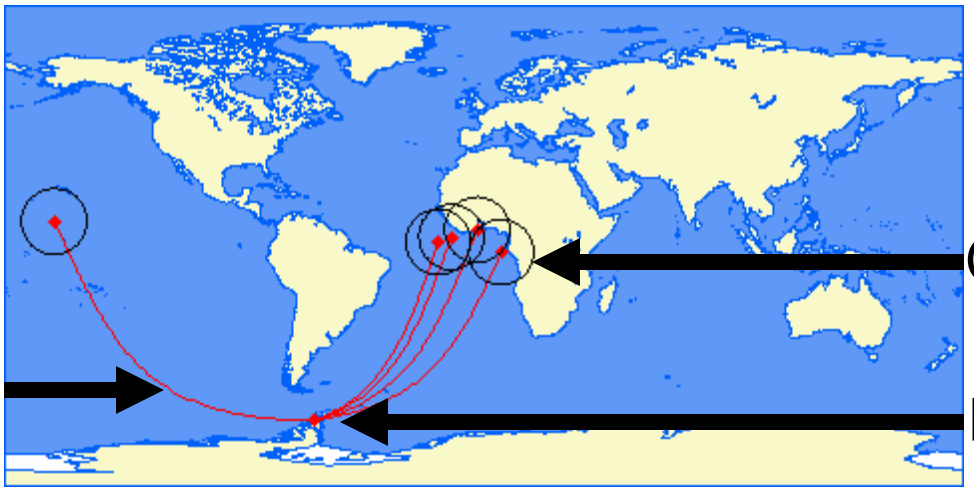






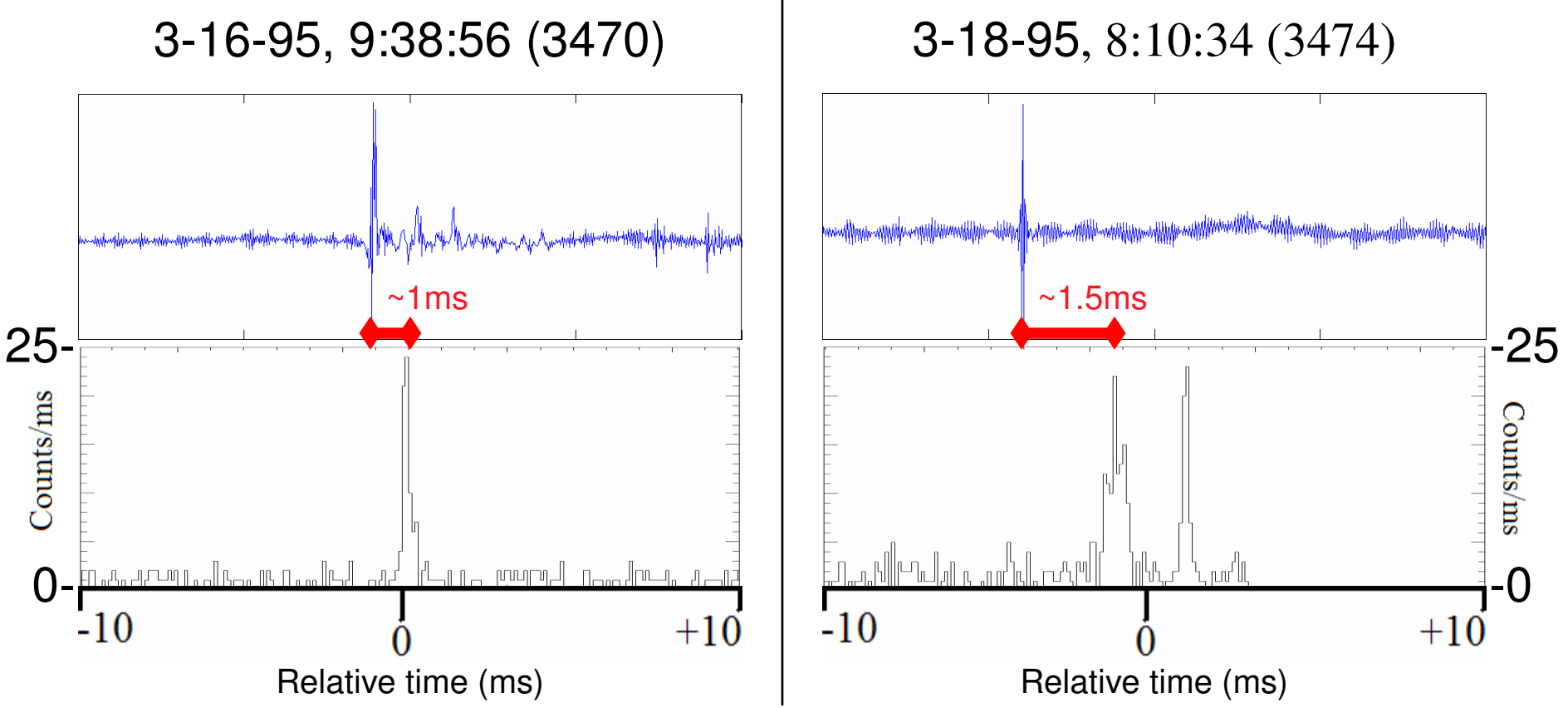


TGF-Lightning Association Analysis from Palmer Station



- Inan et al, 1996, established causative lightning-TGF association in two instances.
- 1995-2000: CGRO instrument detected 37 TGF bursts
- 11 of 37 had available Palmer (Antarctica) VLF data
- 5 of 11 were in Western hemisphere
- 5 remaining cases to analyze

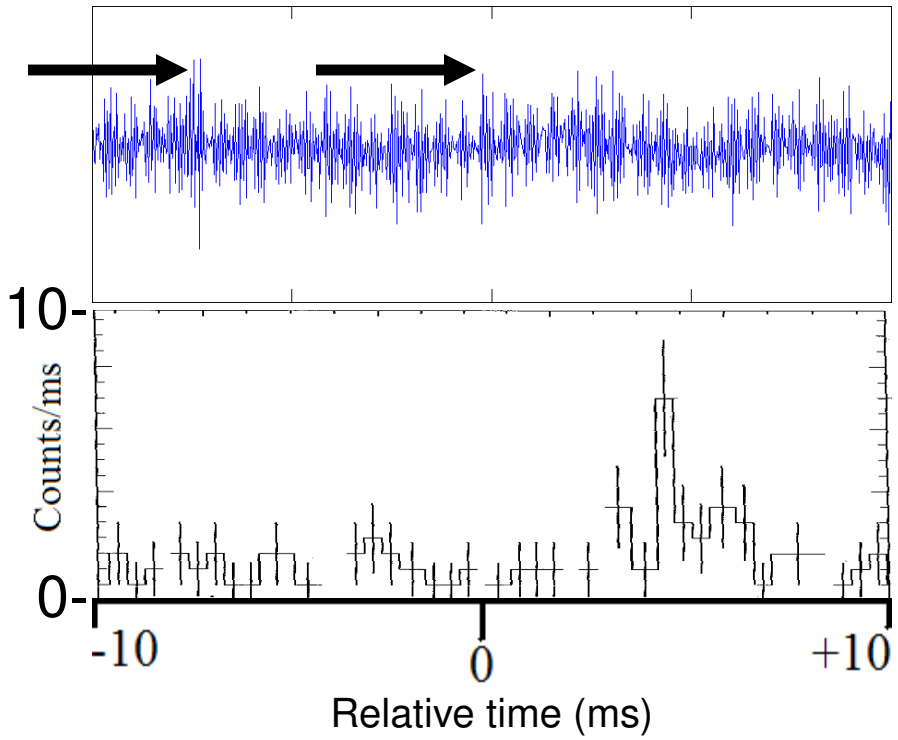
TGF-Lightning Association
The Analysis Result (Part I)



- Sferic found within 1-2 ms of predicted arrival
- Direction of sferic toward CGRO footprint
- Many sferics from that direction (indicates thunderstorm)

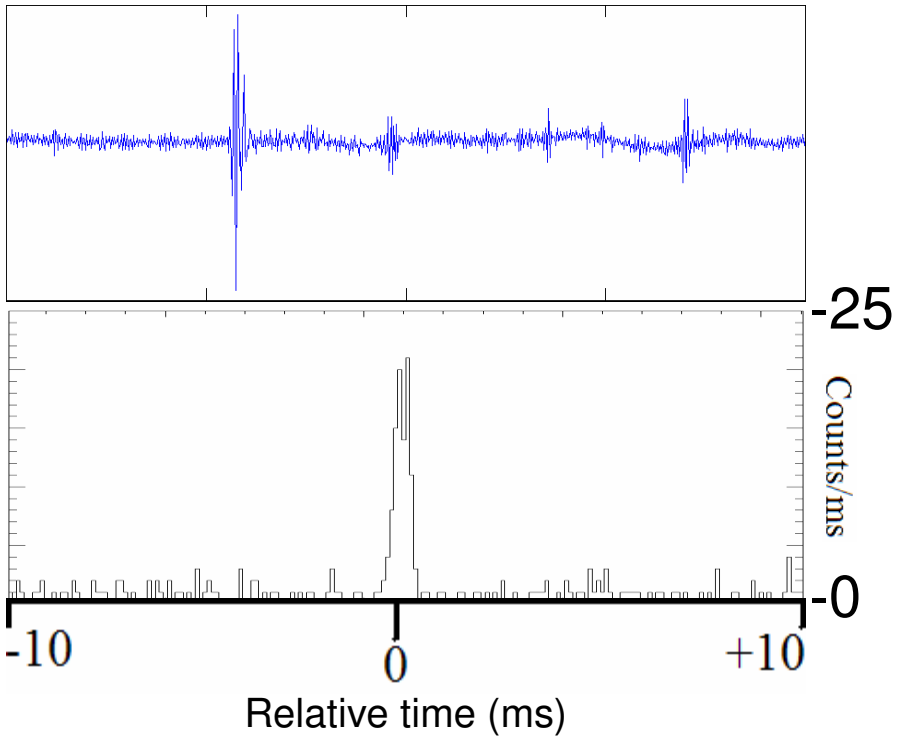
TGF-Lightning Association
The Analysis Result (Part II)

4-14-95, 9:51:59 (3500)



- Two small sferics found
- Time/direction match
- Thunderstorm present

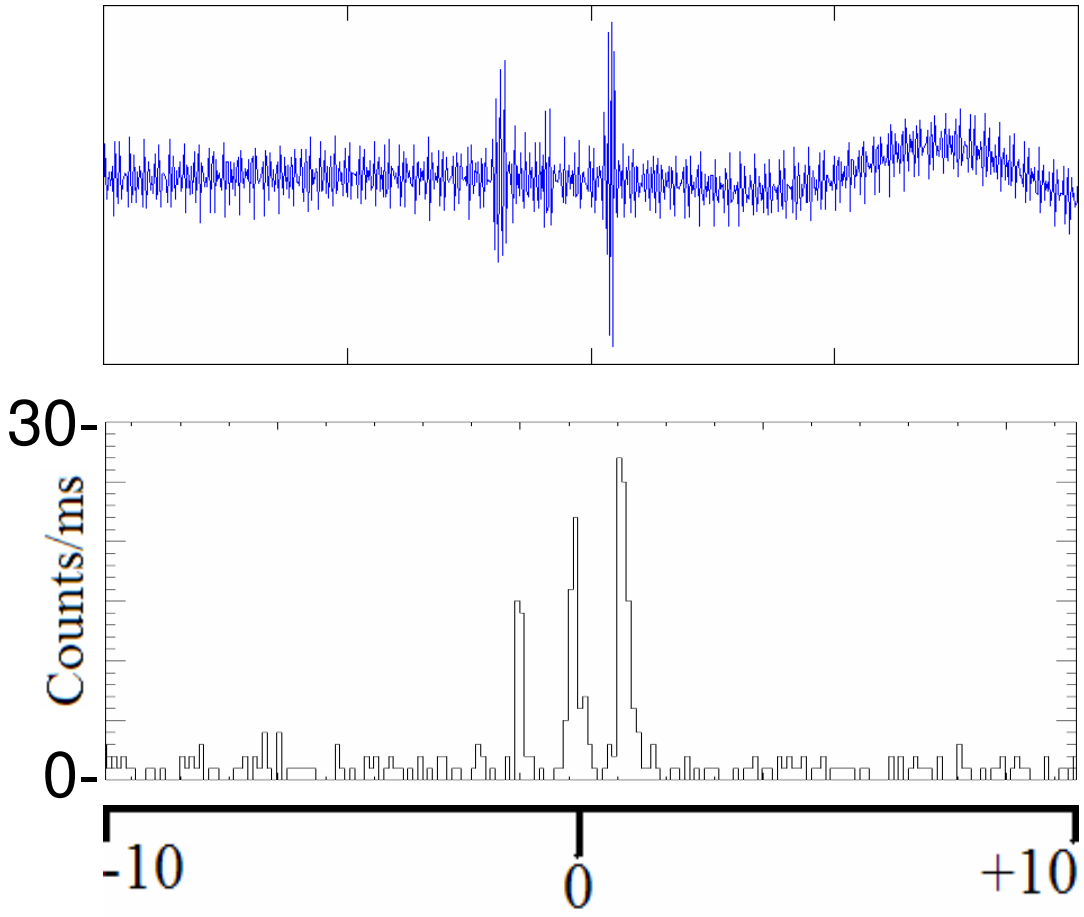
8-17-96, 3:48:21 (5577)



- Multiple sferics
- Azimuths not correct
- Thunderstorm present

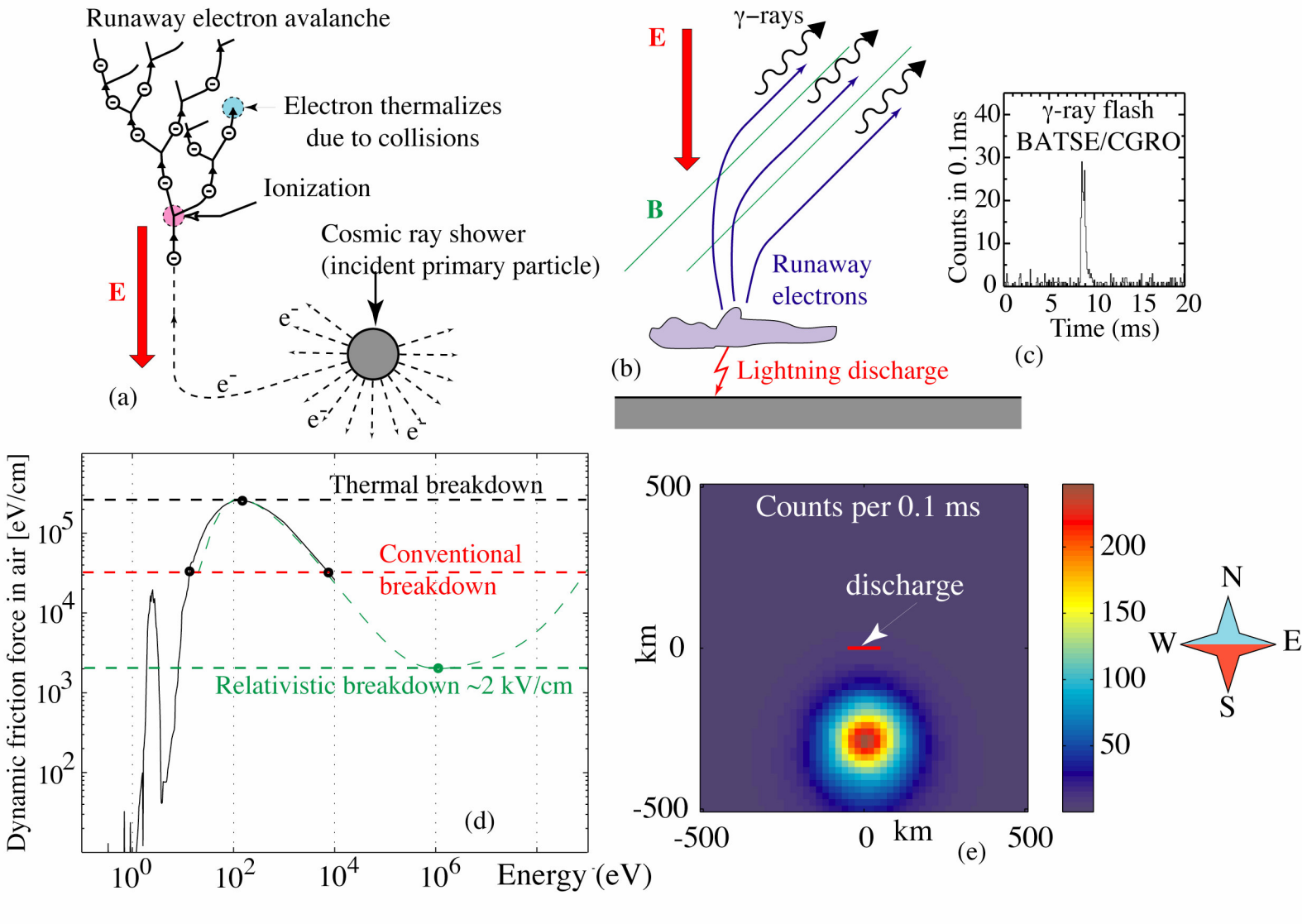
TGF-Lightning Association
The Analysis Result (Part III)

11-28-95, 7:05:39 (3925)

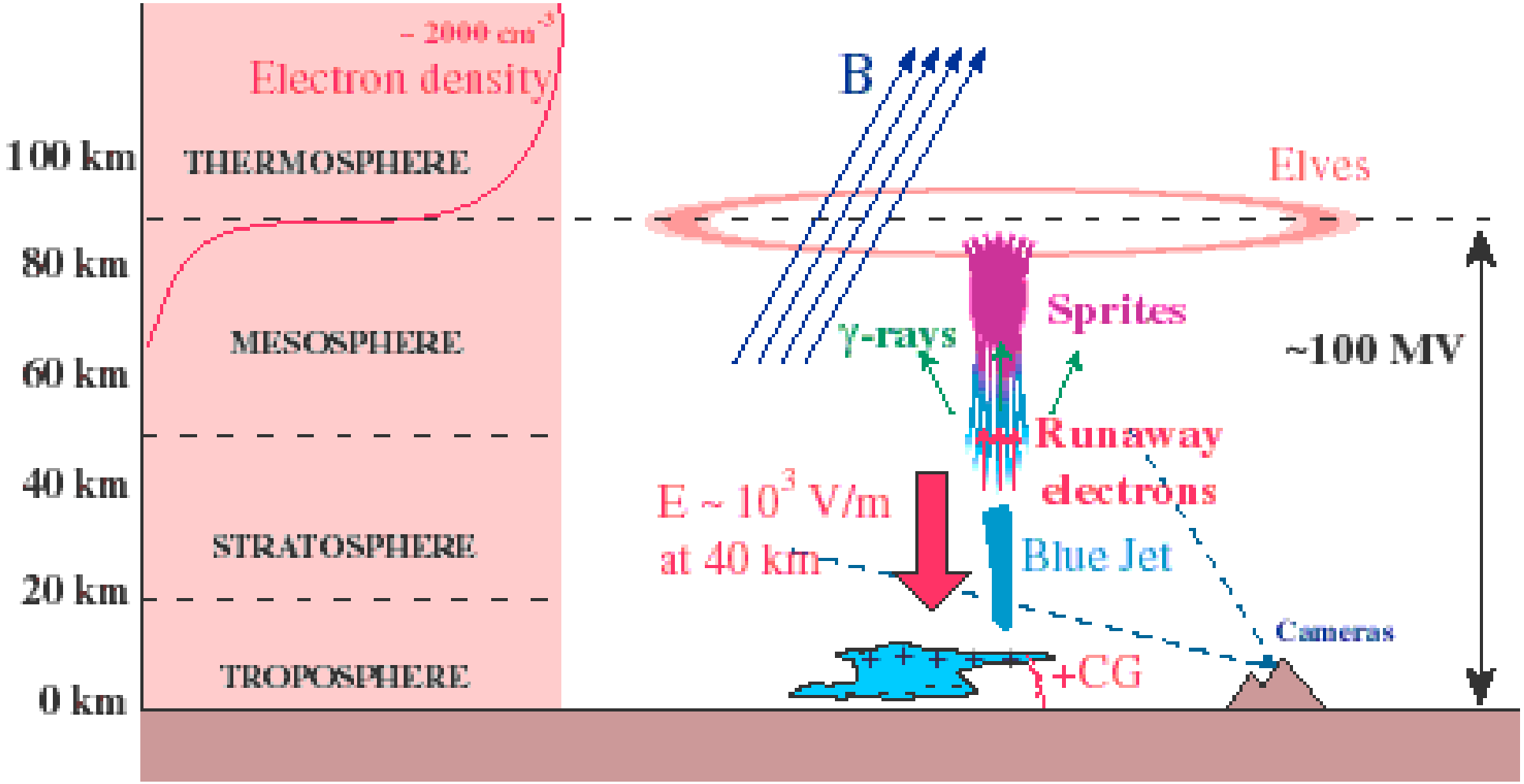


- Three sferics seem to mirror three spikes
- Two of the sferics come from azimuth toward CGRO footprint
- Direction of middle sferic cannot be determined, but appears to be similar
- Thunderstorm detected from CGRO azimuth

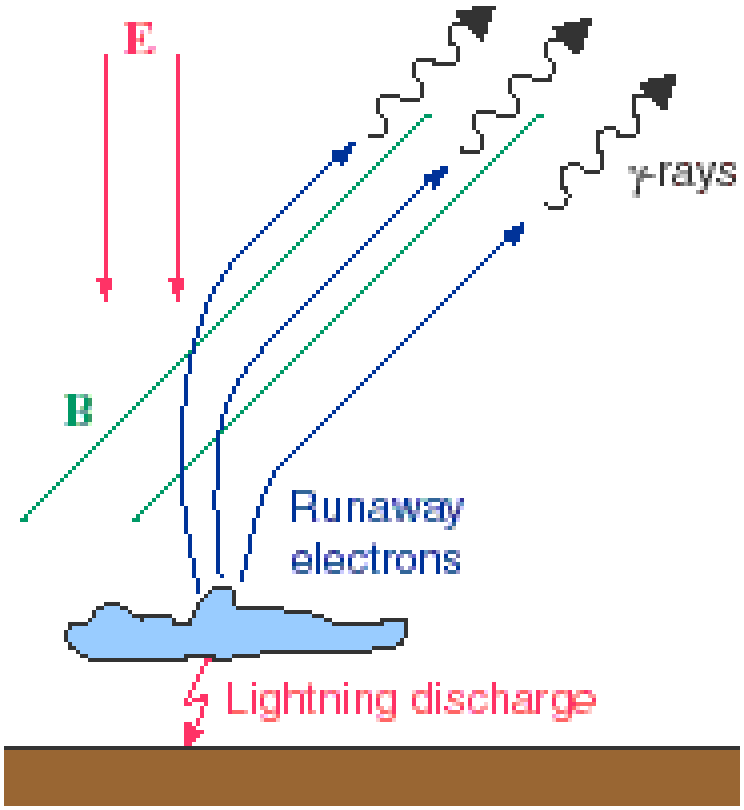
Lehtinen et al. [2000]

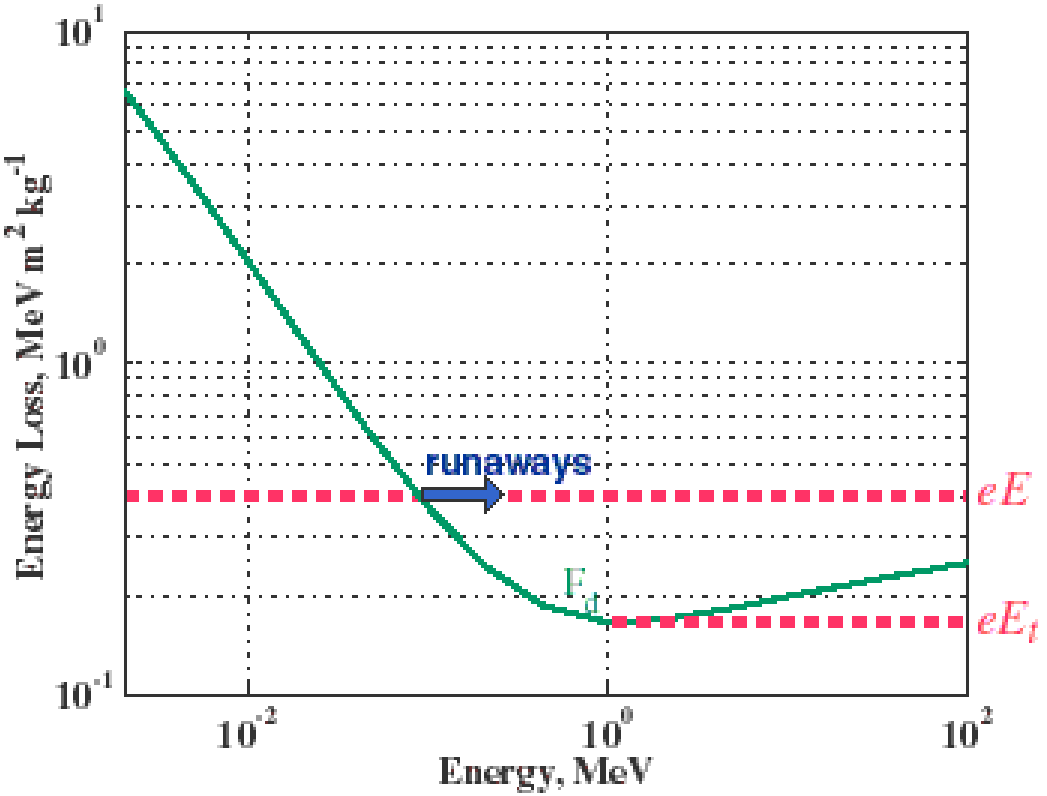


Mesospheric Phenomena

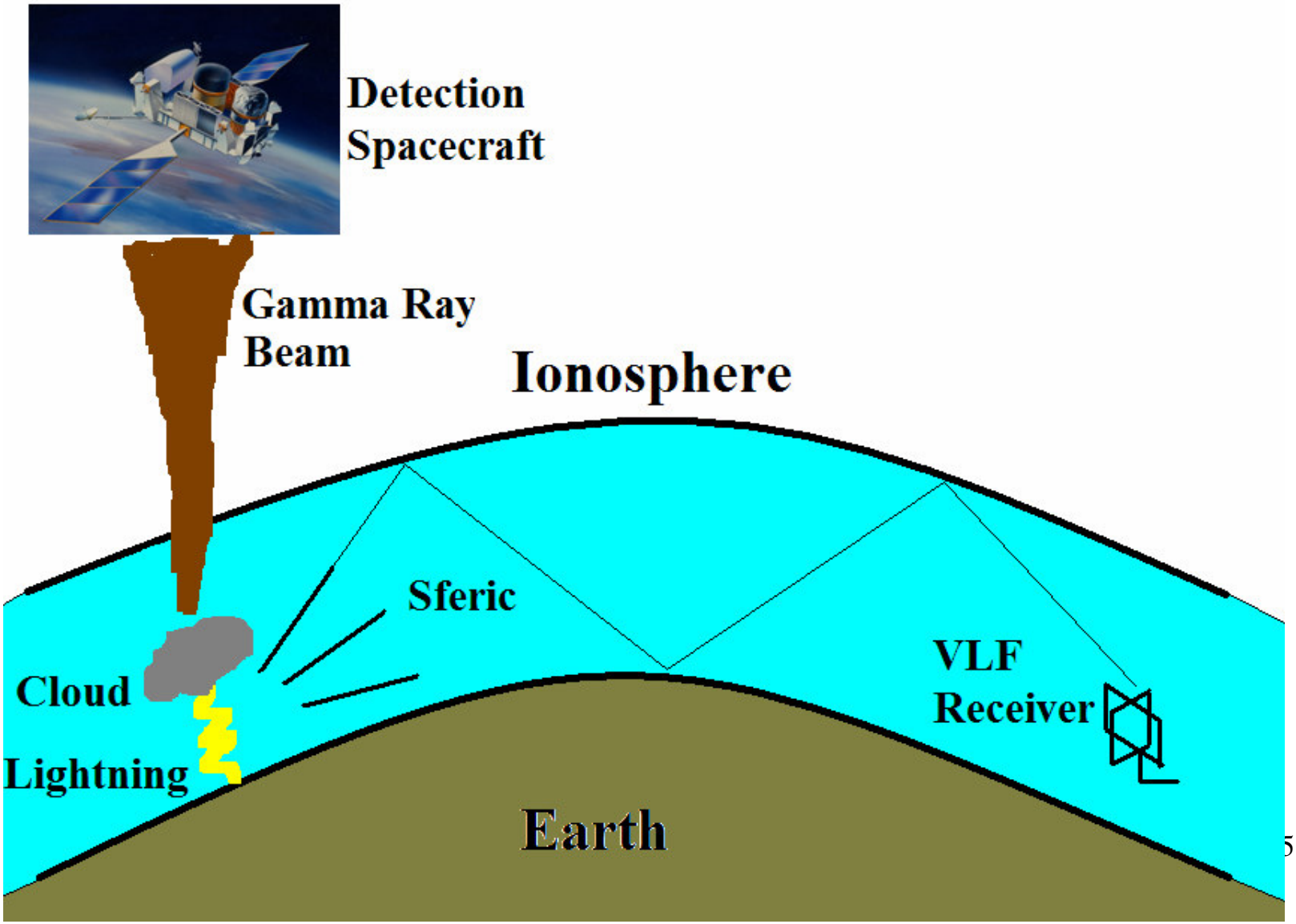


TGF Physical Origins



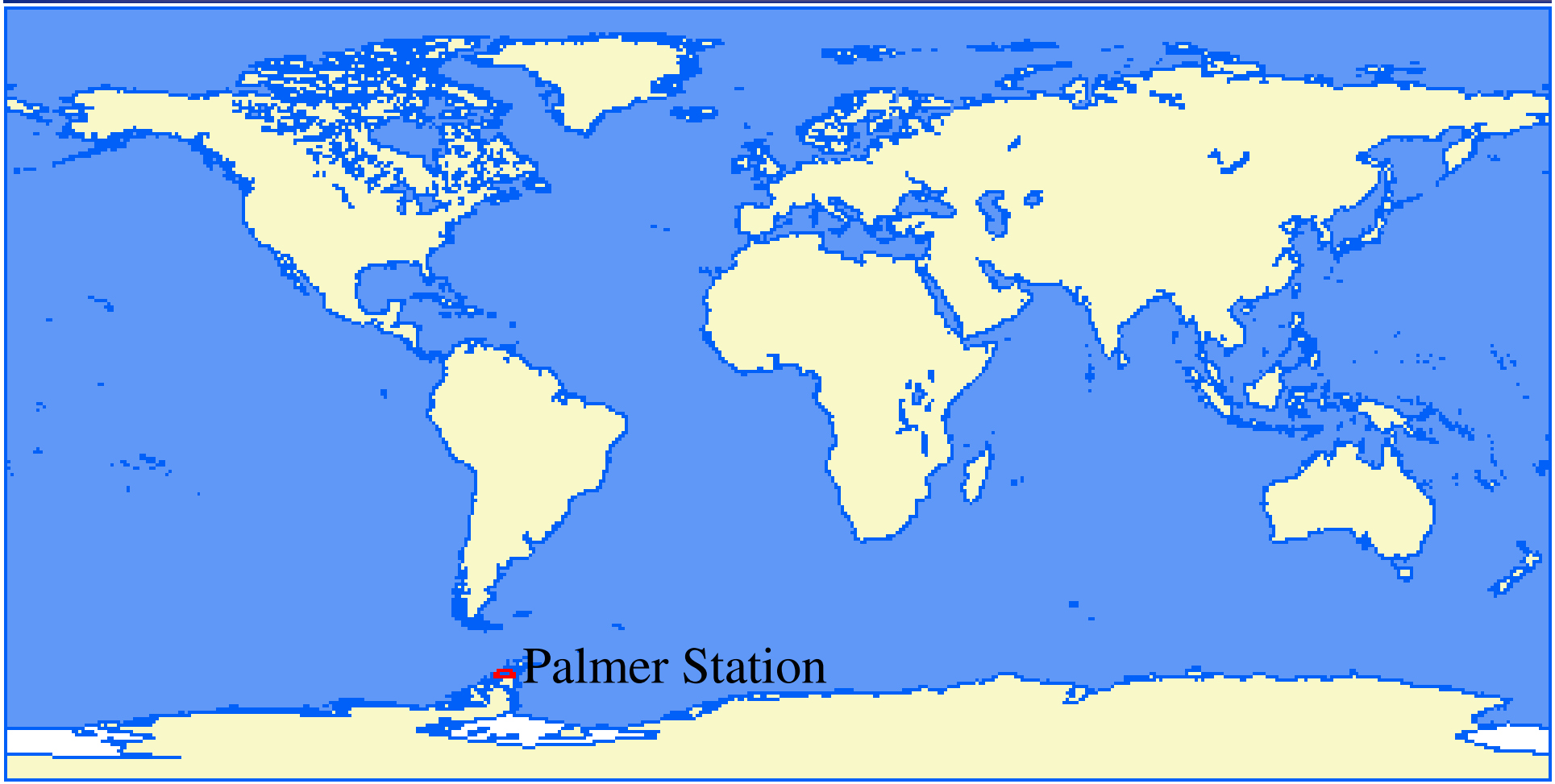


VLF Data Collection

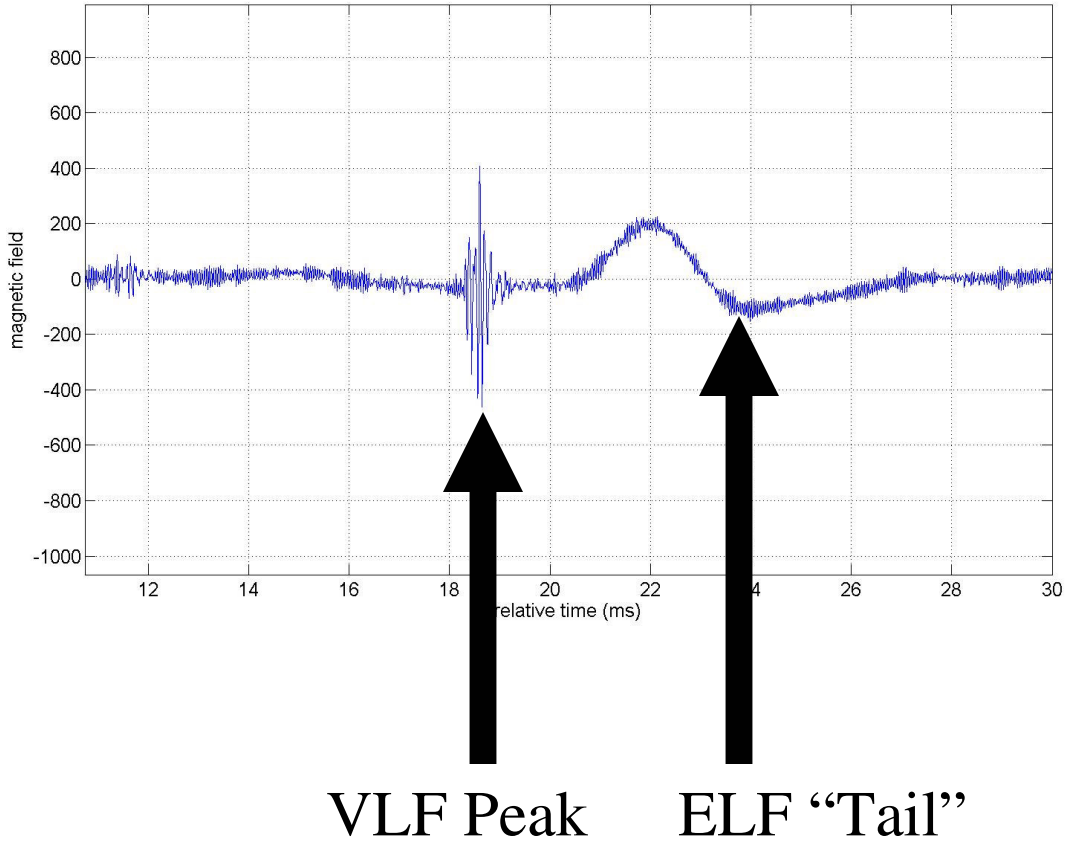


The Stanford VLF Receiver

Palmer Station Monitoring

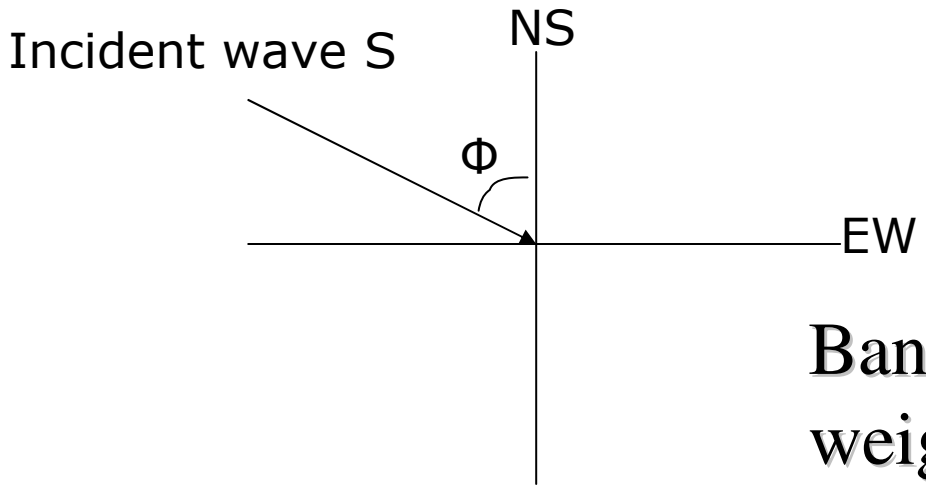


Sferic Characteristics



- VLF peak
  - Mostly TM Modes
  - 8-12 kHz peak energy
- ELF peak
  - Delayed
  - TEM mode
  - Associated with sprites
  - <1kHz energy

Determining Azimuth



Single Frequency:

NS ~ S*cos(Φ)
EW ~ S*sin(Φ)

If same constant of proportionality:

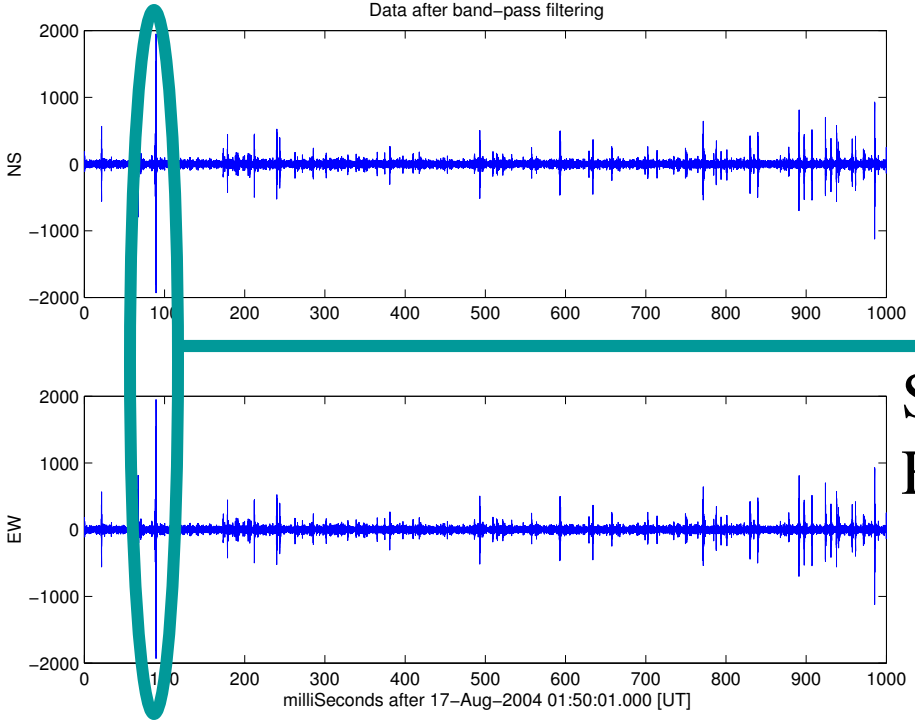
EW/NS = tan(Φ)
Φ = tan^{-1}(EW/NS)

Band of frequencies: use a weighted average

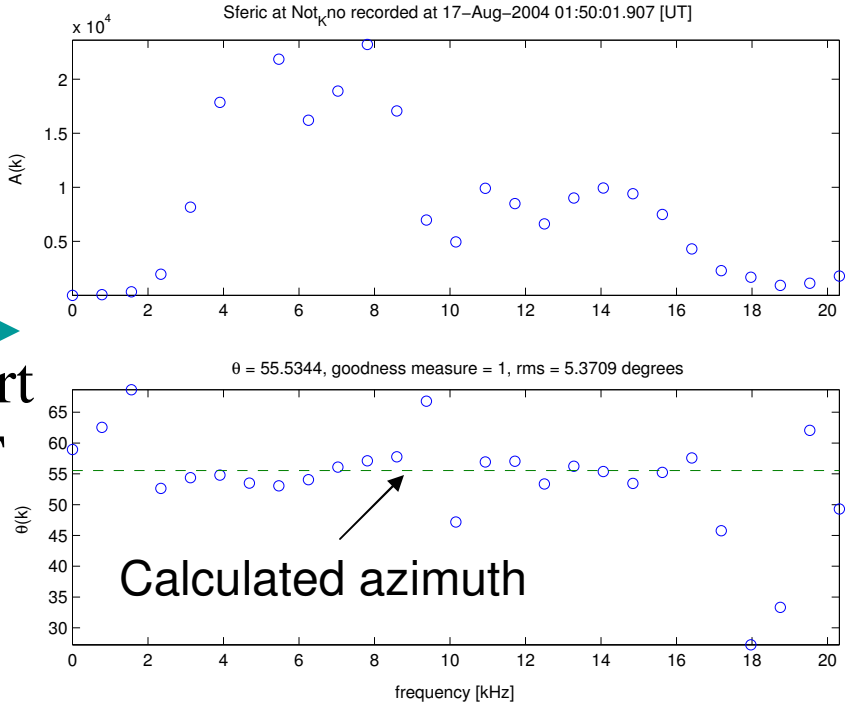
$$\phi \cong \frac{\int_{f_l}^{f_u} \tan^{-1}\left(\left|\frac{EW(f)}{NS(f)}\right|\right)\sqrt{|NS(f)|^2+|EW(f)|^2}\,df}{\int_{f_l}^{f_u}\sqrt{|NS(f)|^2+|EW(f)|^2}\,df}$$

(Introduce a correction factor for misaligned antennas and gain difference)

Determining Azimuth cont'd



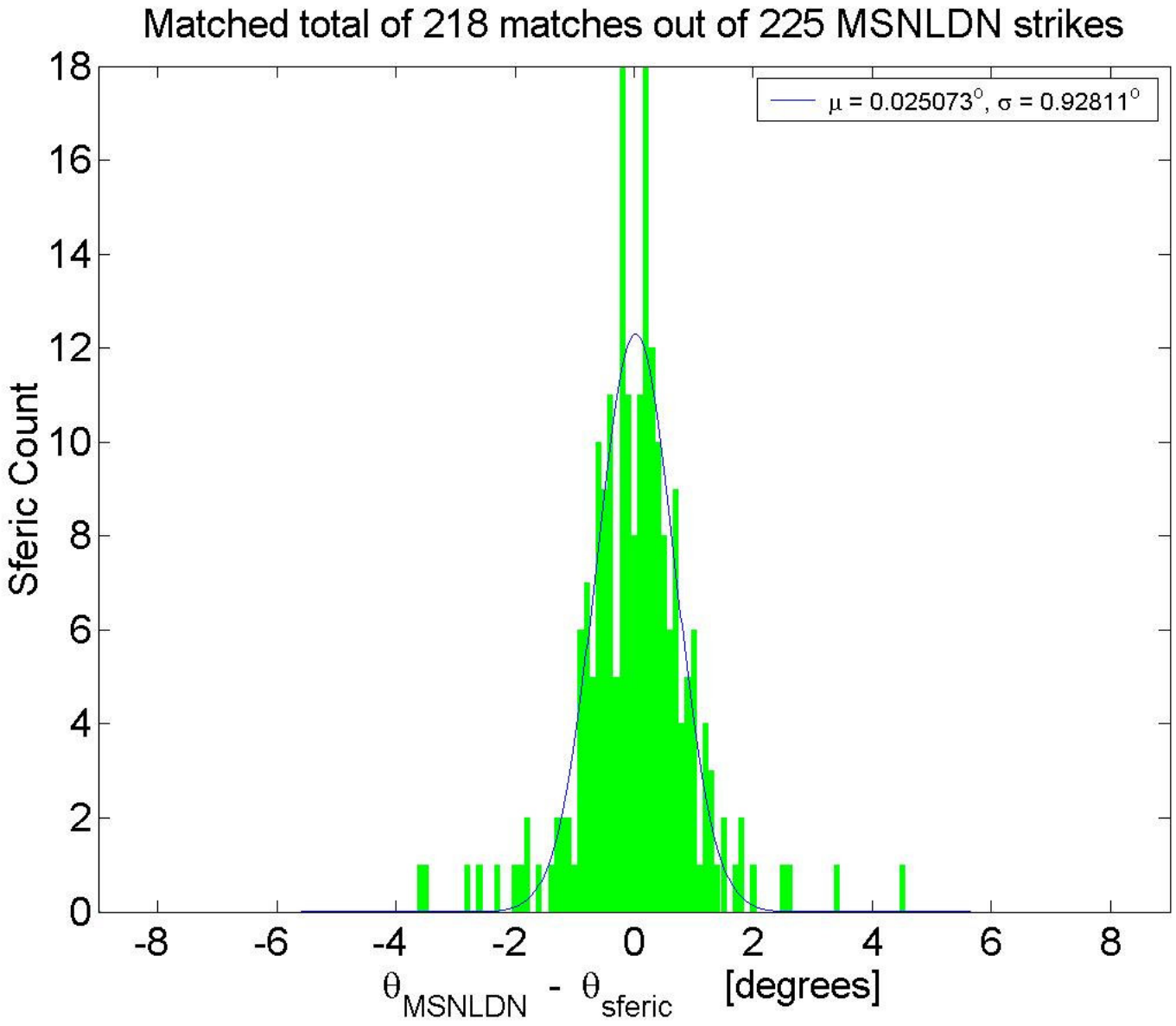
Short FFT



For each frequency, compare magnitude from NS and EW antenna to calculate azimuth, then average over frequency:

$$\phi \approx \frac{\sum_{k=\frac{f_l N}{f_s}}^{\frac{f_u N}{f_s}} \tan^{-1}\left(\left|\frac{EW(\frac{kf_s}{N})}{NS(\frac{kf_s}{N})}\right|\right)\sqrt{|NS(\frac{kf_s}{N})|^2+|EW(\frac{kf_s}{N})|^2}}{\sum_{k=\frac{f_l N}{f_s}}^{\frac{f_u N}{f_s}} \sqrt{|NS(\frac{kf_s}{N})|^2+|EW(\frac{kf_s}{N})|^2}}$$

Comparison to NLDN



TGF-Lightning Association Palmer Data Analysis Methods

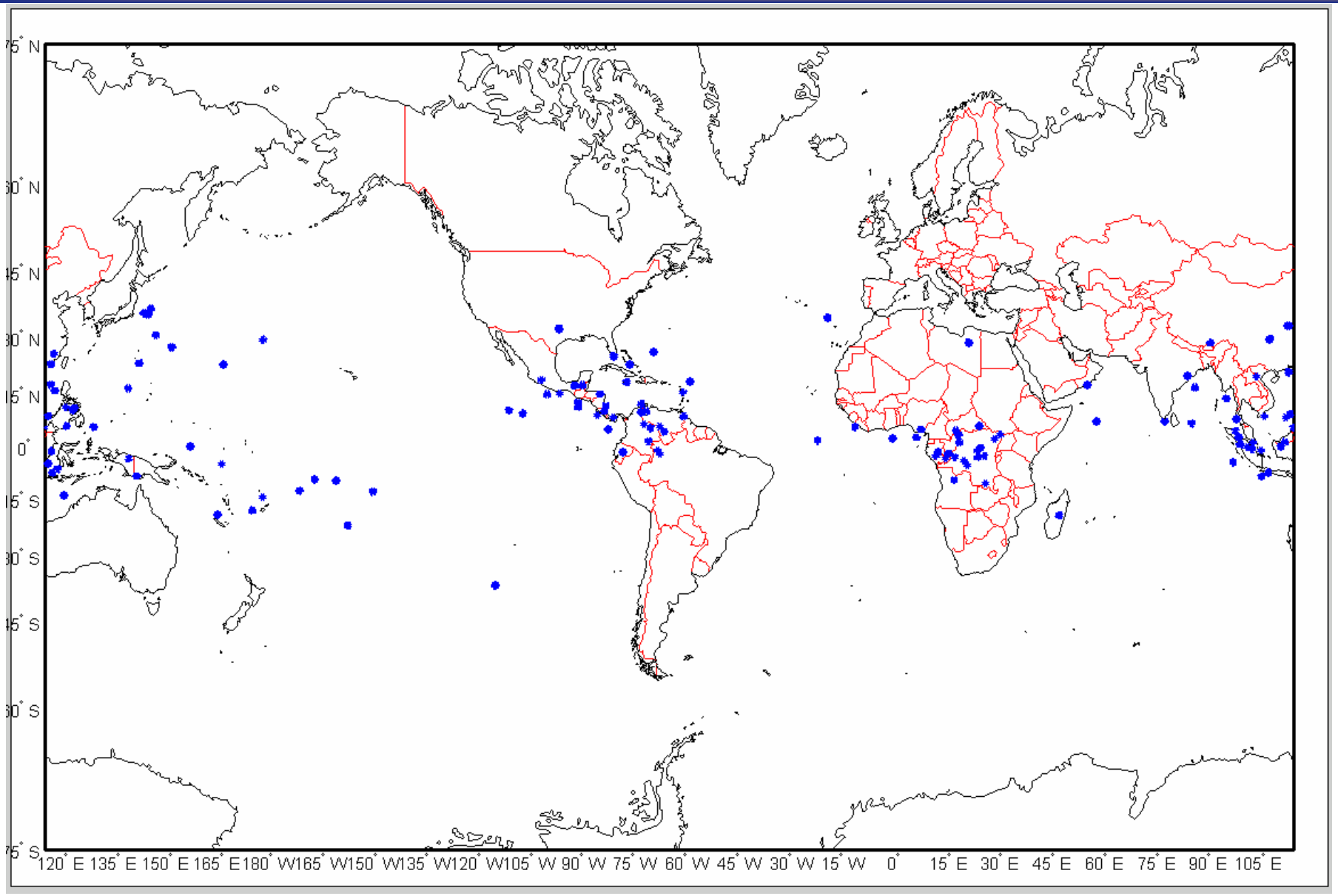
<u>Characterictics of Lightning-TGF Match</u>

- Time coincidence: Expected sferic arrival time calculated
- Space coincidence: Direction finding from two antennas
- Properties of sferic (radiation from lighting)
  - Fast burst in VLF range
  - Delayed tail in ELF range
- Presence of thunderstorm in area

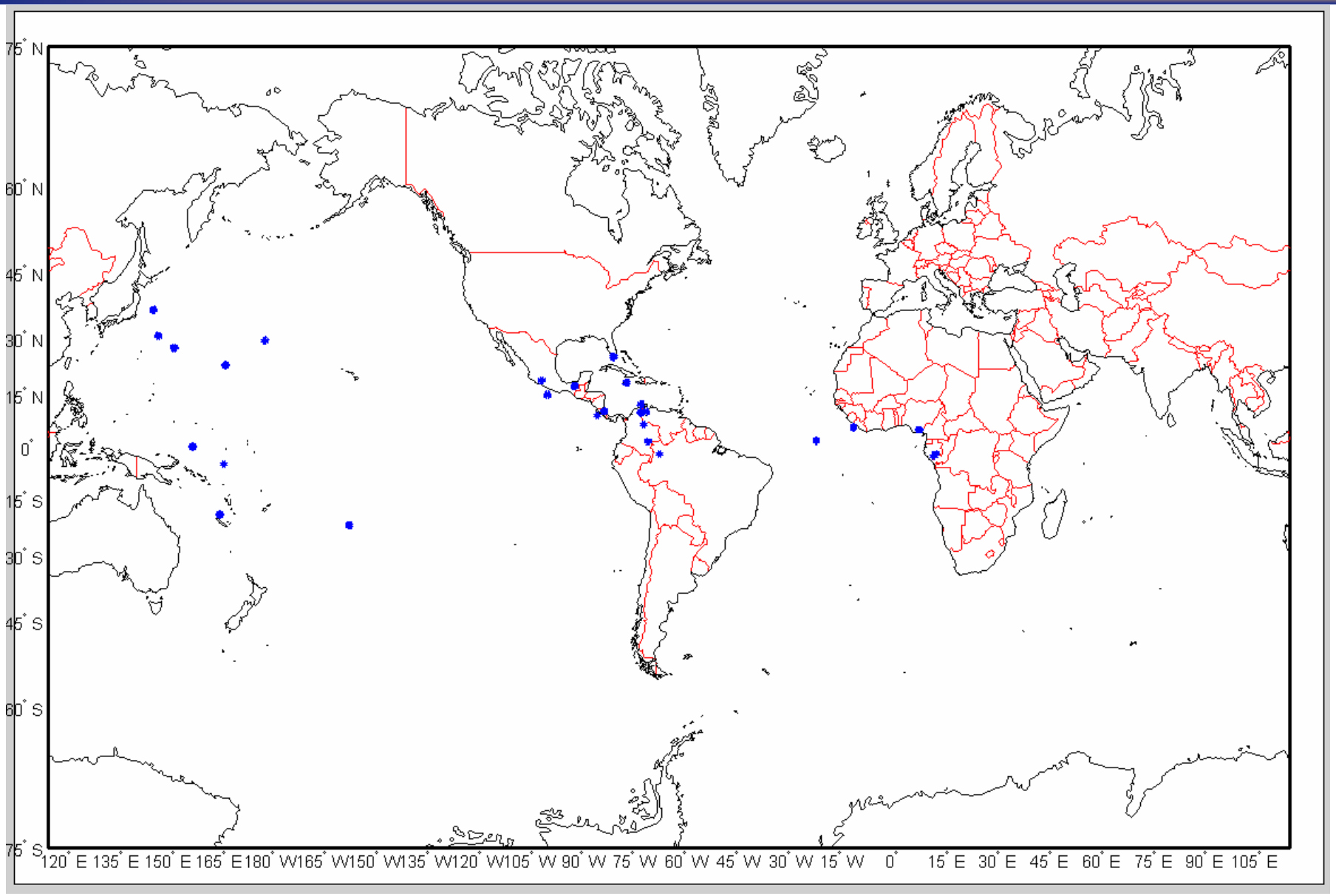
<u>Search Criteria</u>

- Footprint of RHESSI taken as 600 km radius
- Differences in propagation time accounted for
- Error in direction finding
- Acceptance window: +/- 4ms time, +/- 6° arrival direction

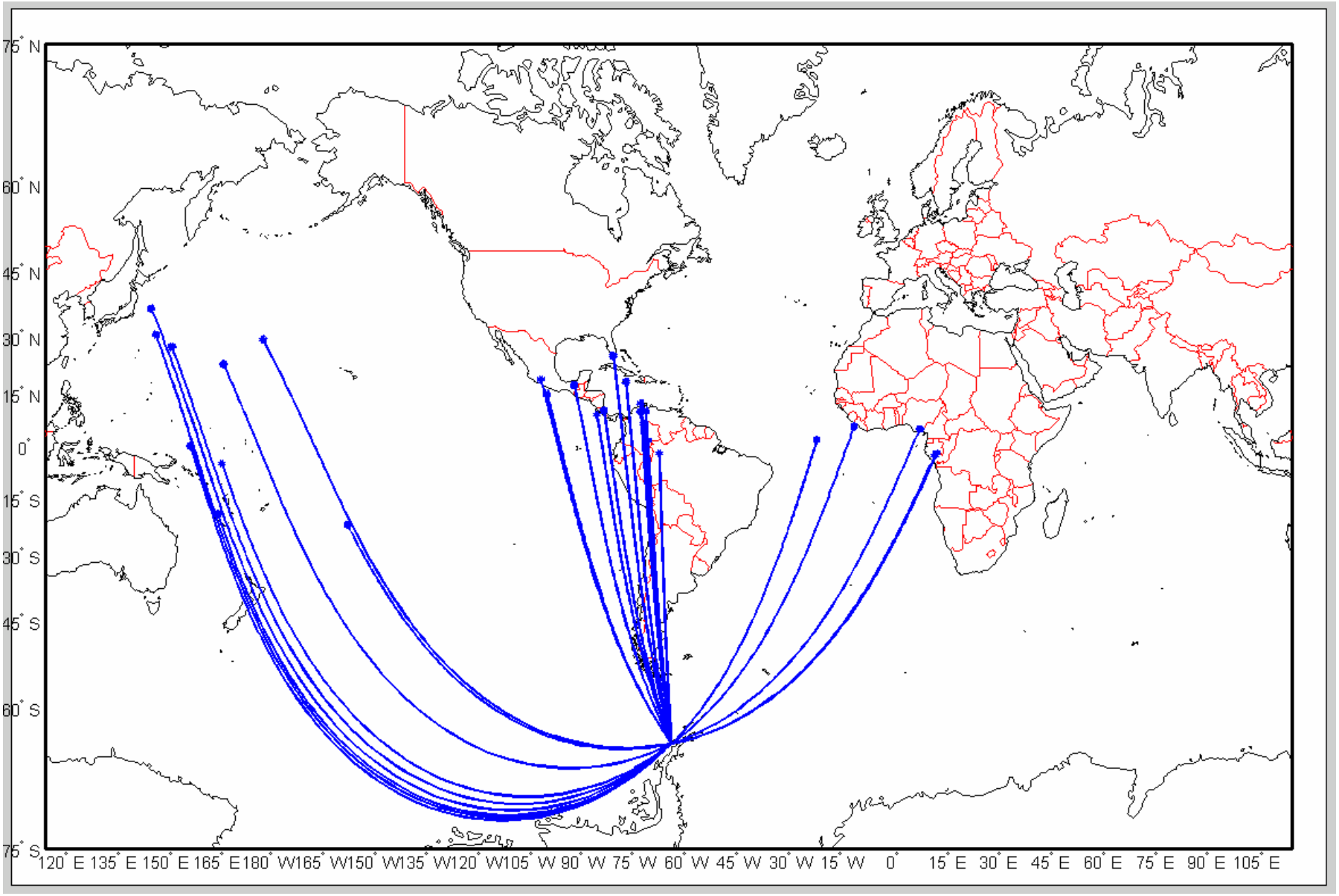
128 Total RHESSI Cases



24 Cases with Palmer Data



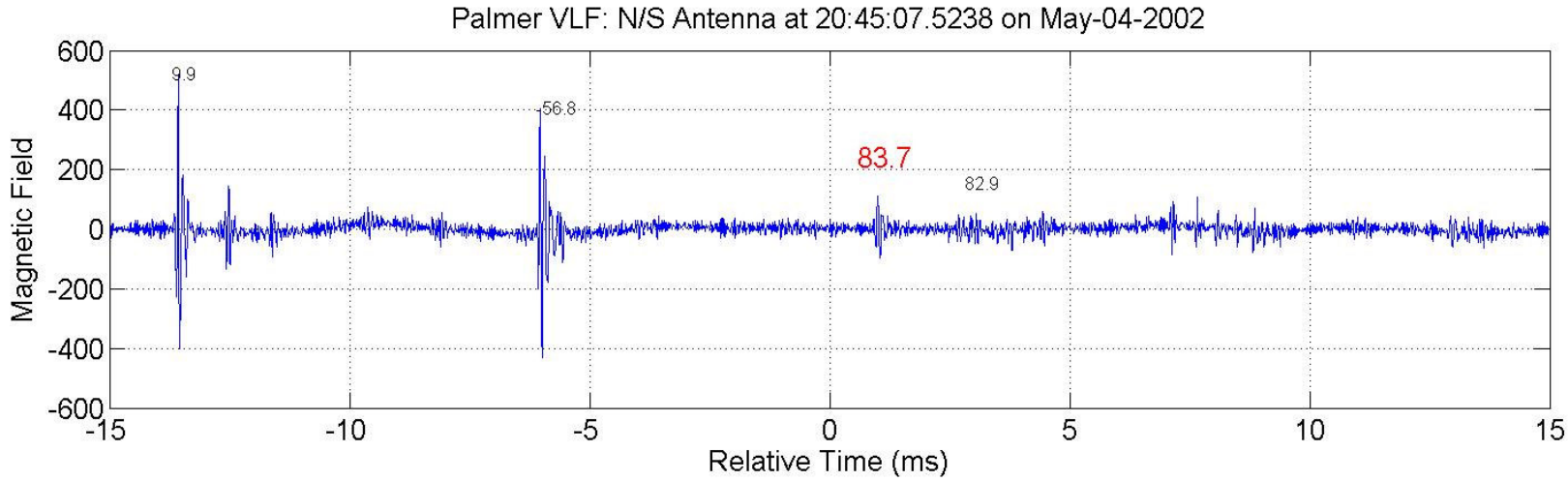
No Propagation Paths Over Ice

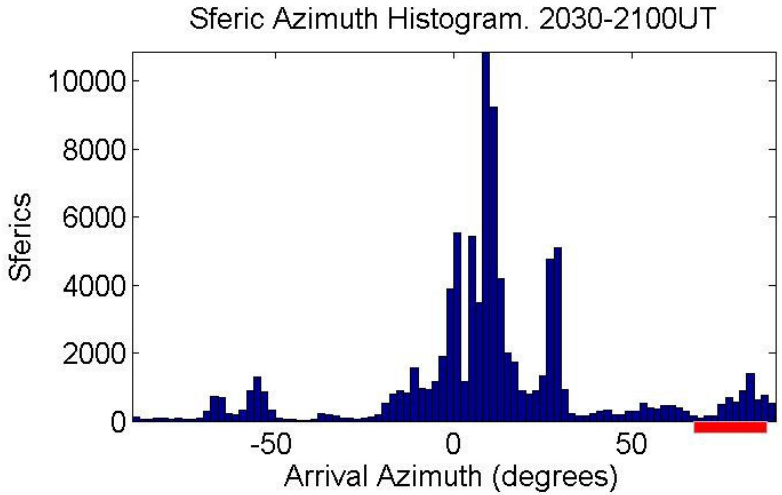


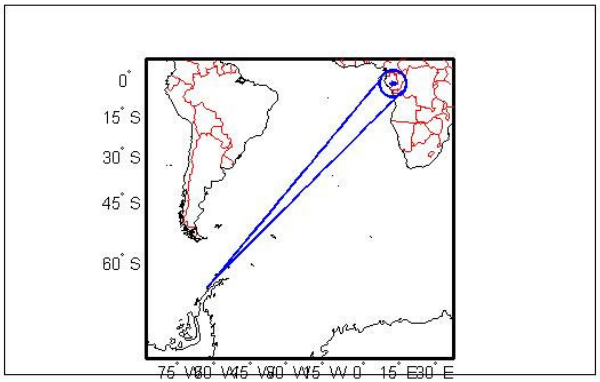
Initial Assumptions

- TGF propagates directly upward
  - Emission is in fact likely to be along B
- TGF can originate from anywhere within 600km radius of footprint
- Altitude of generation ~50km

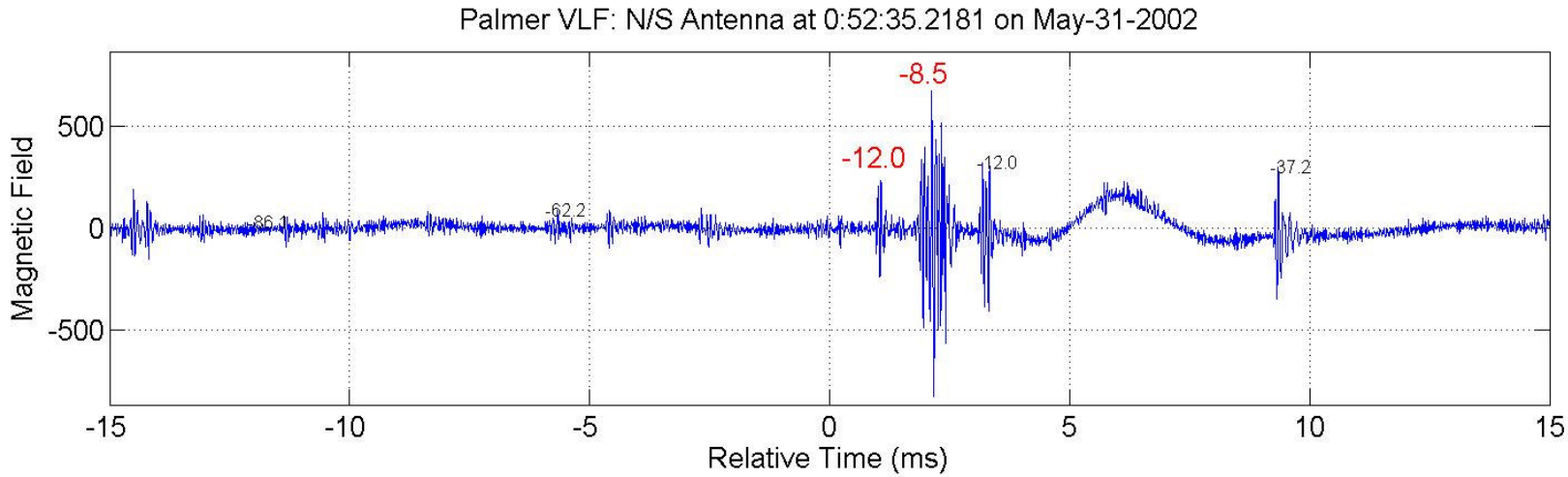
Good Sferic Match Case 1

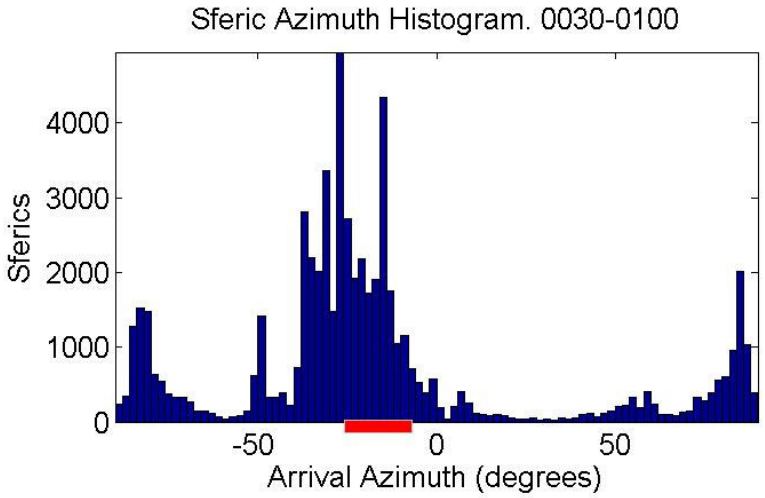


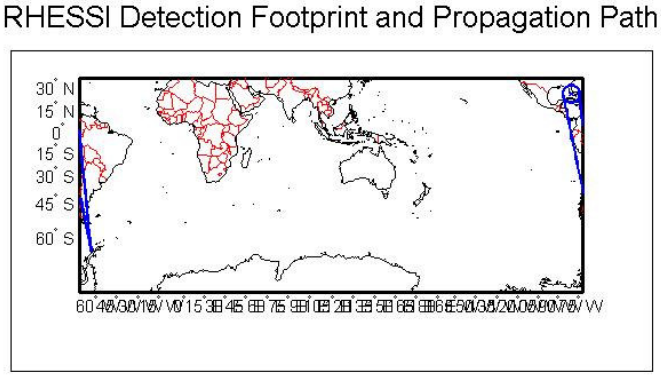




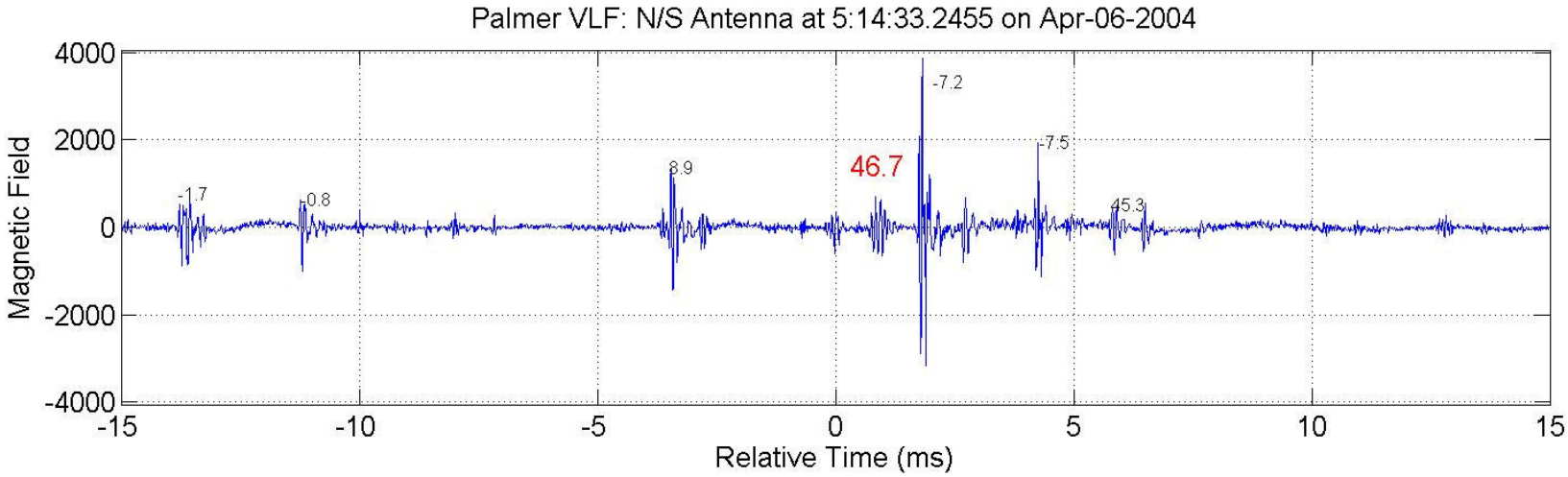
Good Sferic Match Case 2

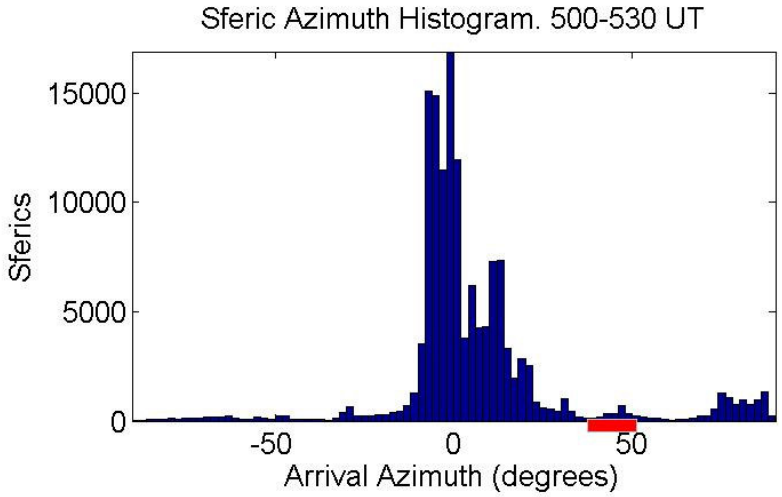


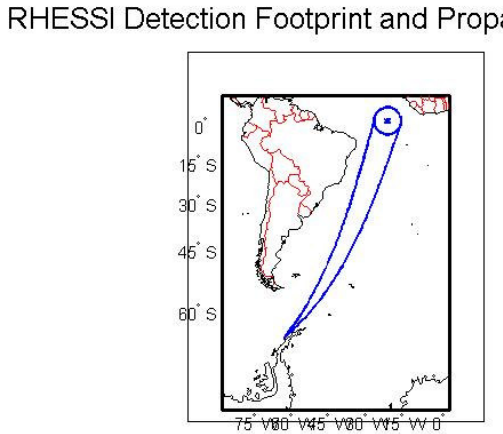




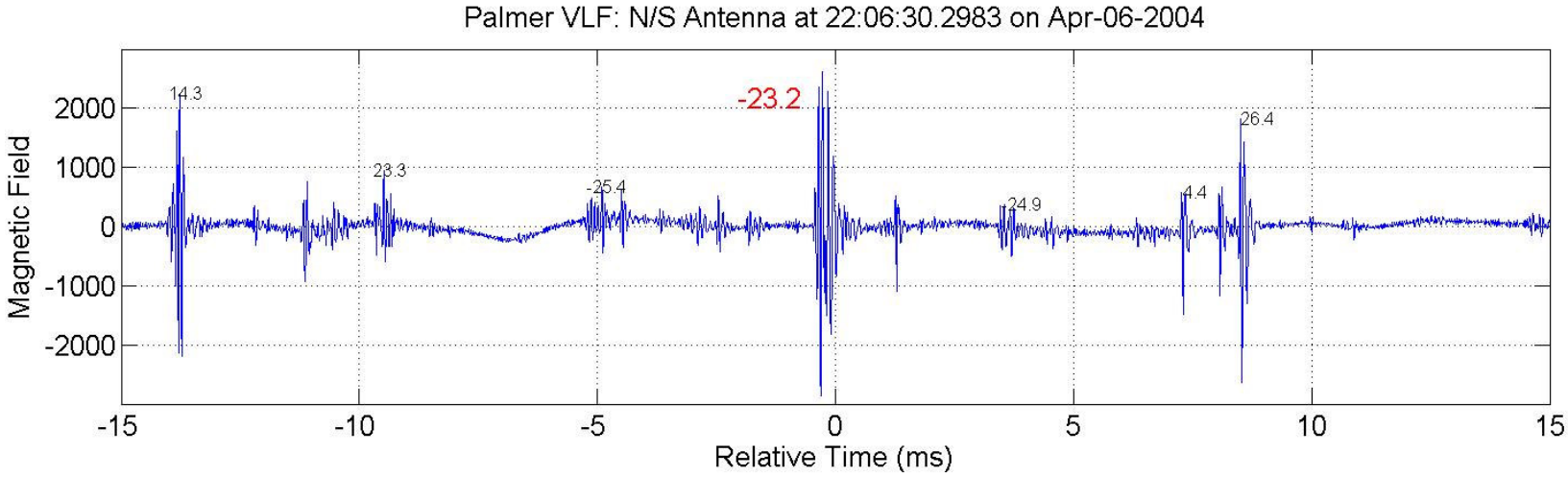
Good Sferic Match Case 3

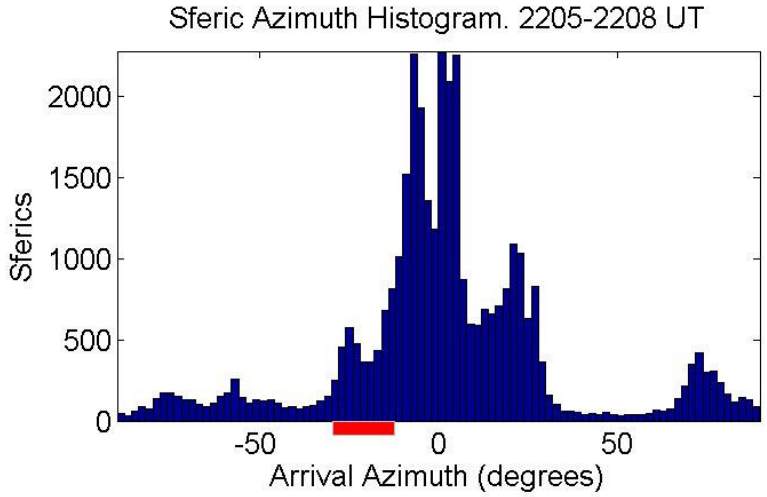


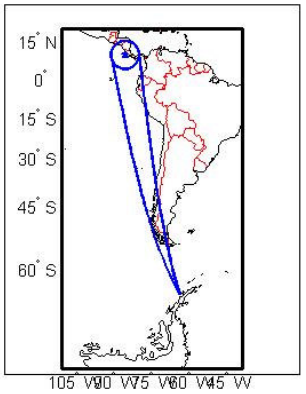




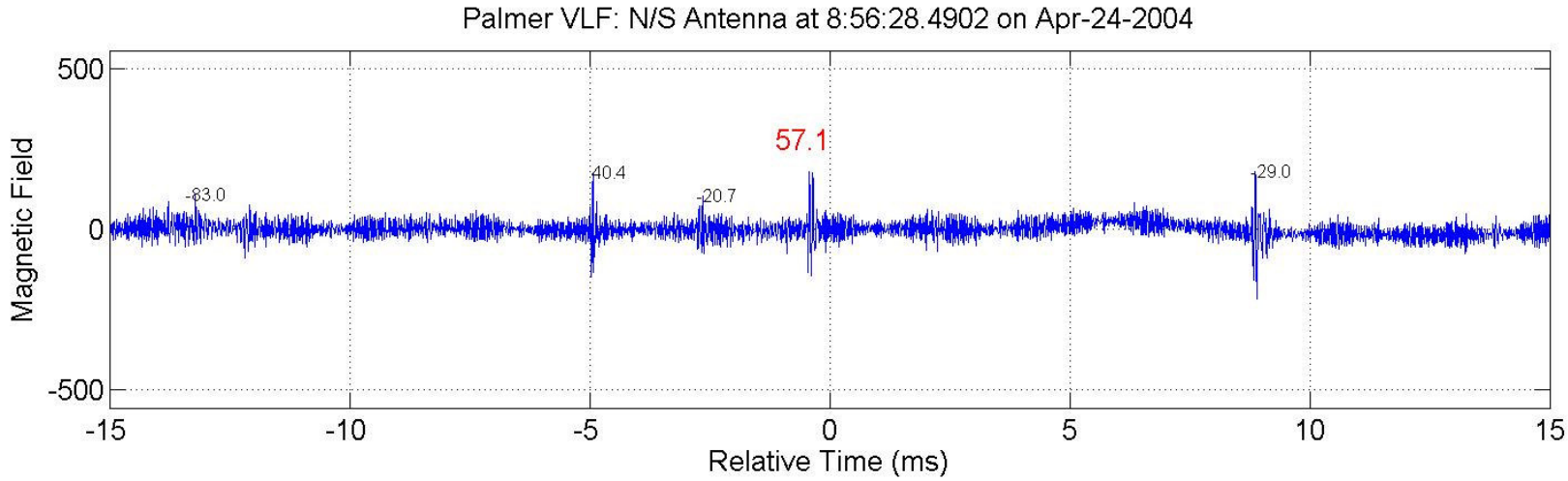
Good Sferic Match Case 4

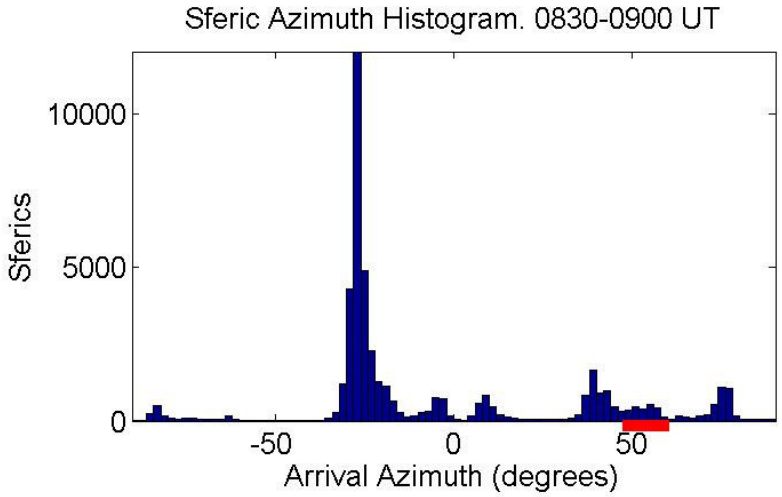


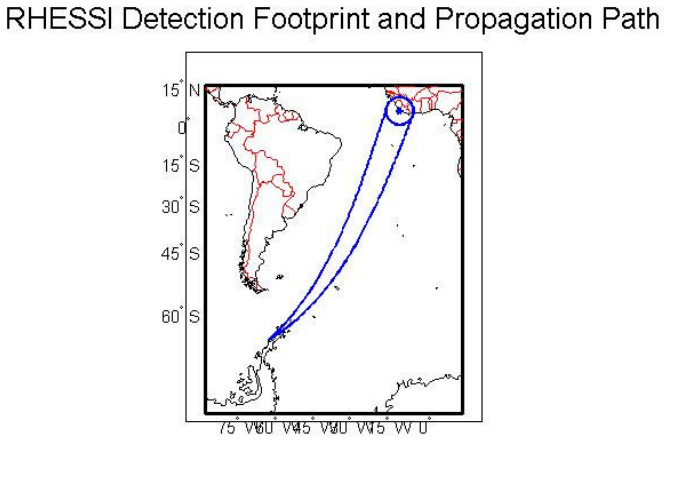




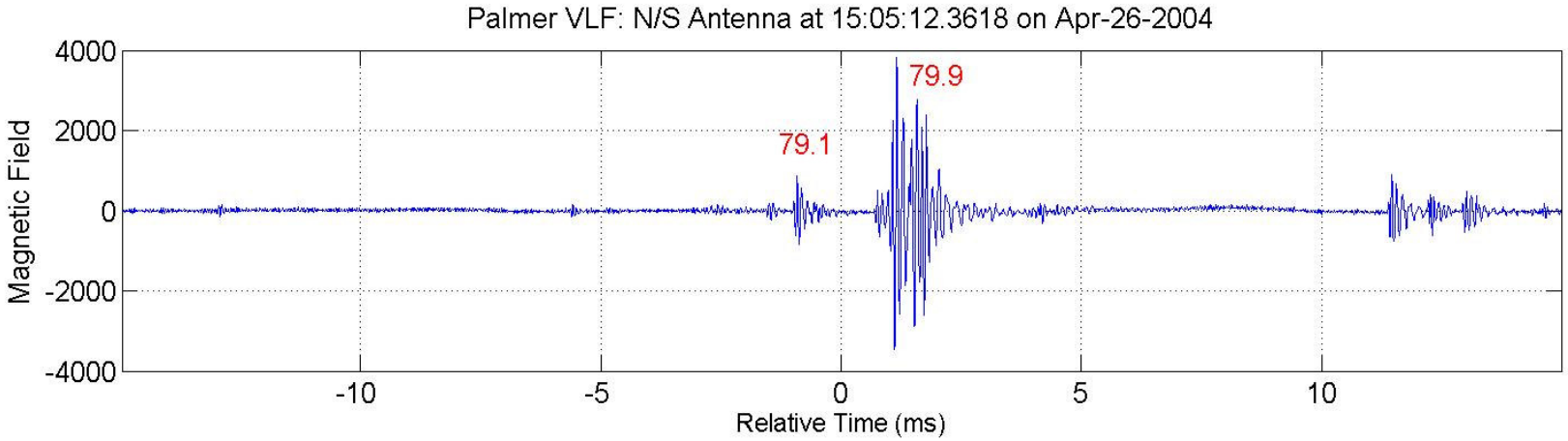
Good Sferic Match Case 5

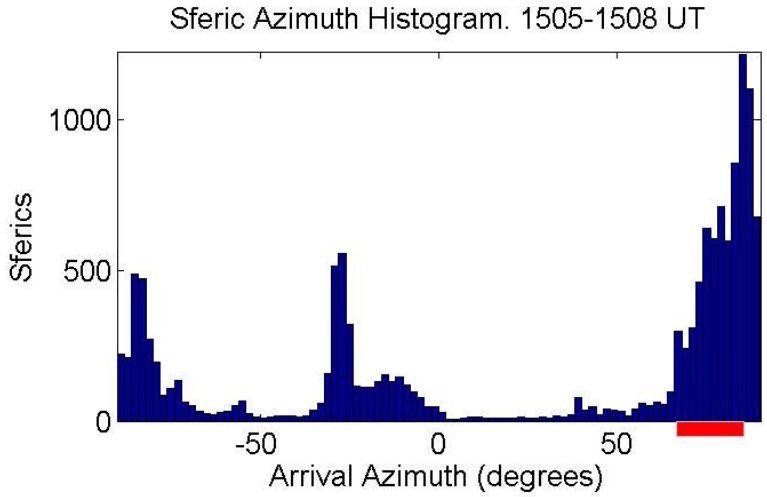


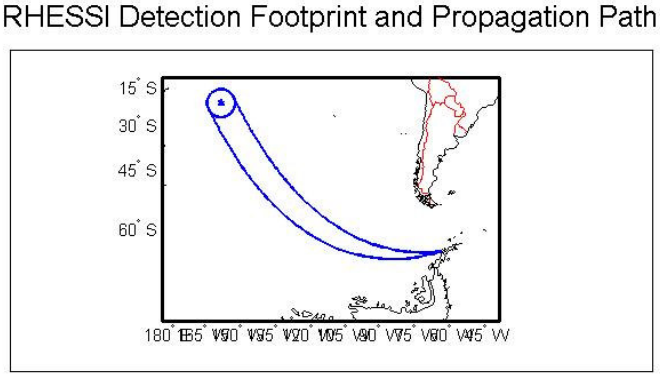




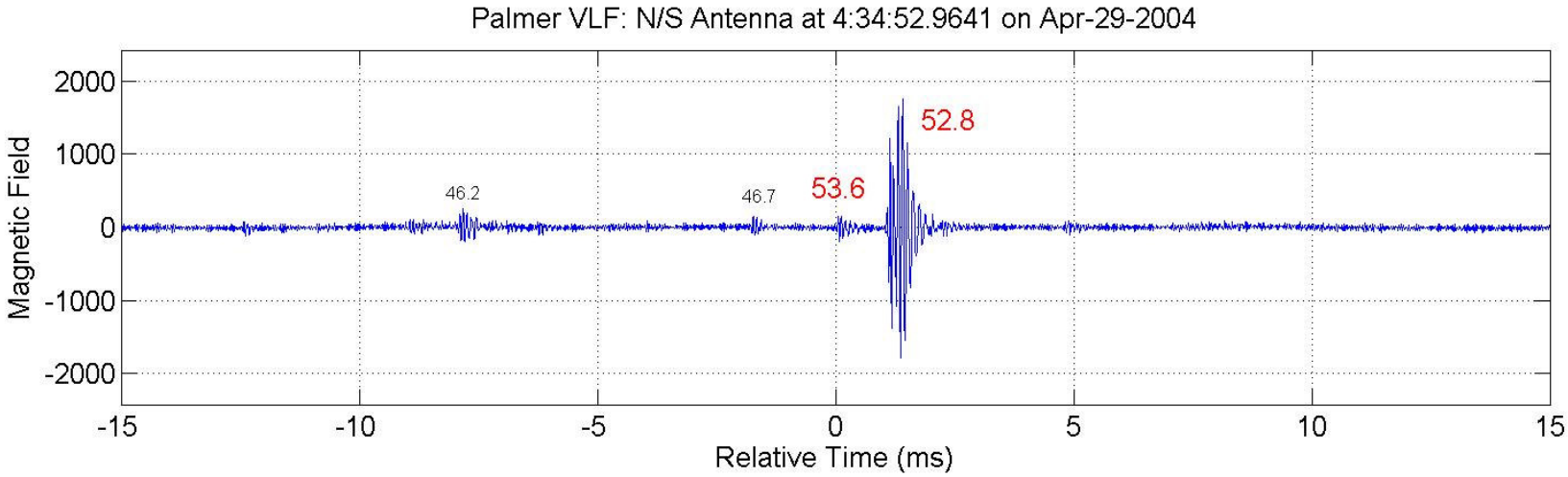
Good Sferic Match Case 6

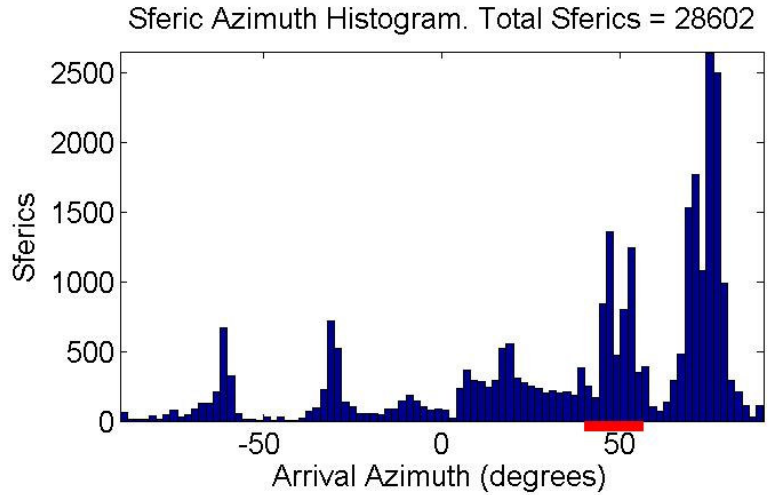


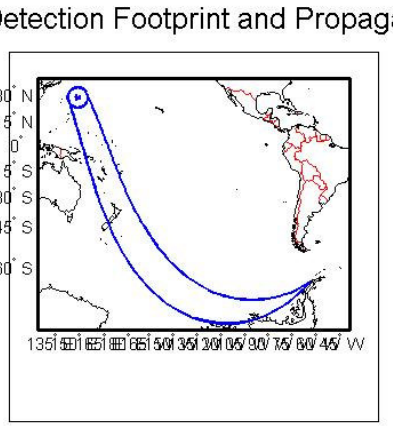




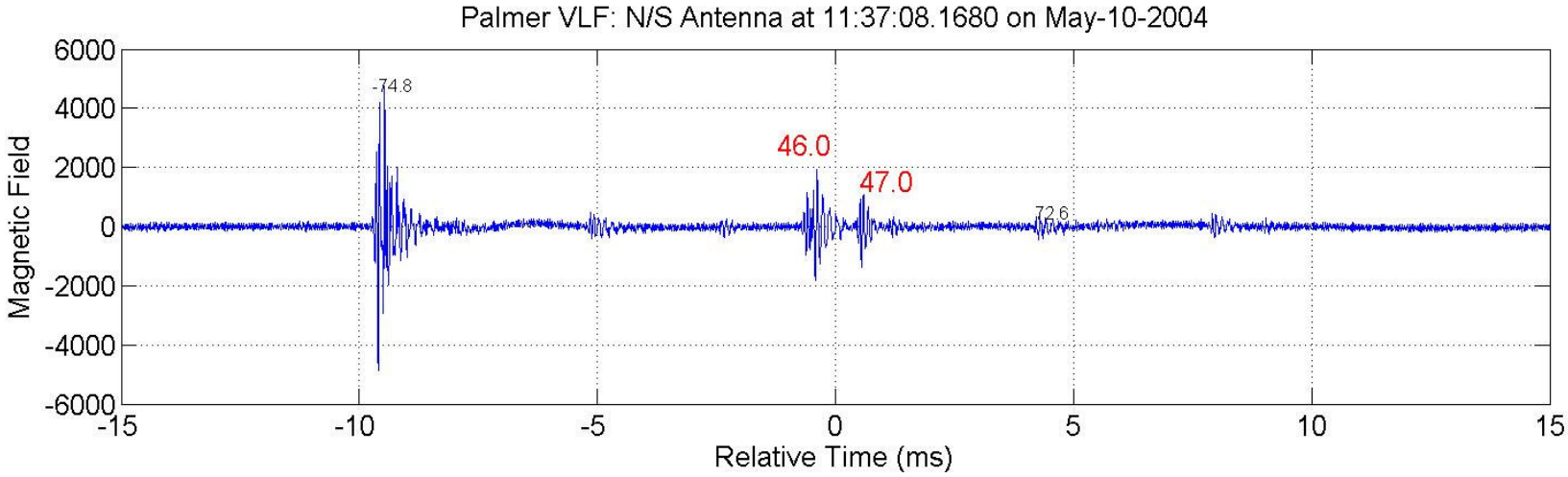
Good Sferic Match Case 7

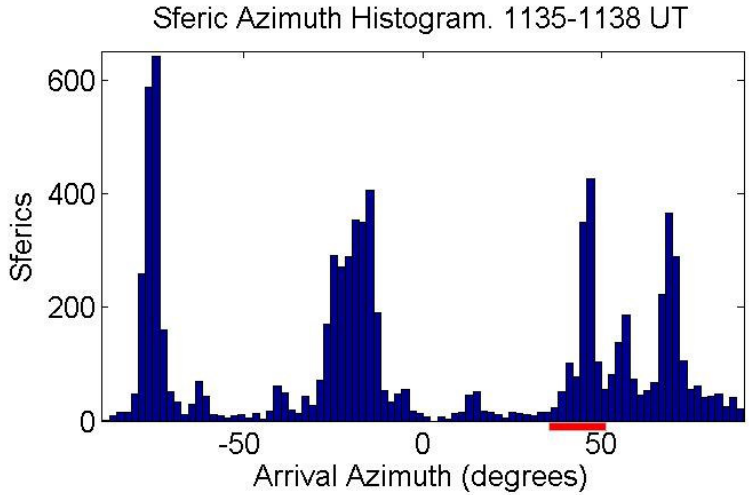


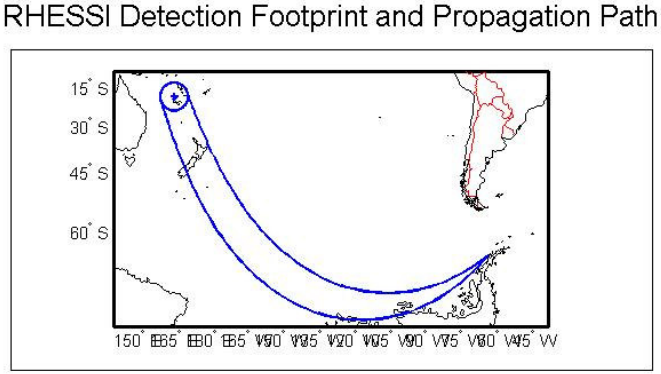




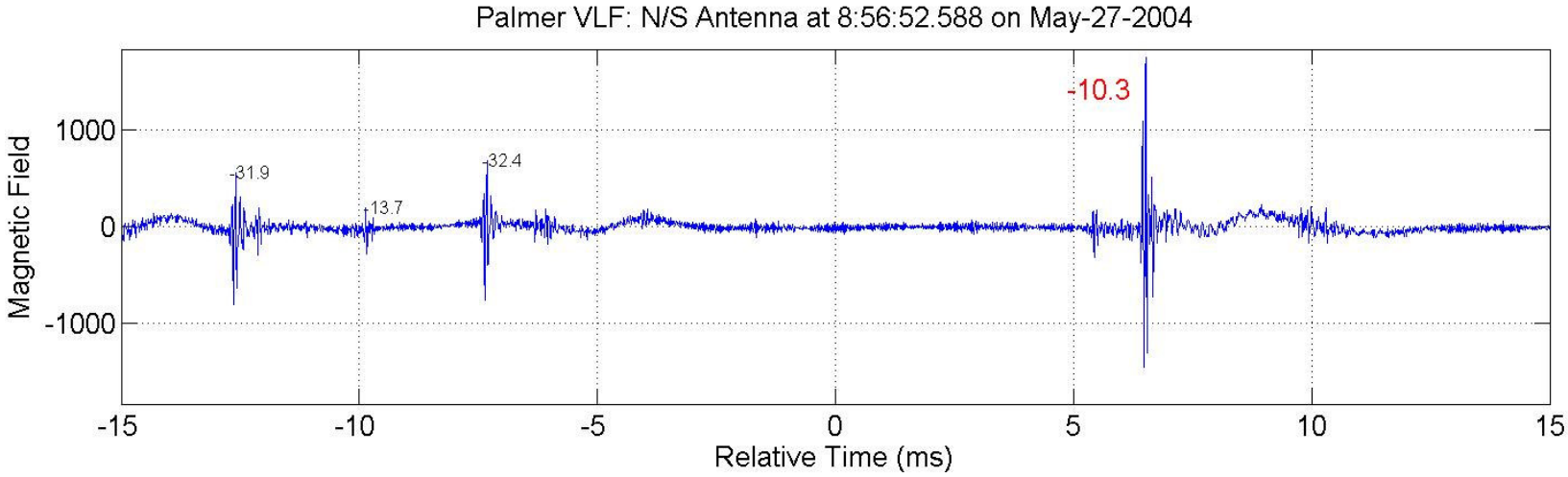
Good Sferic Match Case 8

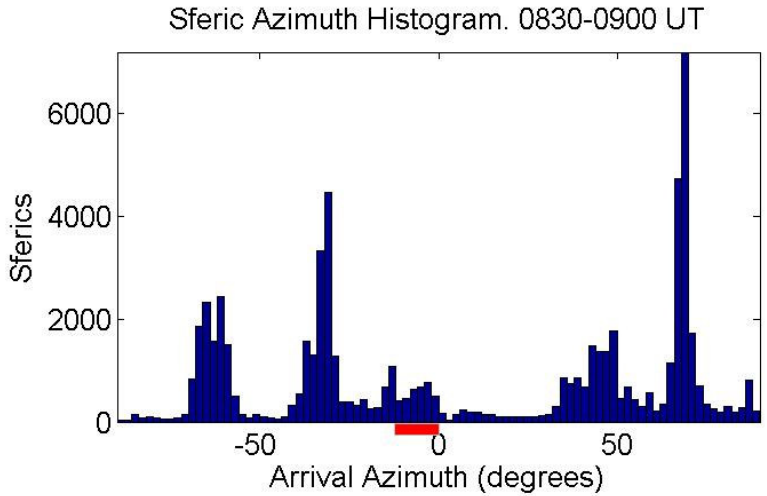


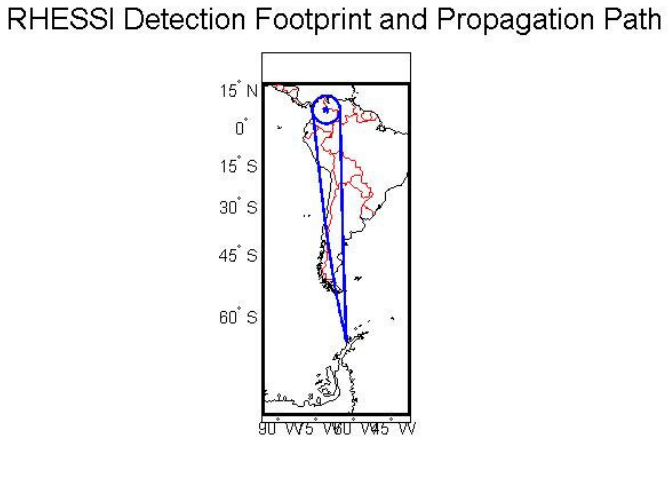




Good Sferic Match Case 9

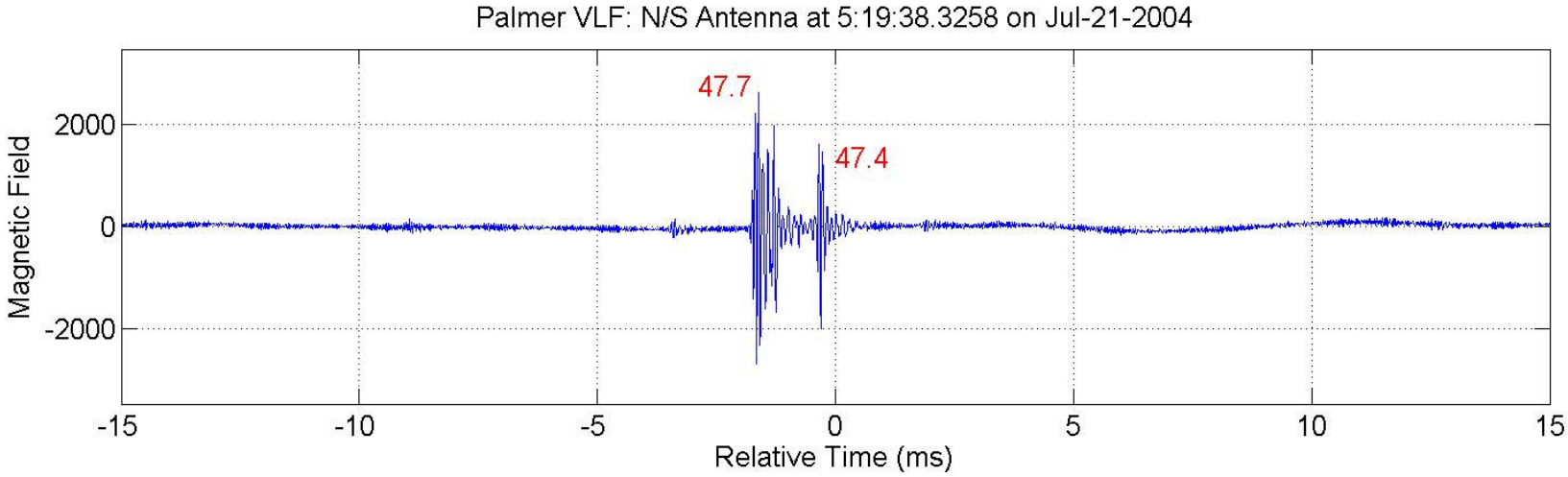


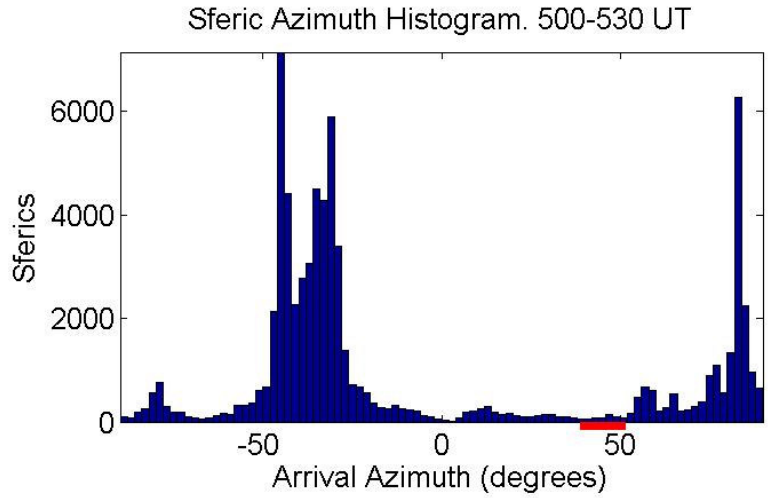


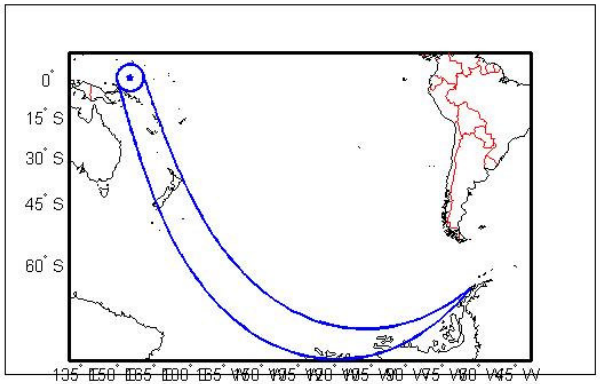


Late sferic explained by B field propagation

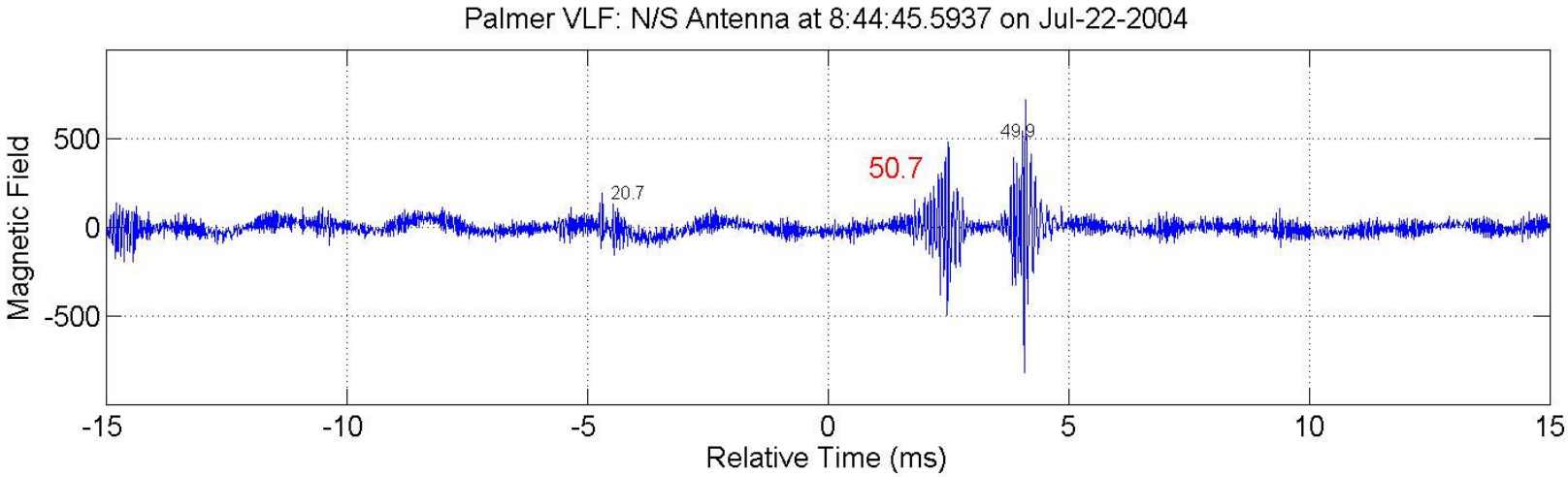
Good Sferic Match Case 10



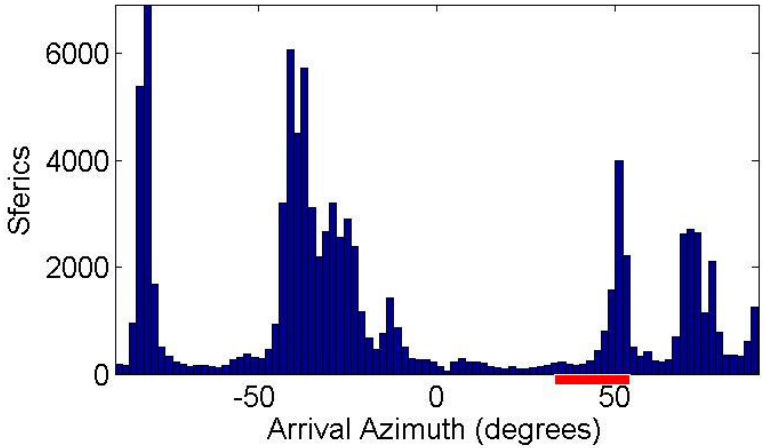




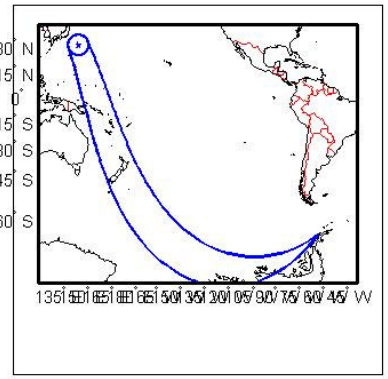
Good Sferic Match Case 11



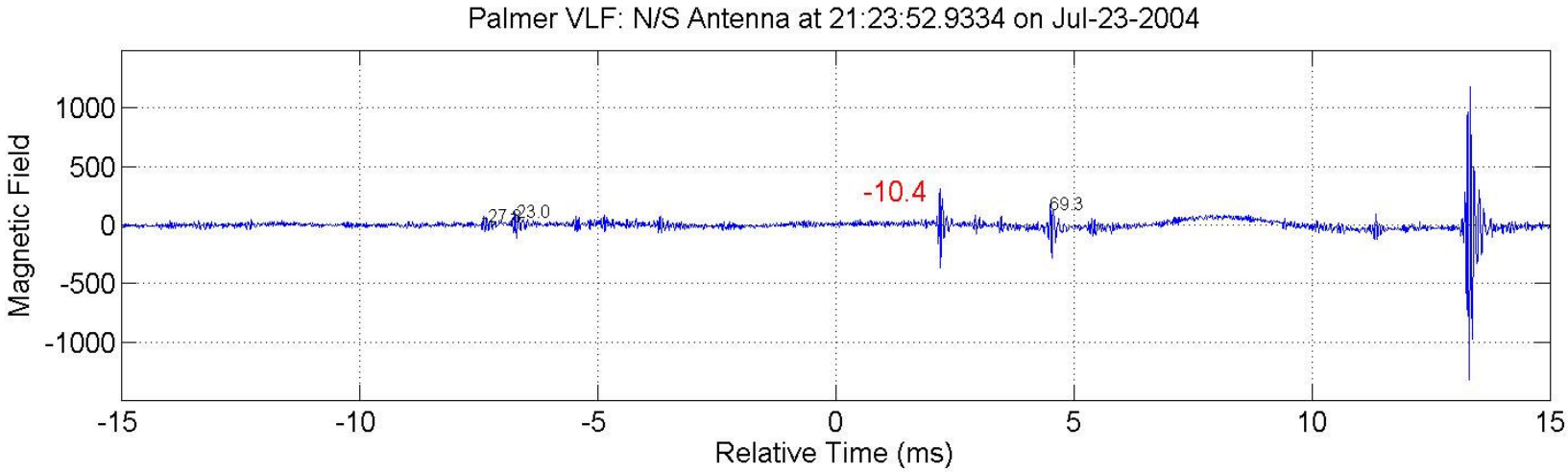
Sferic Azimuth Histogram. 830-900 UT

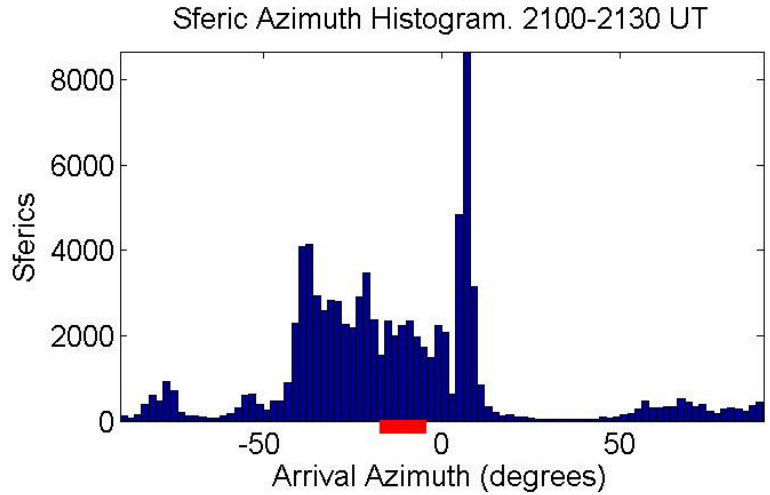


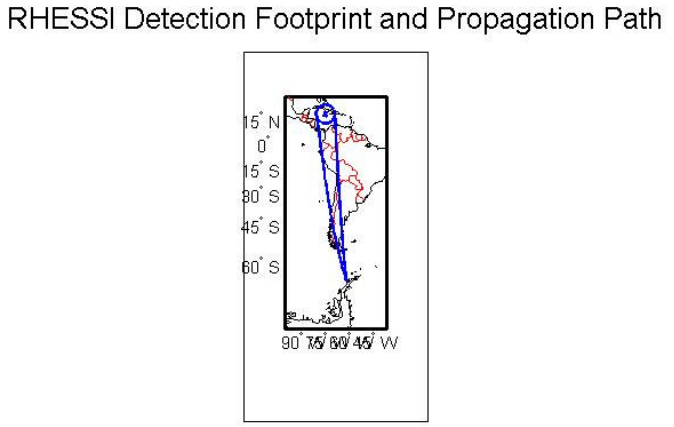
RHESSI Detection Footprint and Propagation Path



Good Sferic Match Case 12

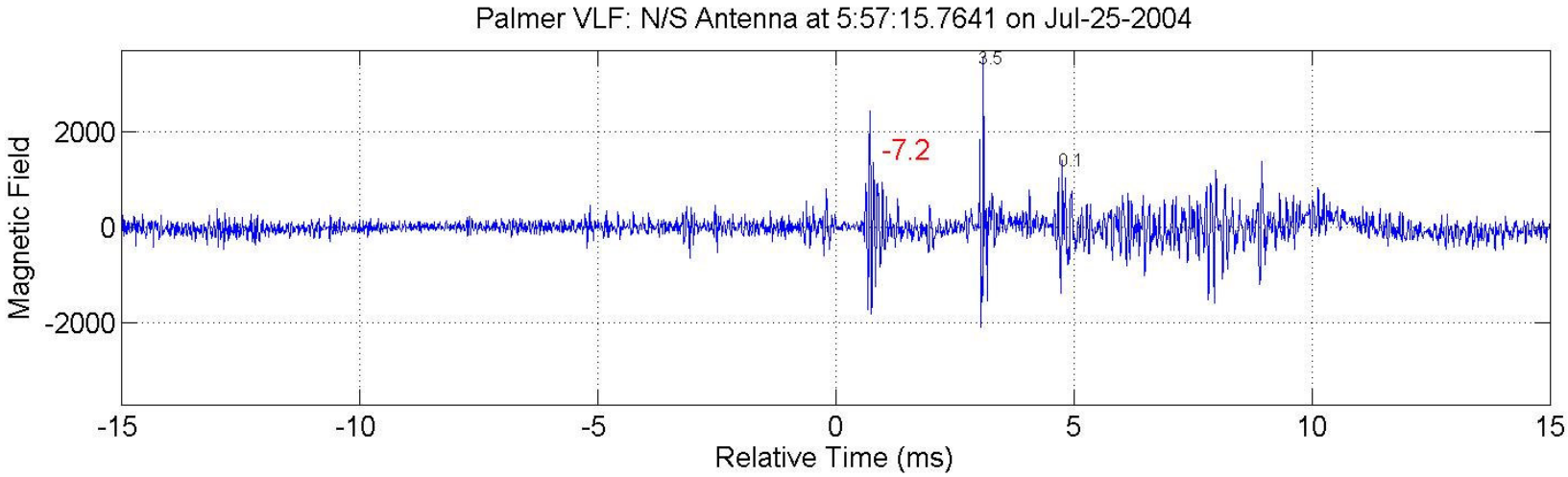


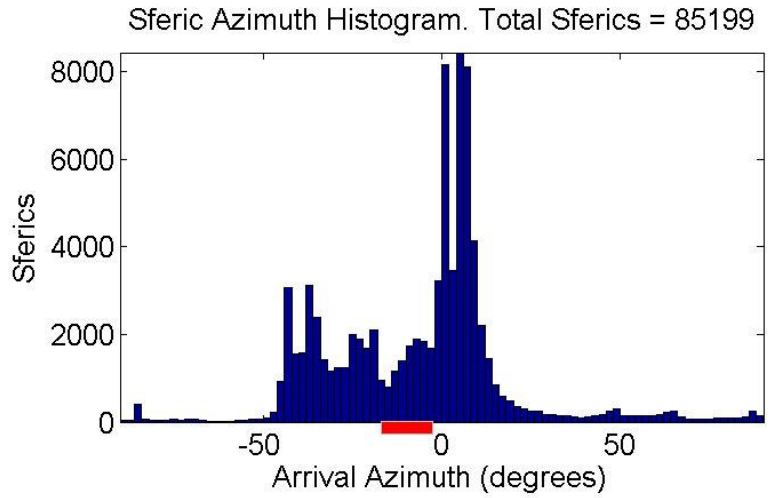


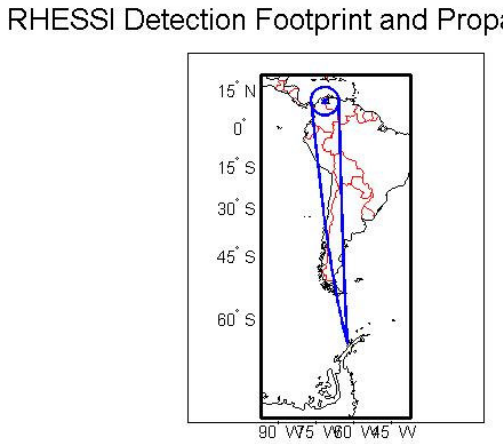


Late sferic explained by B field propagation

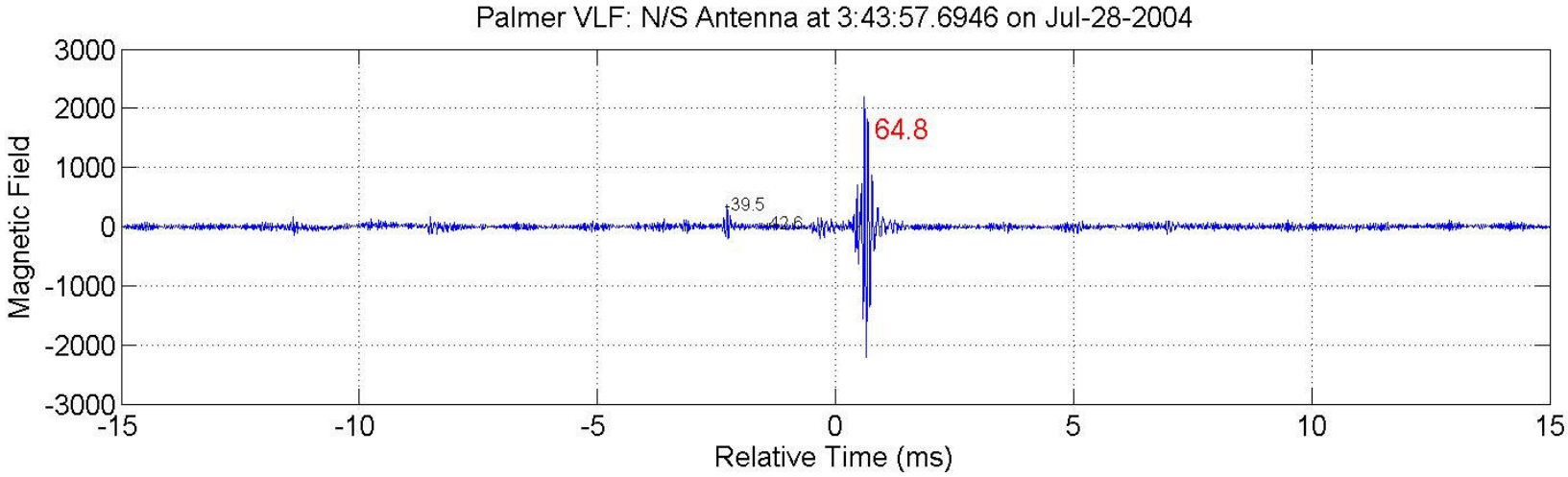
Good Sferic Match Case 13

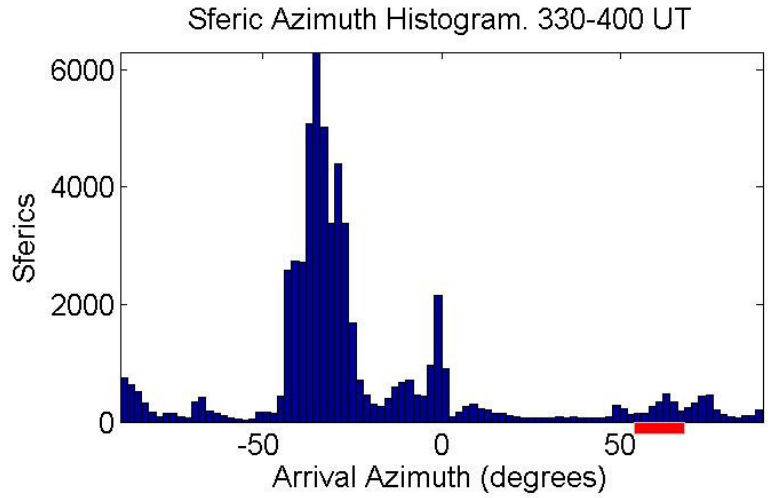


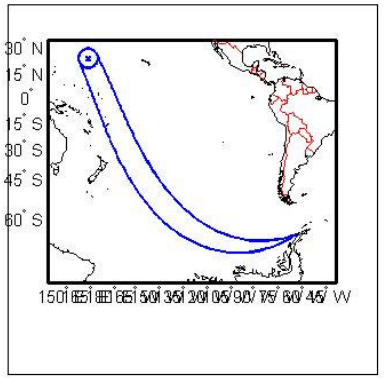




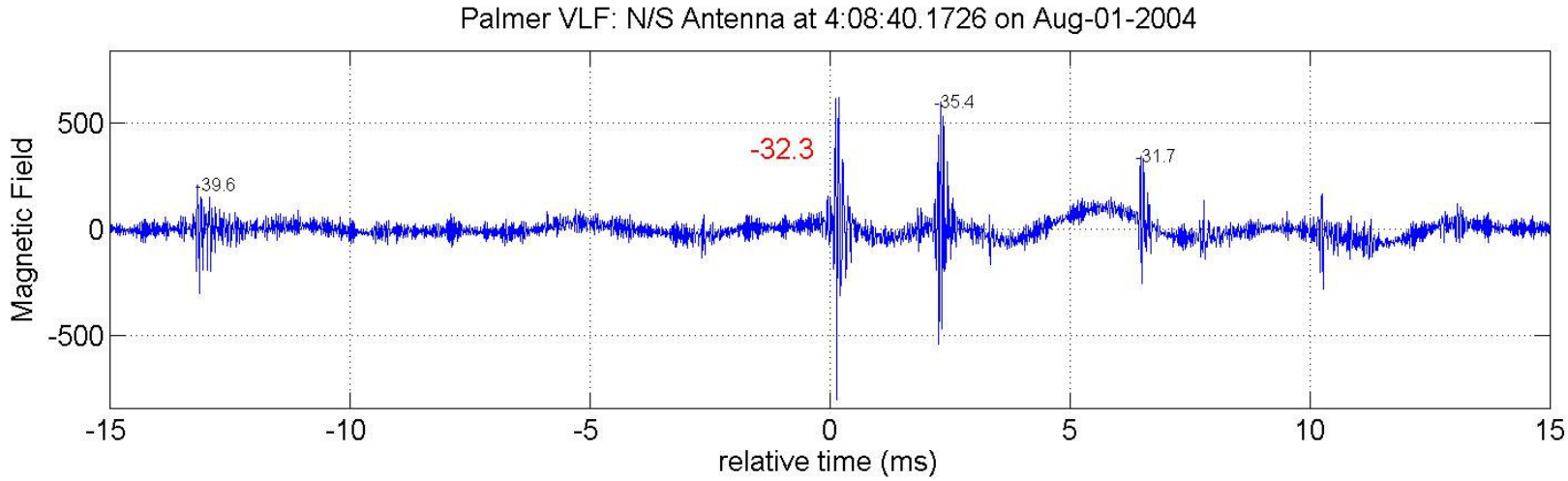
Good Sferic Match Case 14

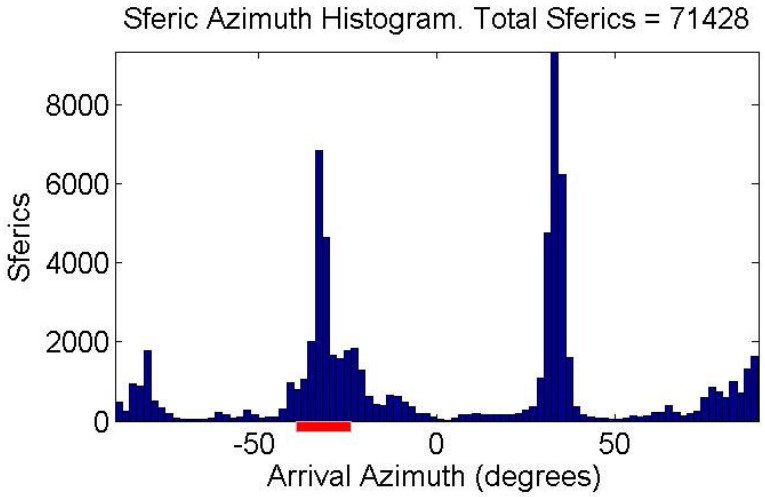


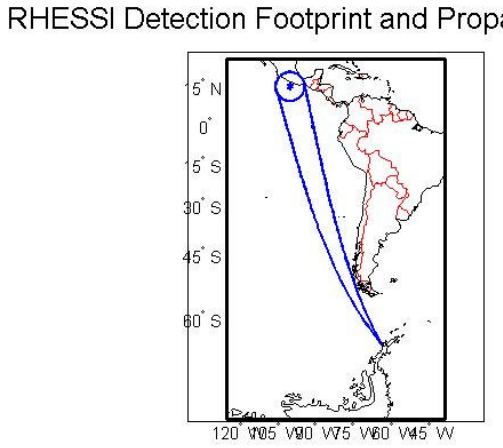




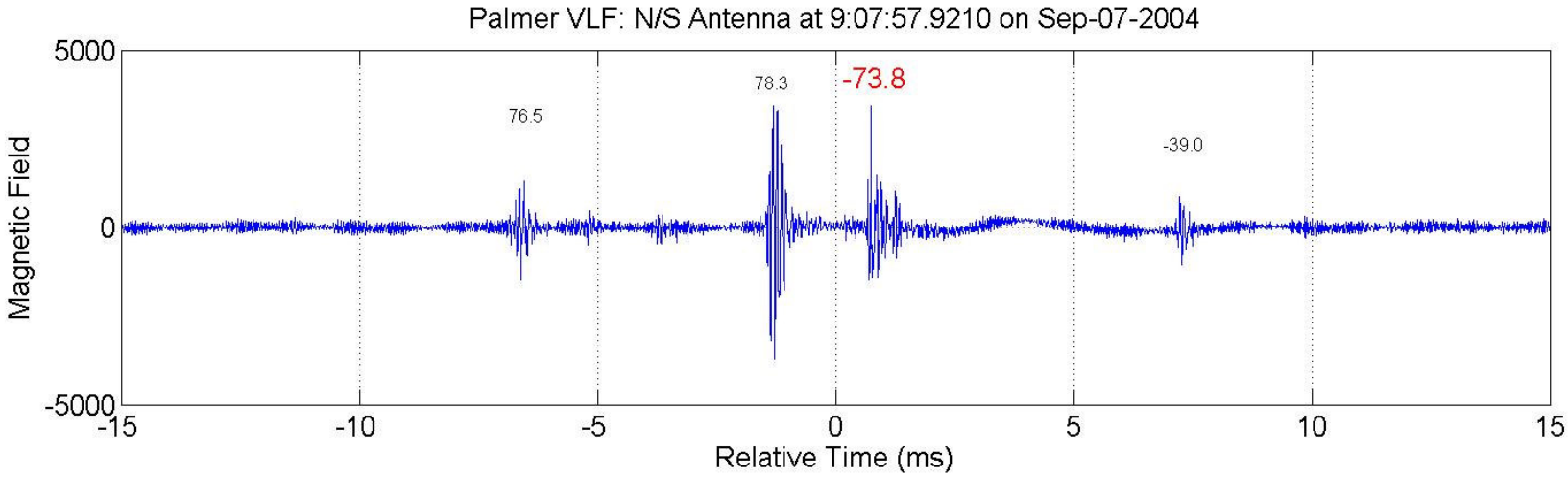
Good Sferic Match Case 15

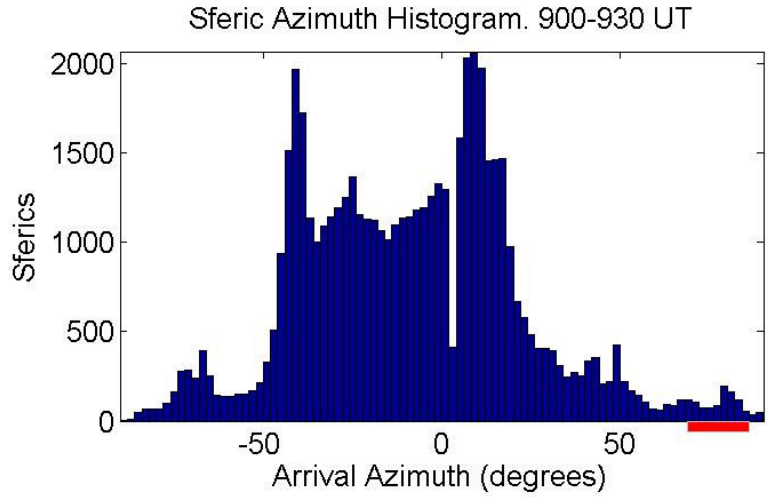


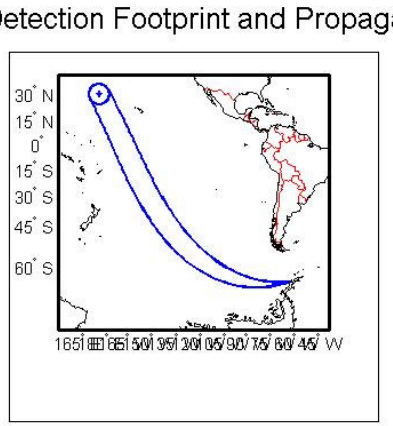




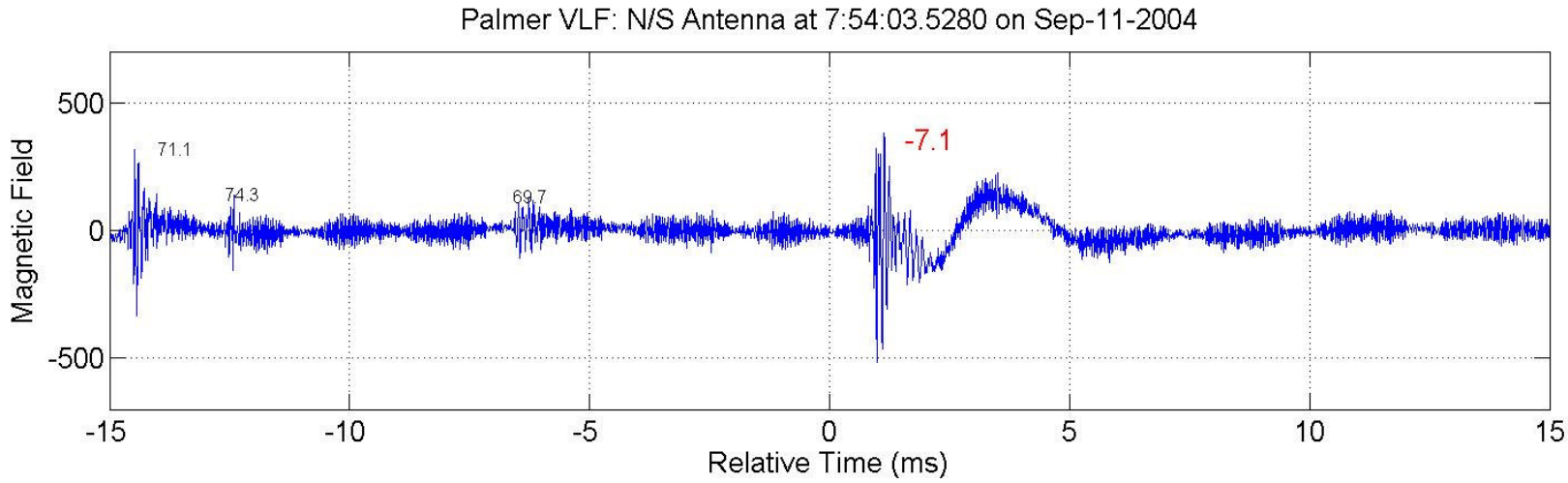
Good Sferic Match Case 16

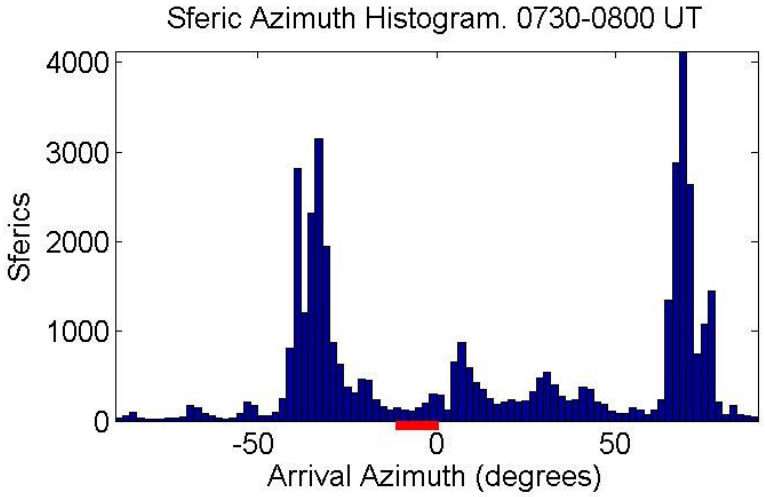


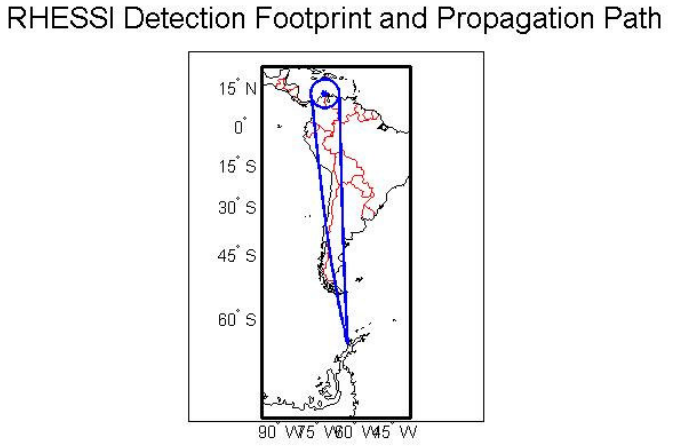




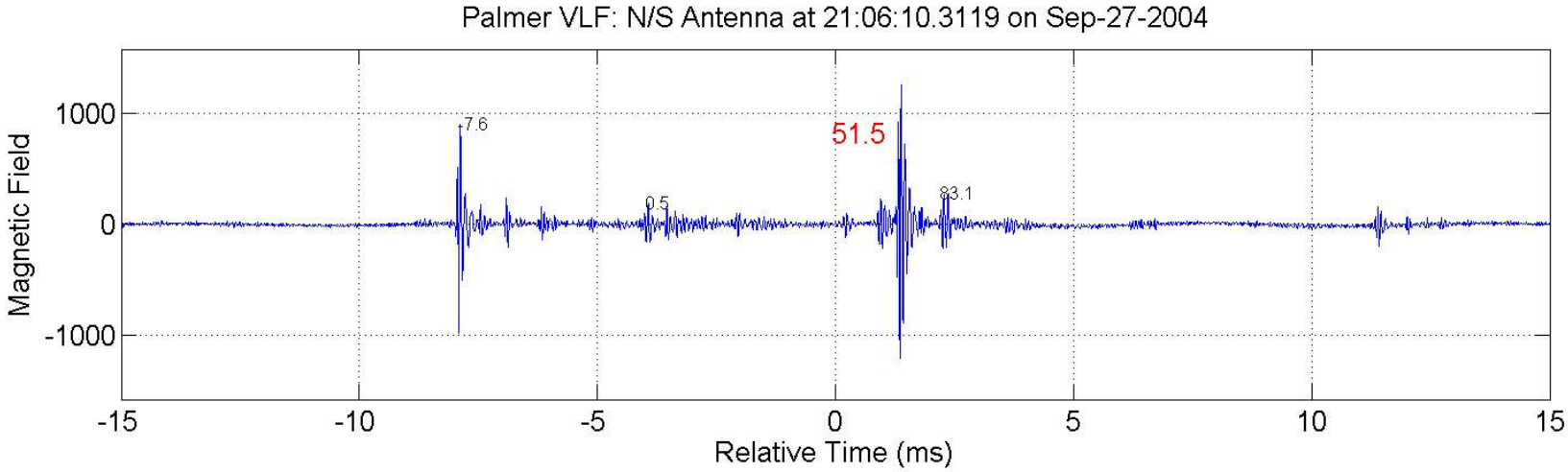
Good Sferic Match Case 17

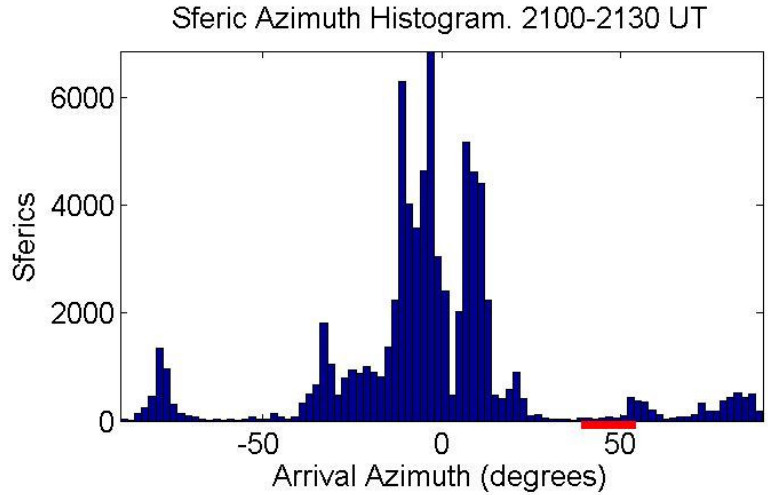


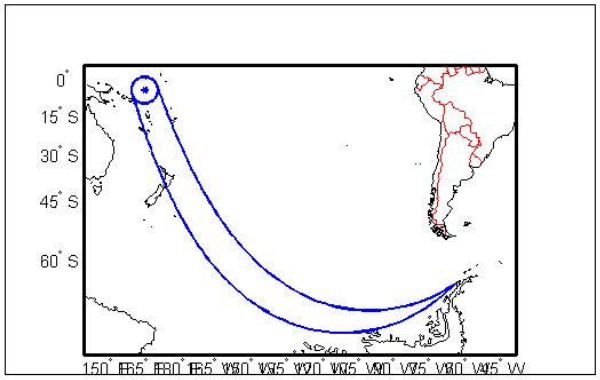




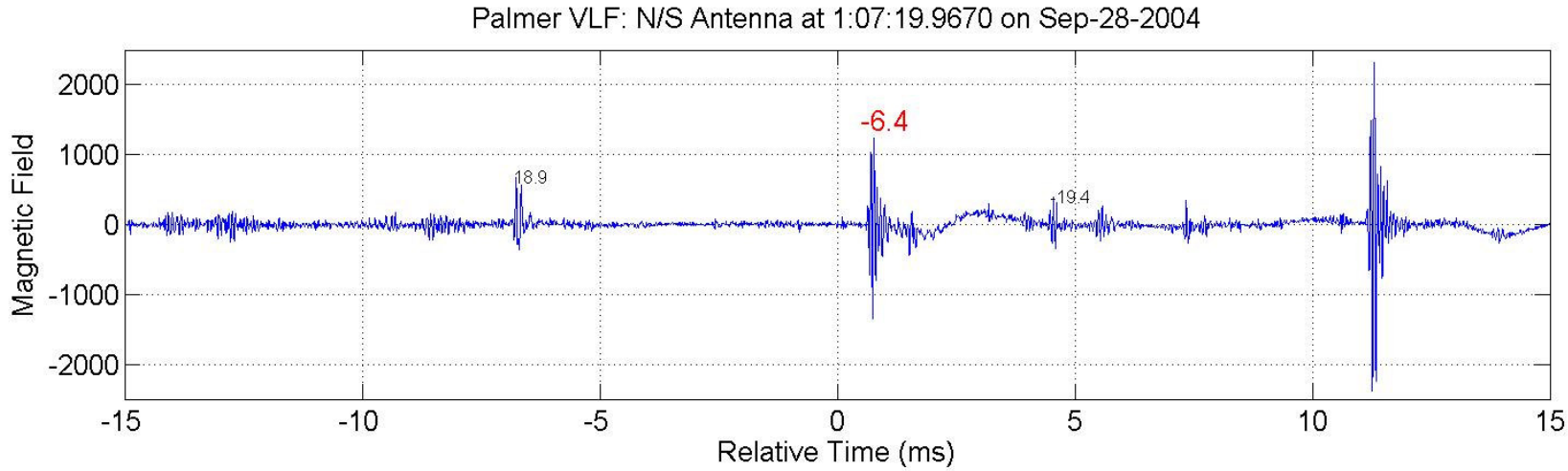
Good Sferic Match Case 18

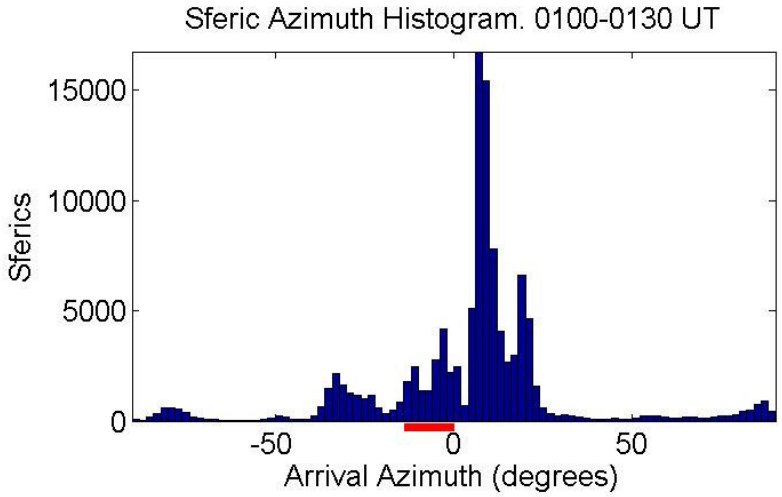


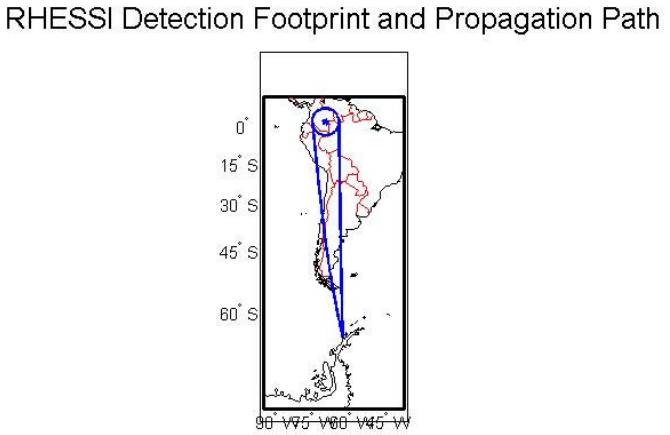




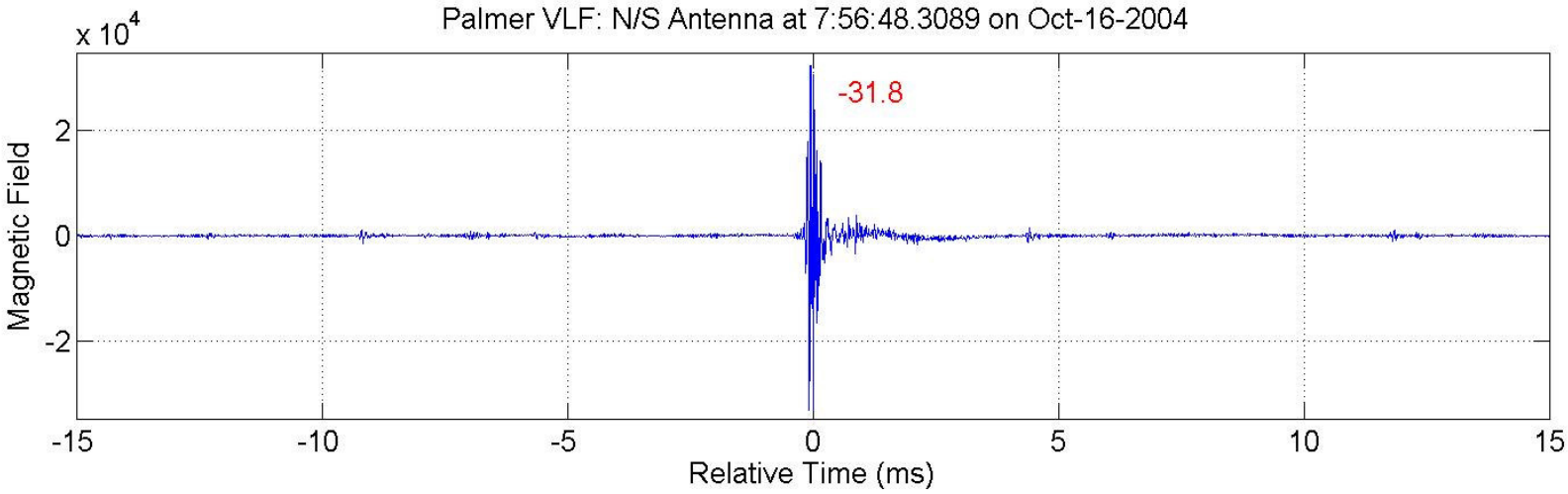
Good Sferic Match Case 19



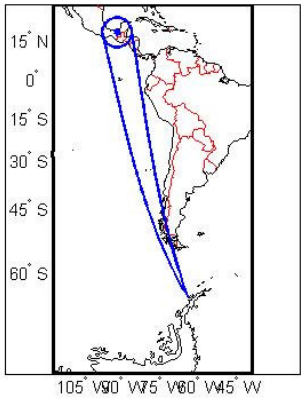




Good Sferic Match Case 20



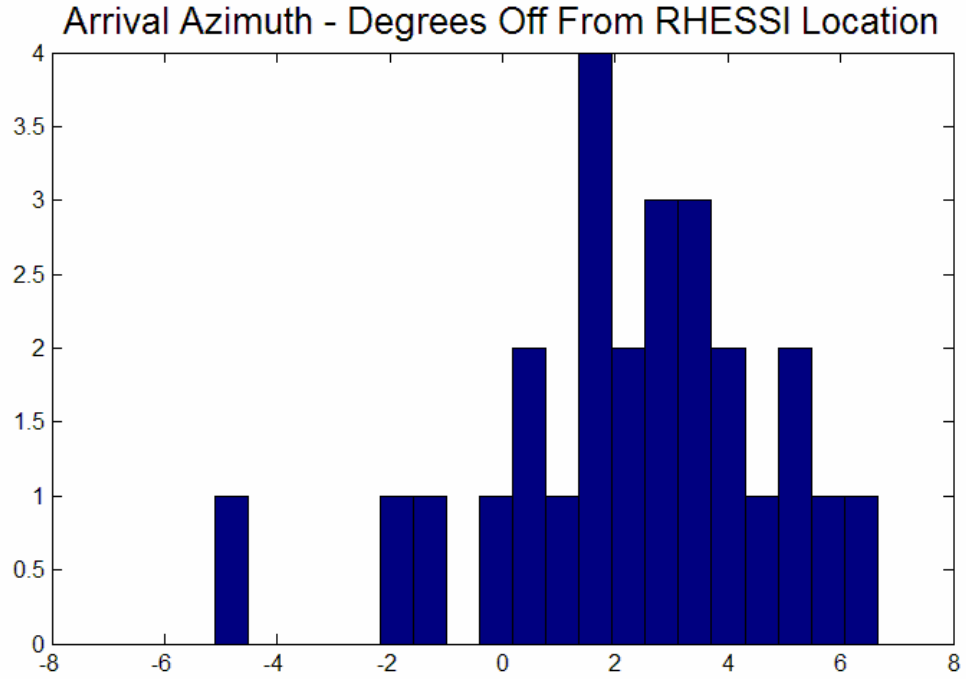
RHESSI Detection Footprint and Propagation Path



Azimuth histogram unavailable

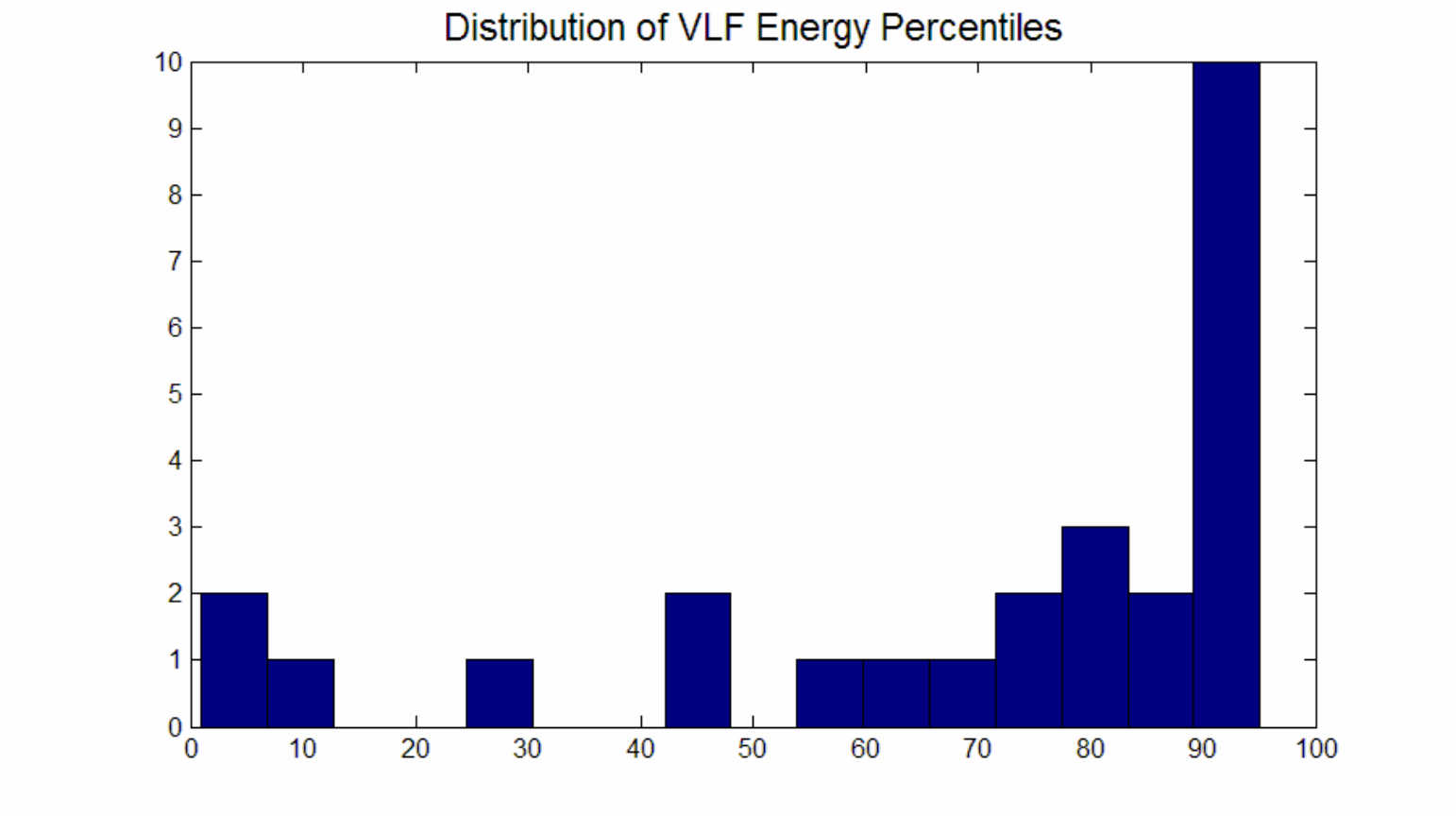
Well Matched RHESSI Cases

- $\mu_{arrive} = 2.2°$
- $\sigma^2_{arrive} = 2.5^2$
- $\sigma^2_{df} = 1.0^2$

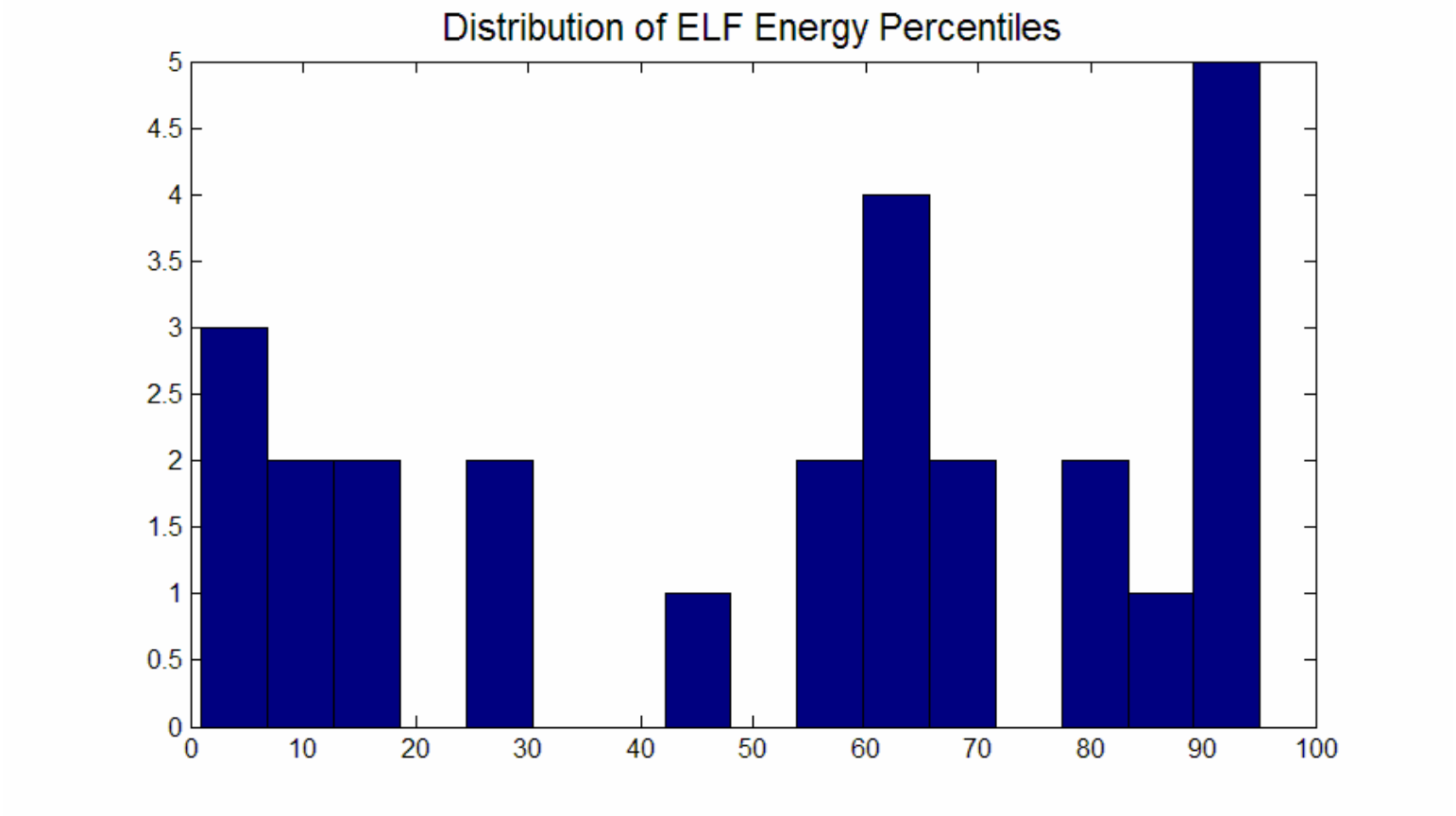


- $\sigma_{TGFs} = (\sigma^2_{arrivals} - \sigma^2_{df})^{½} = 2.30°$
- **Estimated detection radius = 460km**
- **Maximum detection radius = 625km**

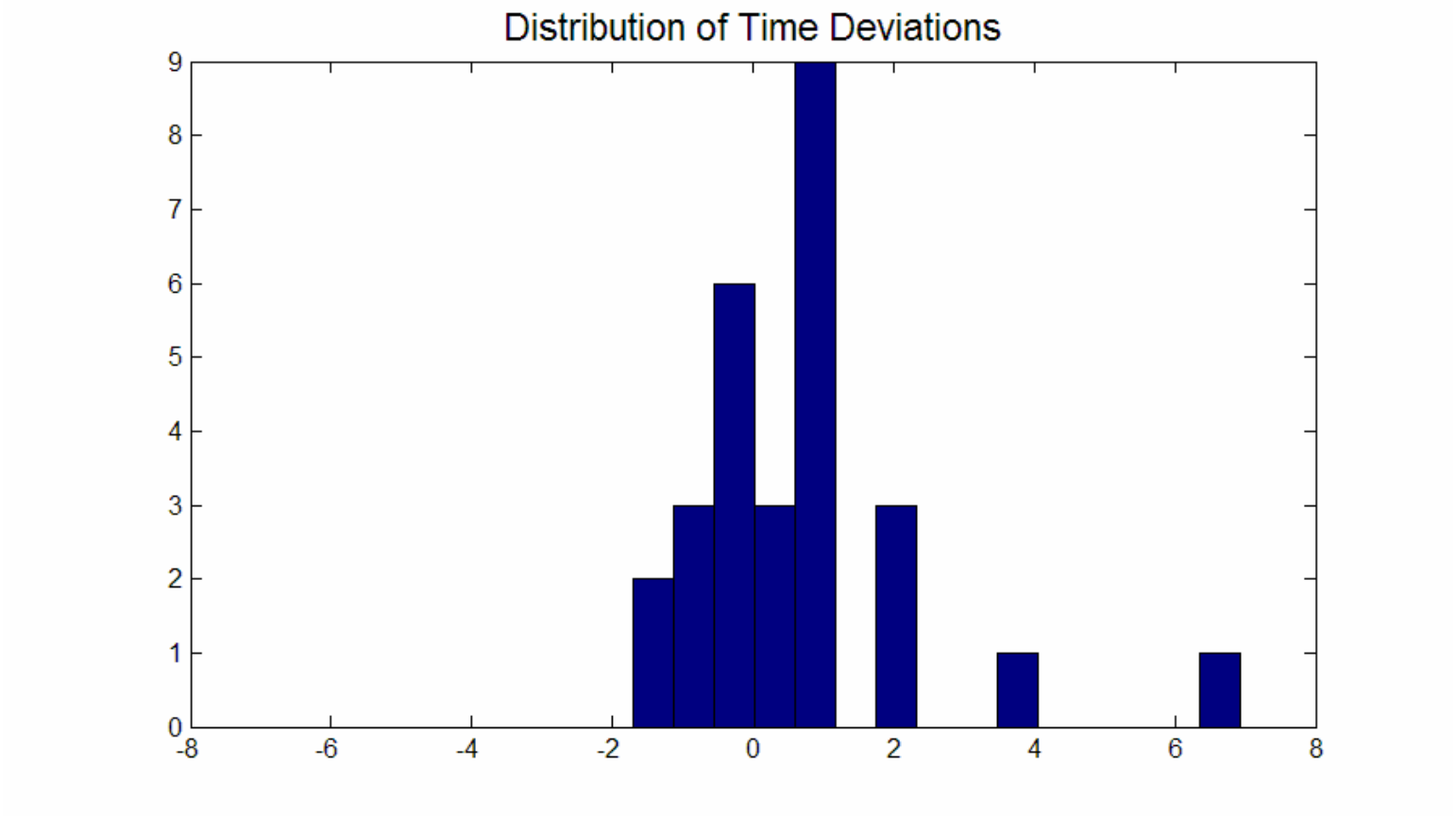
RHESSI Cases



RHESSI Cases



RHESSI Cases

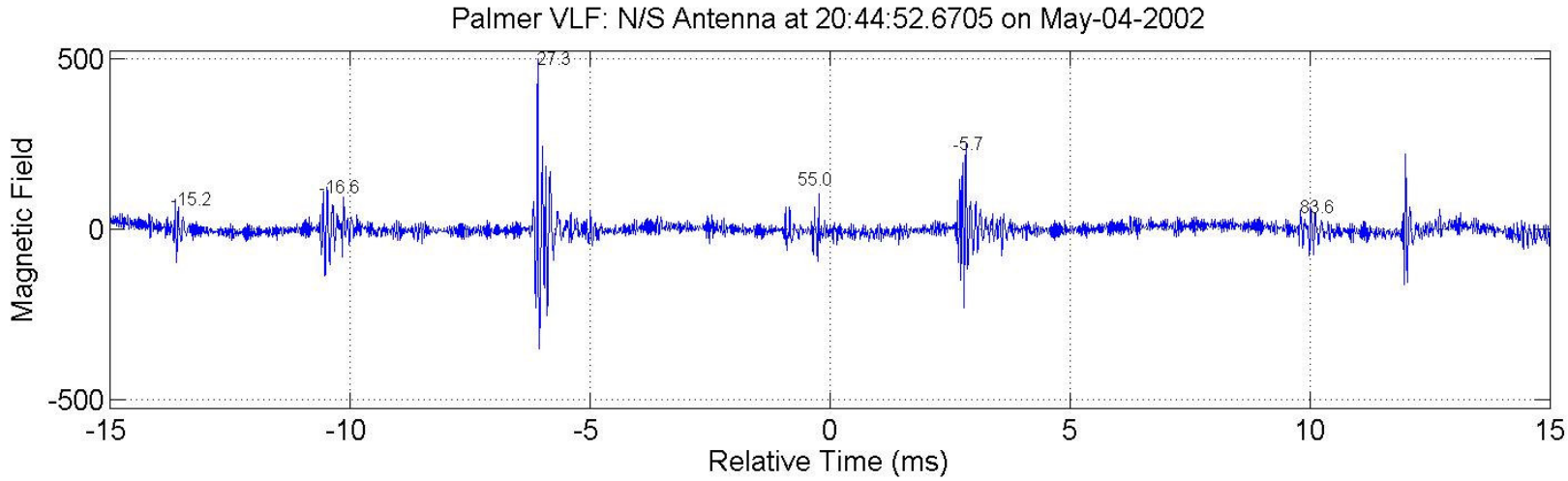


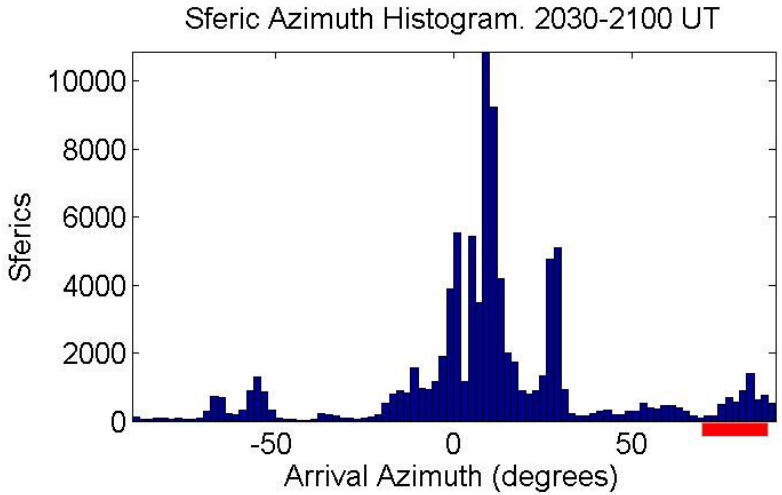
Poorly Matched Cases

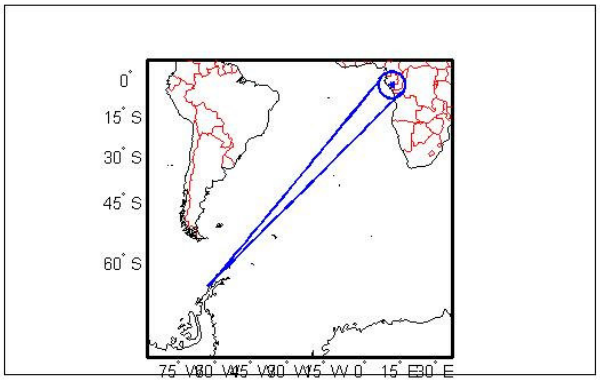
STANFORD ELECTRICAL ENGINEERING

- Little or no evidence of sferic
- Possible reasons
  - QTE mode sferic
  - Sferic too small to reach Palmer
  - Another cause of TGFs
  - Reported event is not a TGF

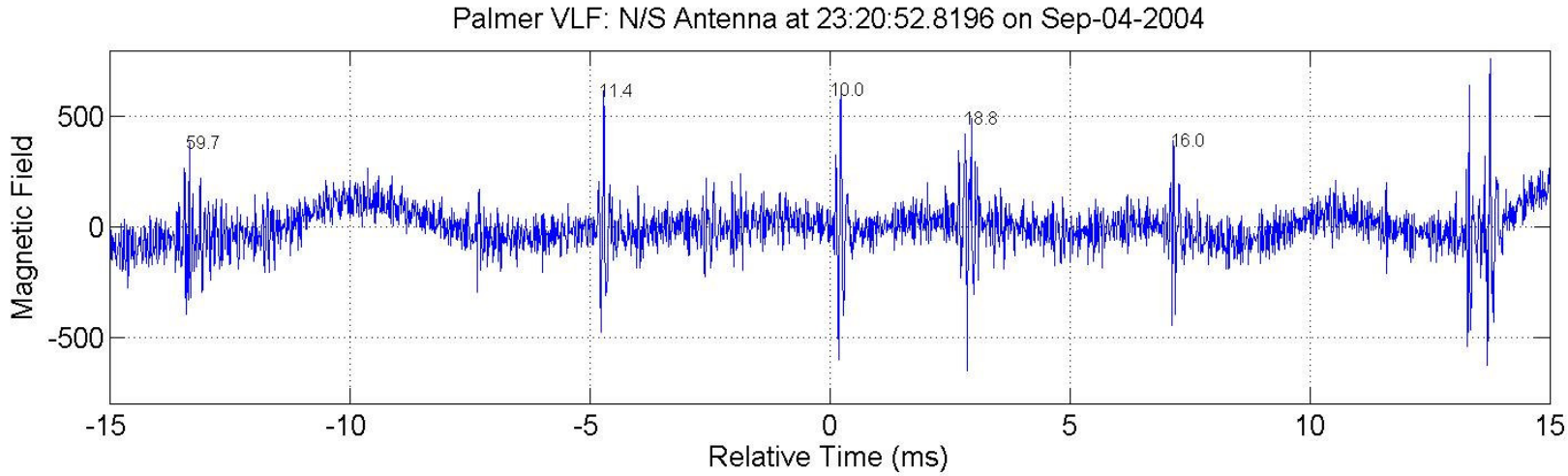
RHESSI Poor Match 1

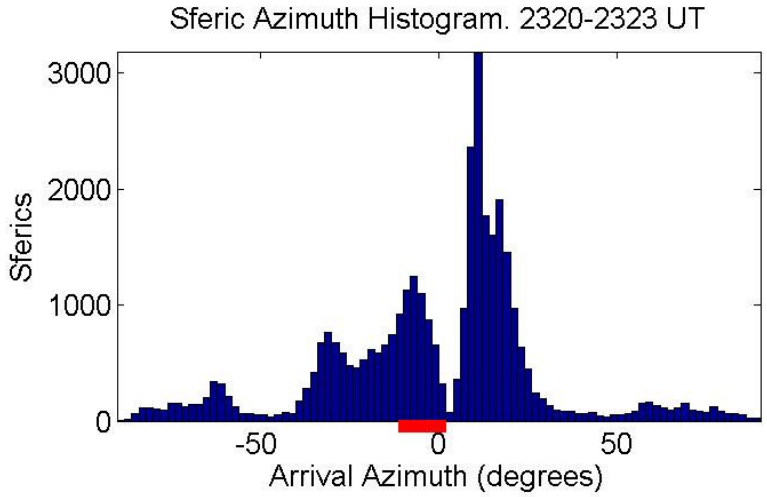


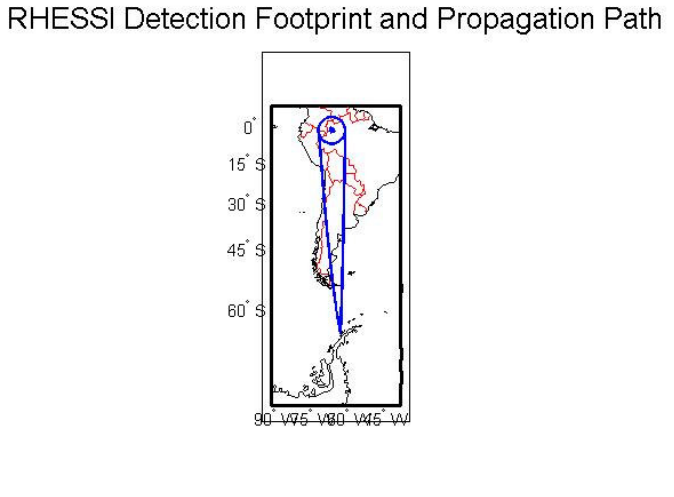




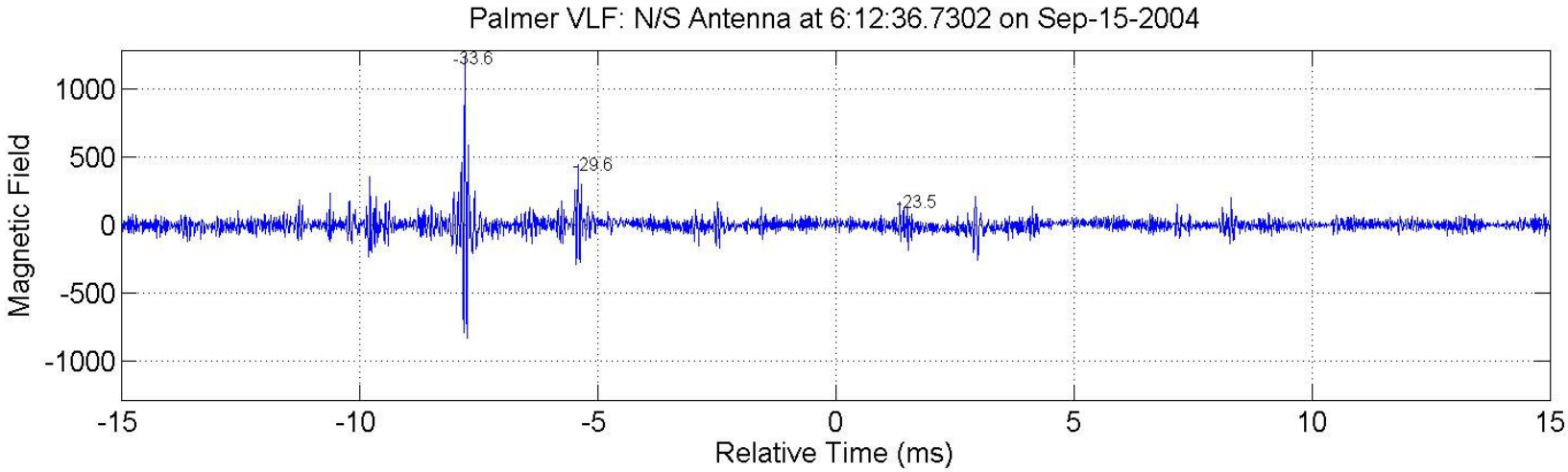
RHESSI Poor Match 2

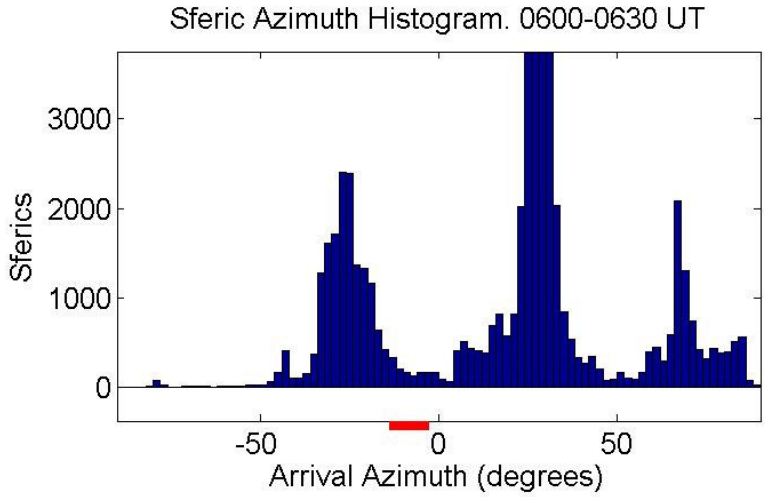


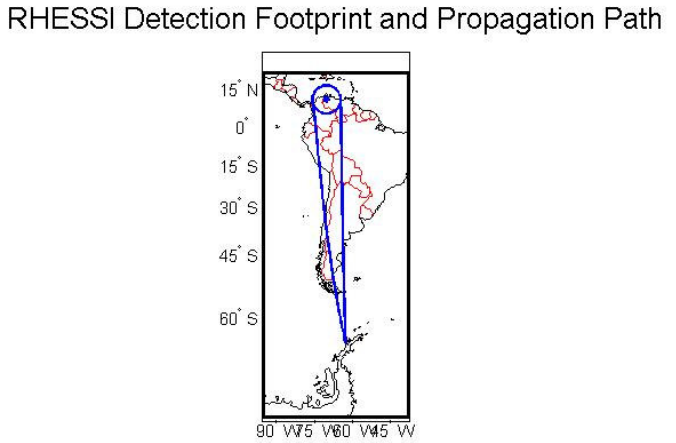




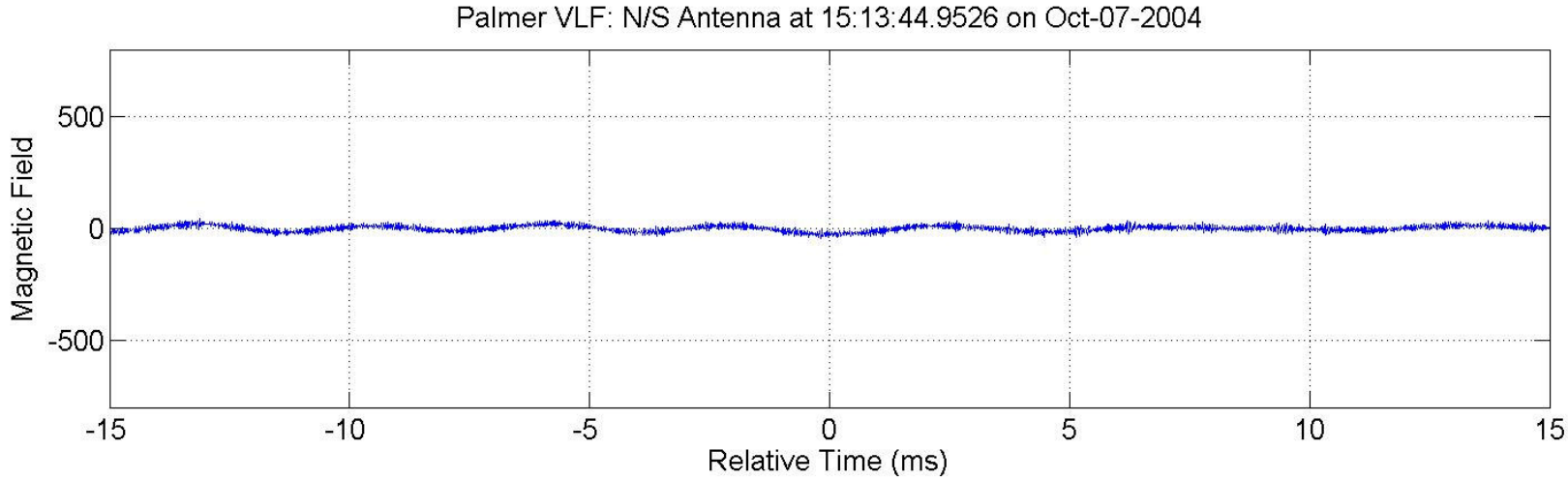
RHESSI Poor Match 3

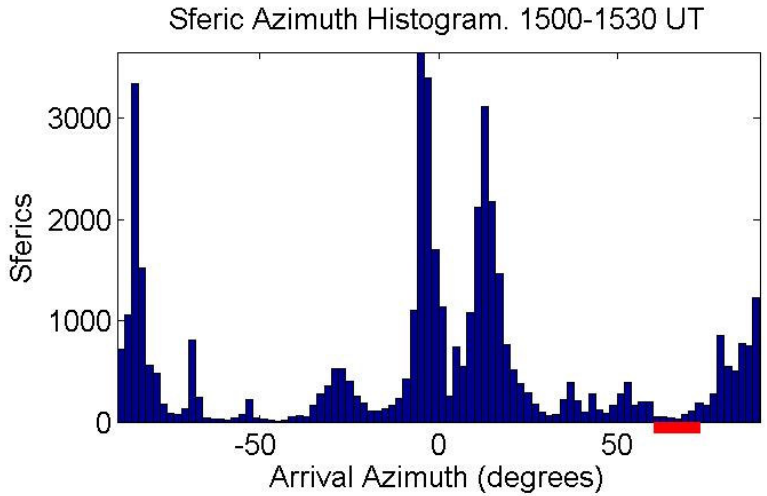


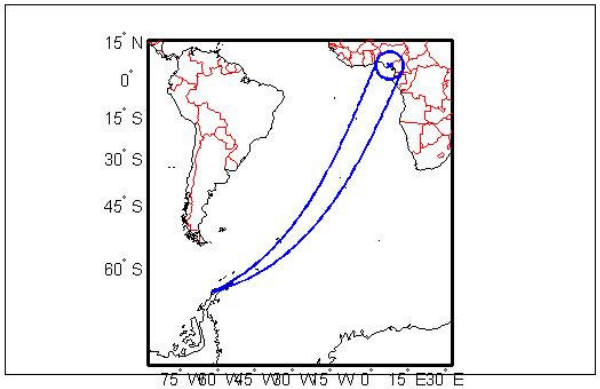




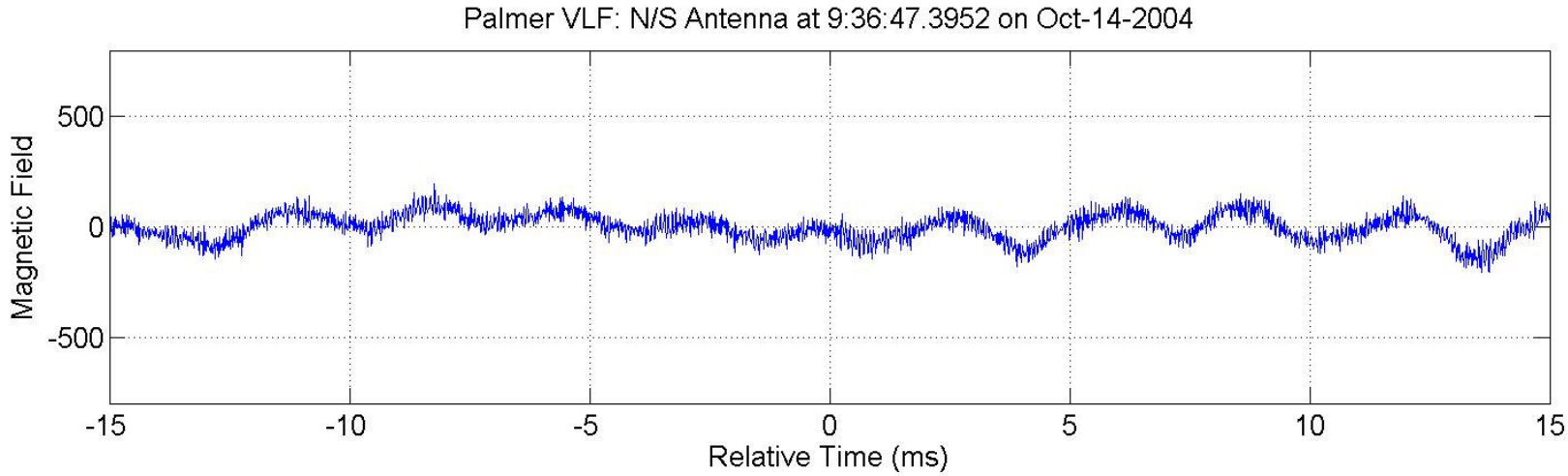
RHESSI Poor Match 4

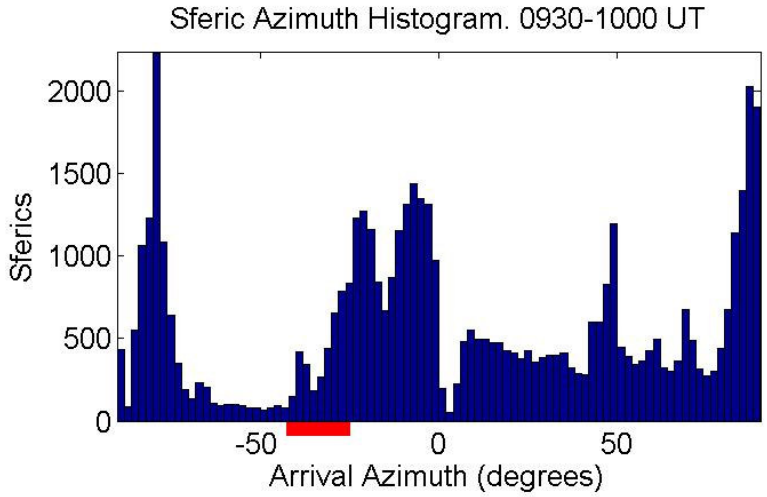


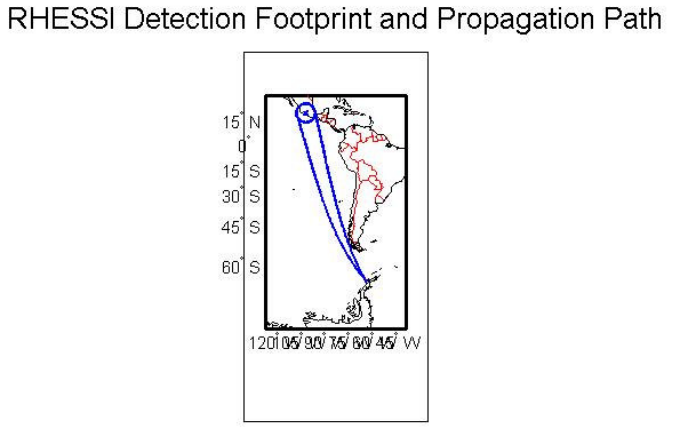




RHESSI Poor Match 5







Looking Ahead

STANFORD ELECTRICAL ENGINEERING

- Rapid processing of VLF files
- "Real time" saving of VLF data
- Process latest TGFs, update statistics
- Analyze data from other VLF stations
  - Geo-location via triangulation

Questions To Be Answered

- Width of TGF beam
- Generation altitude
- Global occurrence rate
- Conditions for TGF production
- Connection to sprites, elves, etc
- Conjugate TGF?