Oceanic Lightning observed with GLD360 and Ship-Borne LF sensors

Fadi Zoghzoghy[1], Dr. Morris Cohen[2]
Dr. Ryan Said[3], Dr. Umran Inan[1,4]

September 24, 2013

1. Stanford University
2. Georgia Institute of Technology
3. Vaisala Inc., Boulder Operations
4. Koc University

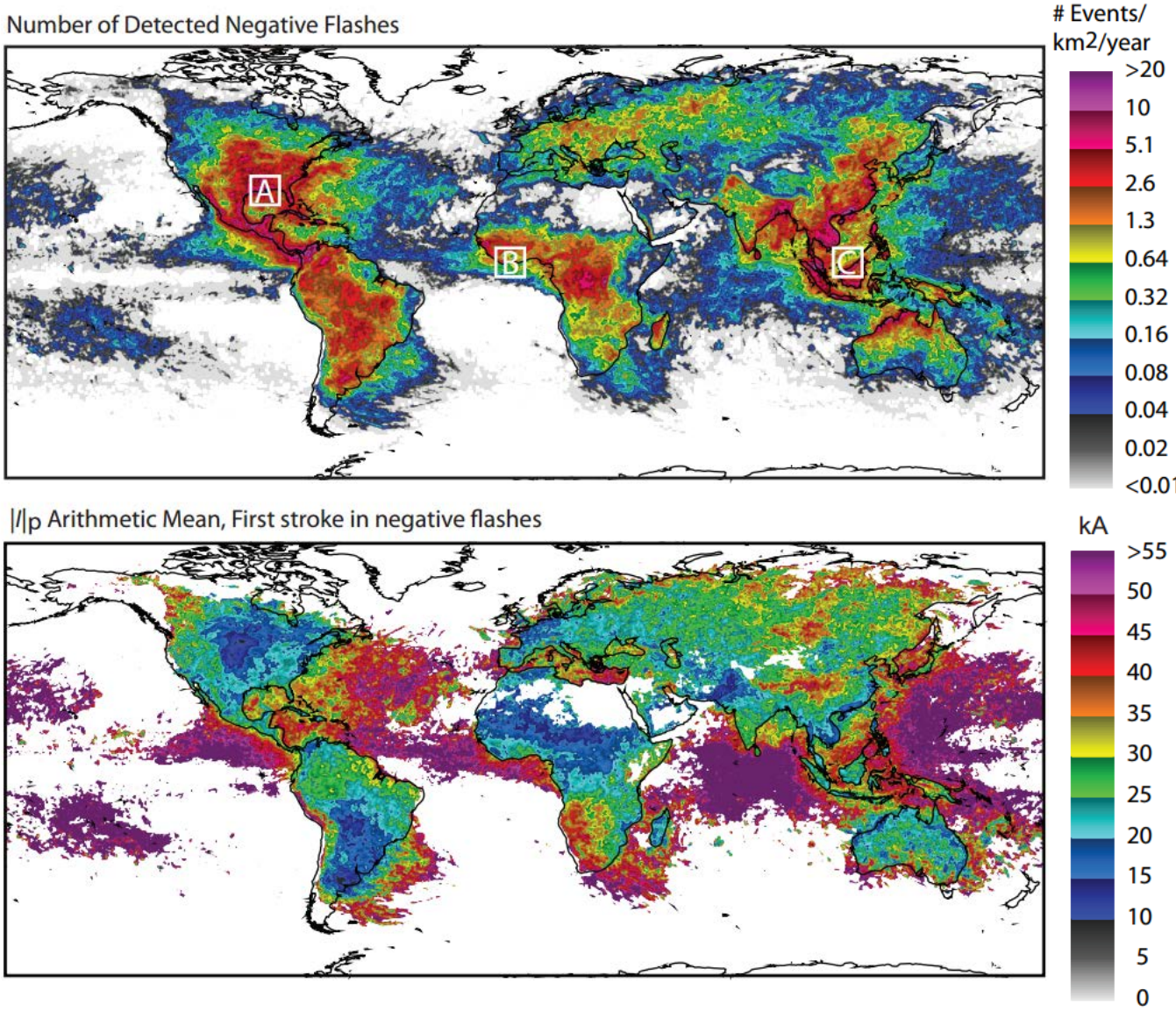
Talk Structure

- Motivation
  - Land vs. Ocean lightning
- Stanford VLF-LF AWESOME receivers
- Ship-Borne experiment - Ron Brown
- Results & Lightning statistics
  - Lightning Imaging Sensor (LIS)
  - NLDN flash clustering
  - Ron Brown waveforms

Oceanic Lightning is More Intense

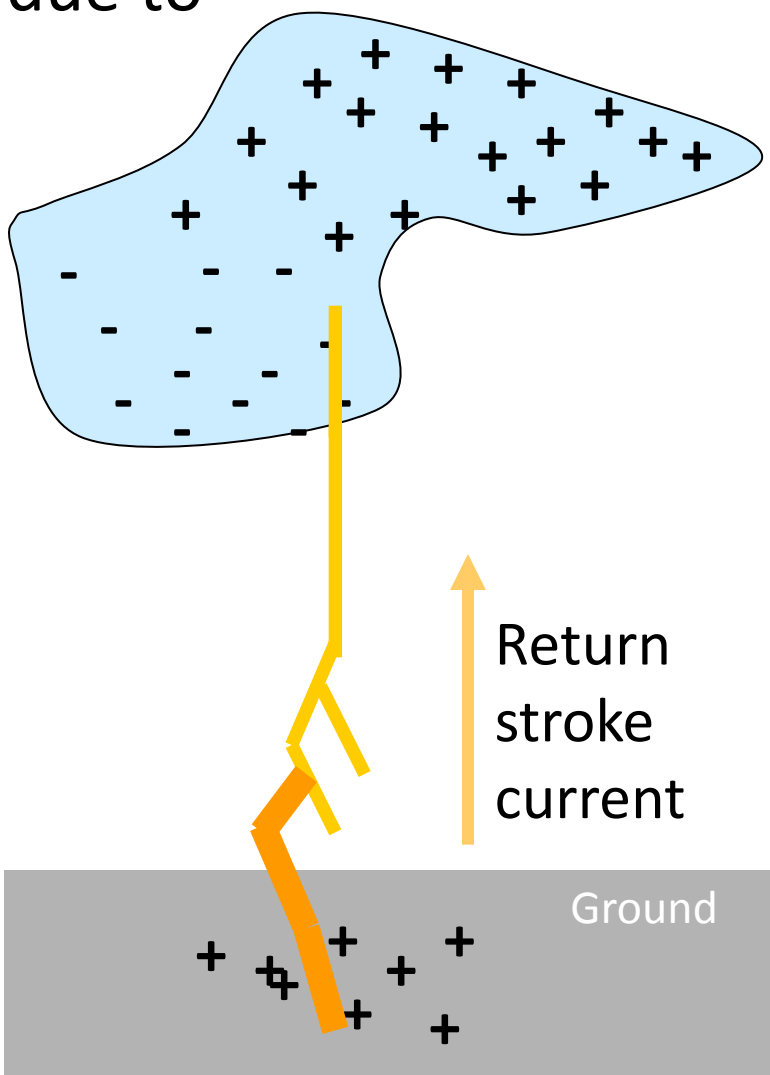
Said *et al.* 2013

- More intense lightning over the ocean
- Sharp transition on boundaries
- Not a network artifact
- More >75kA over ocean
- 150kA turnover pt.



Possible Explanations

- More Intense VLF EMP, could be due to
  - Faster return stroke speed
  - Faster return stroke rise time
  - Higher peak current
- And resulting from
  - Different attachment process
  - Higher conductivity of salt water
  - Meteorological differences
  - Flat terrain
  - Propagation path



“AWESOME” VLF Receiver Design

IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 48, NO. 1, JANUARY 2010 3

Sensitive Broadband ELF/VLF Radio Reception With the AWESOME Instrument

Morris B. Cohen, *Member, IEEE*, Umran S. Inan, *Fellow, IEEE*, and Evans W. Paschal

***Abstract*—A new instrument has been developed and deployed for sensitive reception of broadband extremely low frequency (ELF) (defined in this paper as 300–3000 Hz) and very low frequency (VLF) (defined in this paper as 3–30 kHz) radio signals from natural and man-made sources, based on designs used for decades at Stanford University. We describe the performance characteristics of the Atmospheric Weather Electromagnetic System for Observation, Modeling, and Education (AWESOME) instrument, including sensitivity, frequency and phase response, timing accuracy, and cross modulation. We also describe a broad range of scientific applications that use AWESOME ELF/VLF data involving measurements of both subionospherically and magnetospherically propagating signals.**

***Index Terms*—Amplifiers, analog circuits, broadband amplifiers, ionosphere, lightning, low-frequency (LF) radio, magnetosphere, radio receivers, remote sensing, waveguide antennas.**

I. Introduction

THE ANALYSIS of radio waves of extremely low frequencies (ELF) (defined in this paper as 300 Hz–3 kHz) and very low frequencies (VLF) (defined in this paper as 3–30 kHz) is useful for studying the dynamics of the Earth's ionosphere and magnetosphere as well as subterranean imaging and global communications and navigation. For instance, lightning radiates the bulk of its electromagnetic energy in the ELF/VLF frequency range [1, p. 118], launching signals known as radio atmospherics (or sferics) which are almost entirely reflected at the D region (70–90 km altitude) of the ionosphere. These signals (like others in this frequency range) are efficiently guided to global distances in the so-called Earth-ionosphere waveguide. Attenuation rates are typically only a few decibels per megameter [2, p. 389] after the first ~500 km for waveguide mode structure to be established. Propagation characteristics in the Earth-ionosphere waveguide are in general a strong function of the ionospheric conditions, which leads to dramatically different propagation characteristics between daytime and nightime. In addition, some of the ELF/VLF energy leaks upward in the plasma whistler mode to the magnetosphere, where it can strongly impact the electron dynamics of the Van Allen radiation belts and can be received in the geomagnetic conjugate region [3]. Natural ELF/VLF signals known as chorus and hiss can also be generated *in situ* in the magnetosphere, particularly at mid and high geomagnetic latitudes, as a result of the interaction between energetic electrons in the radiation belts and ELF/VLF whistler-mode waves (see [4], and references therein). Due to the long-distance propagation of ELF/VLF waves, as well as the relatively deep (10 s of meters skin depth) penetration of ELF/VLF waves into seawater, a number of VLF transmitters operate at frequencies between 10 and 60 kHz for naval communication with surface ships and submerged submarines. A global collection of such transmitters has also been used for accurate navigation via phase-coherent triangulation, such as the so-called “Omega” system [5]. Because ELF/VLF propagation is strongly influenced by D-region ionospheric conditions, these VLF transmitter signals are also used to remotely sense ionospheric disturbances resulting from different physical processes. Moreover, because of the relatively high (hundreds of meters, due to the skin effect) penetration into the Earth, ELF/VLF waves are a useful tool for subterranean prospecting and imaging [6].

The first observations of natural signals at ELF and VLF frequencies were made serendipitously in the late 19th and

Cohen *et al.* 2010

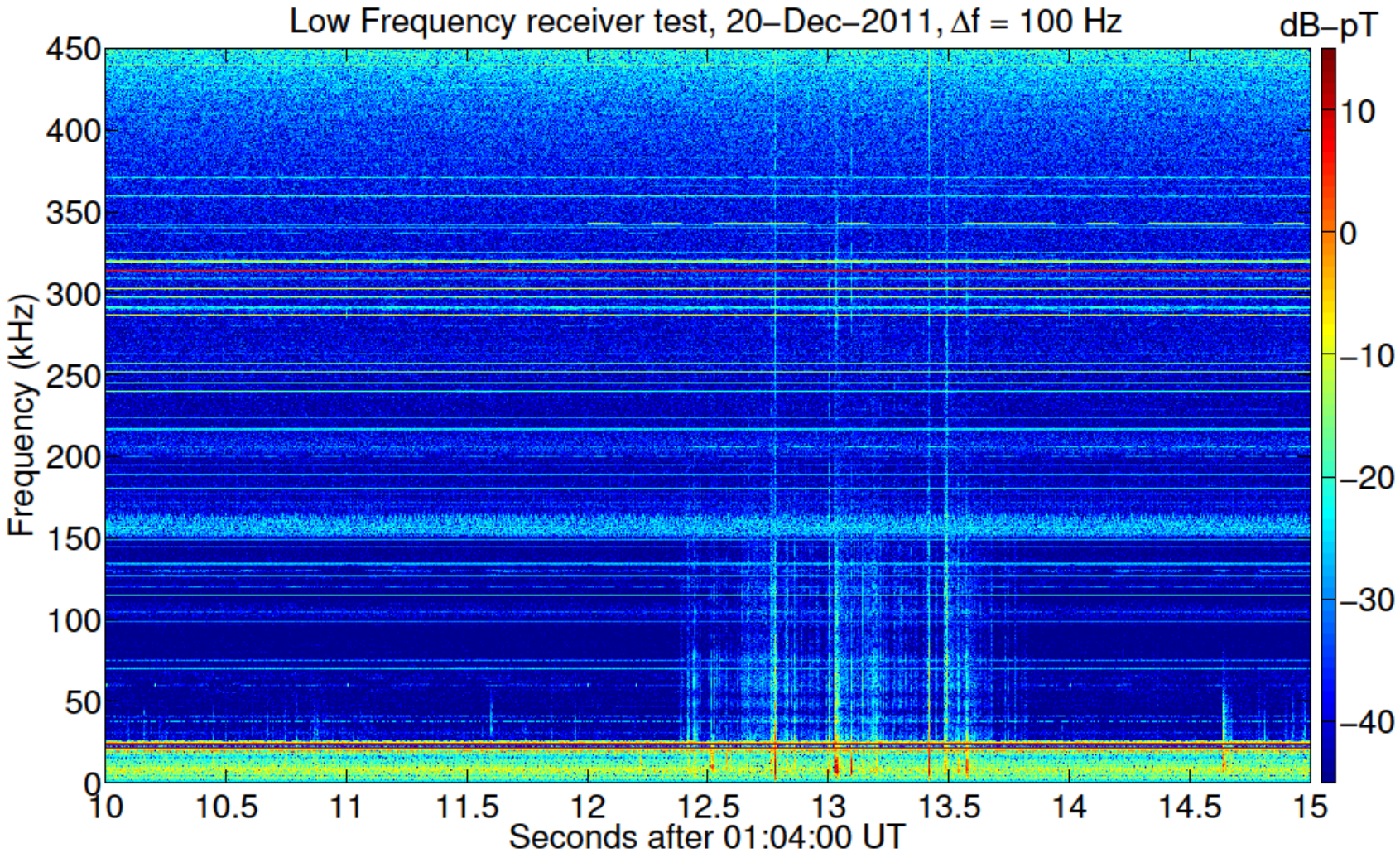
VLF Version

- 100 kHz sampling
- 0.3 – 47 kHz band
- Two orthogonal wire loop channels
- 96 dB dynamic range
- Sensitivity in the fT/rt-Hz range

New LF Version

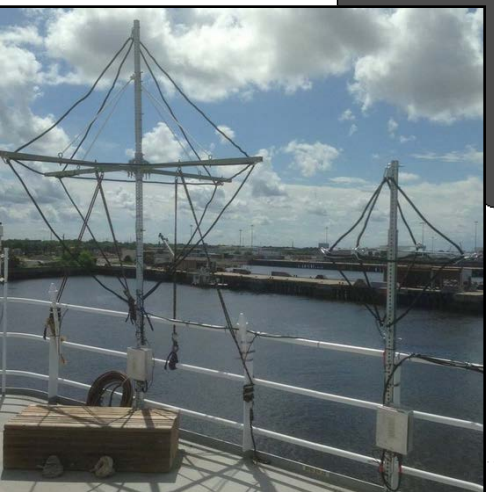
- 1 MHz sampling
- 0.3 – 450 kHz band
- Developed to study oceanic lightning
- Better extract the shape of lightning waveforms

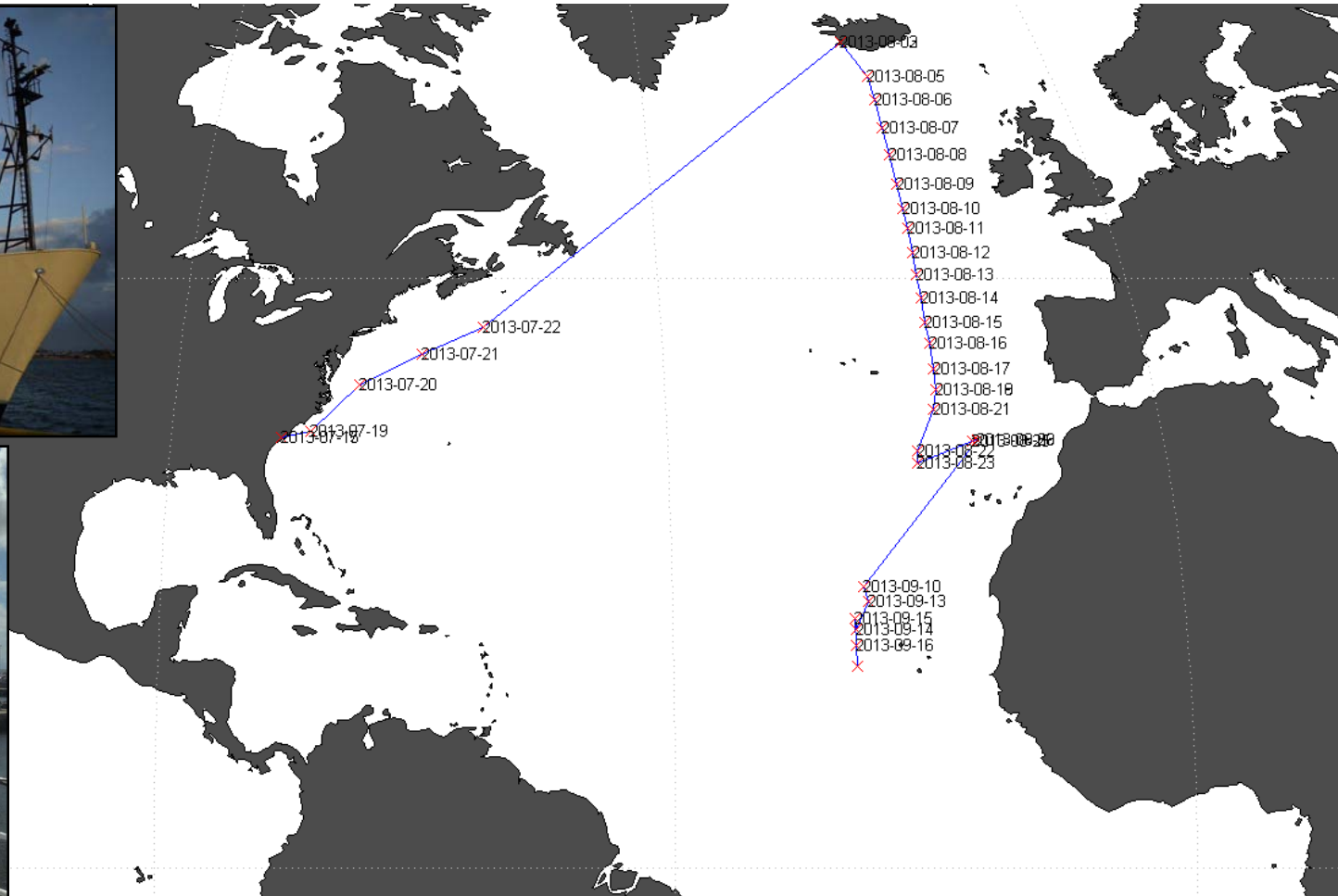
New LF (1 MHz) – 2,500 km Lightning



Ship-Borne Oceanic Lightning Study

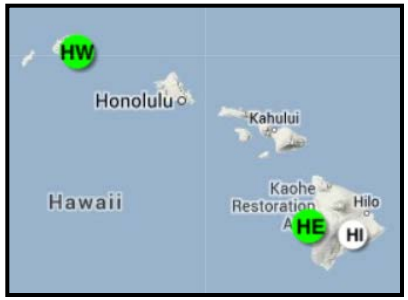
- NOAA Ron Brown - 7 month voyage
- Stanford LF & VLF on board – proximity to lightning



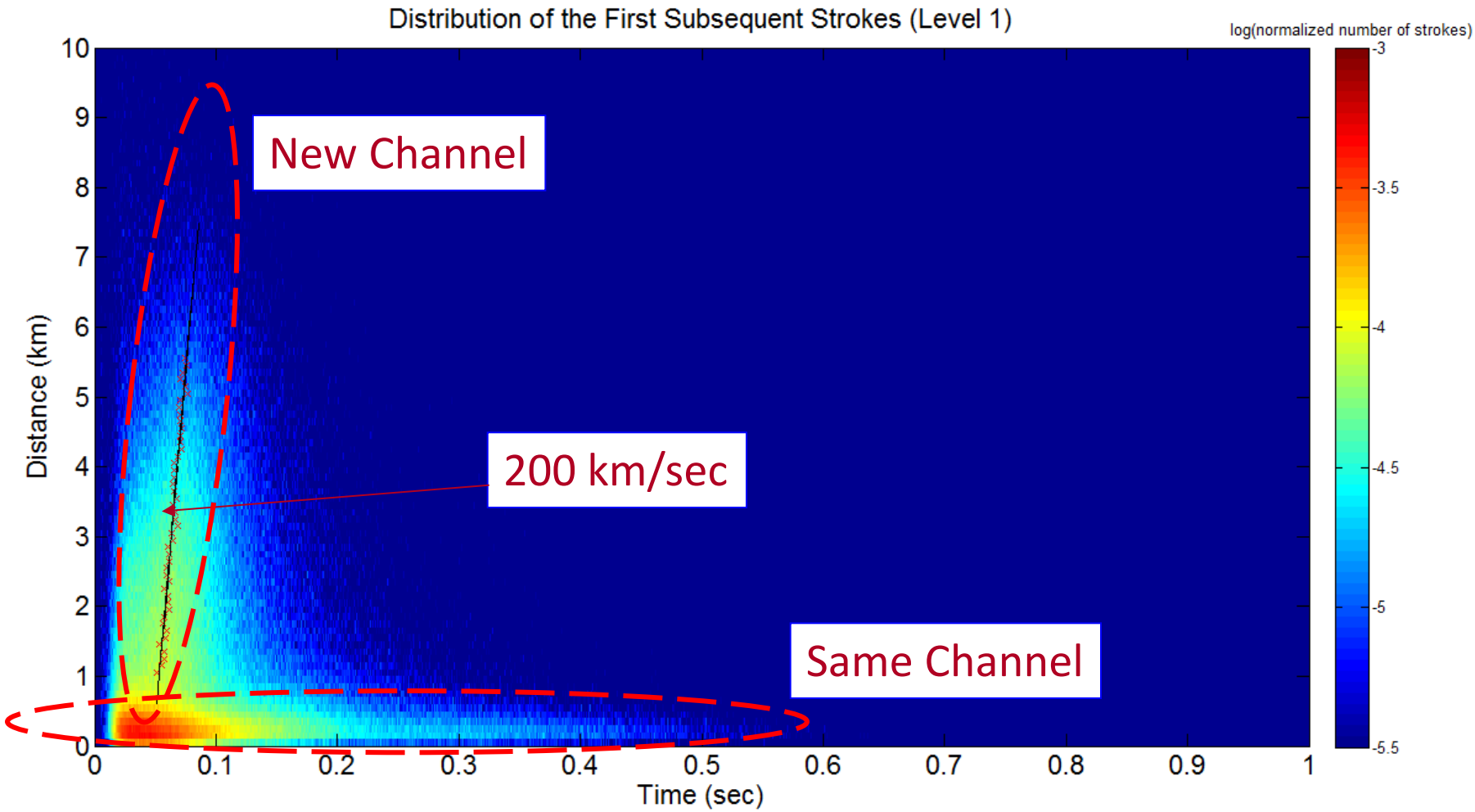


Stanford land and oceanic arrays

- Oklahoma array (6 LF receivers)
- Hawaii (2 LF) and Puerto Rico (1 LF) arrays



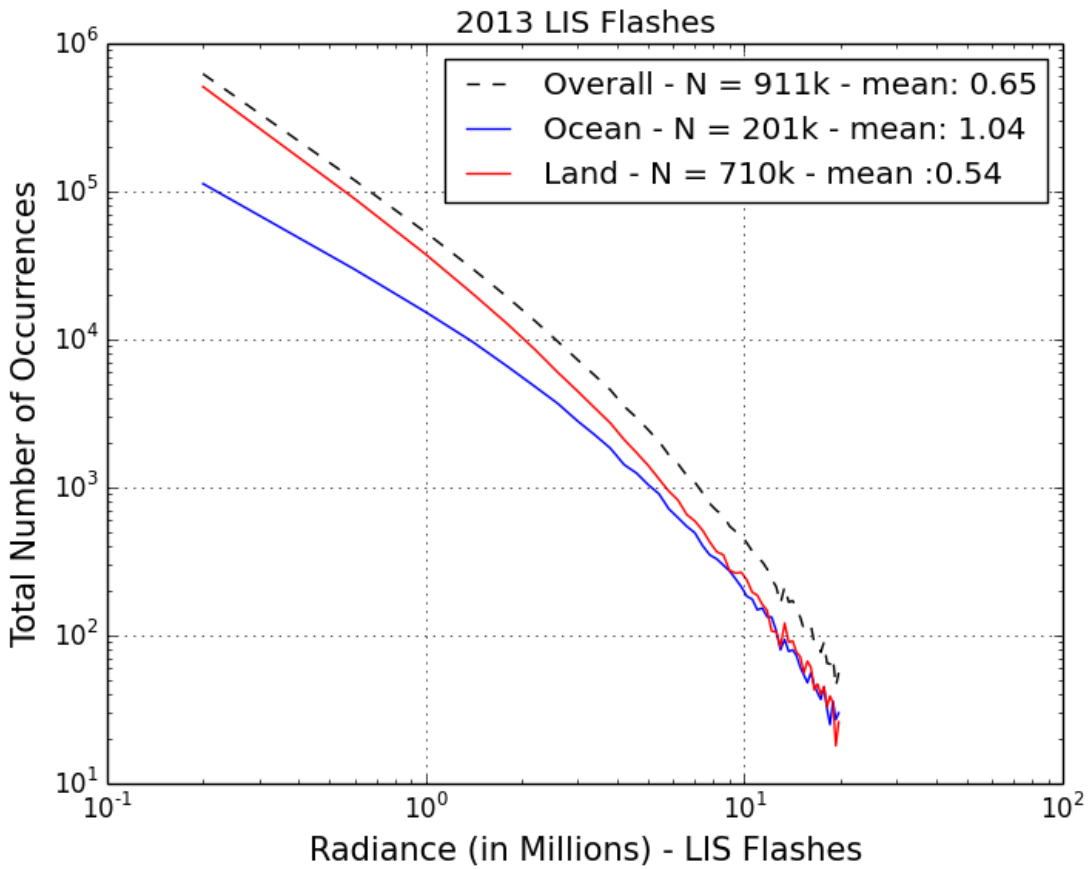
Evolution of the neg-CG Flash, NLDN



- NLDN Clustering algorithm

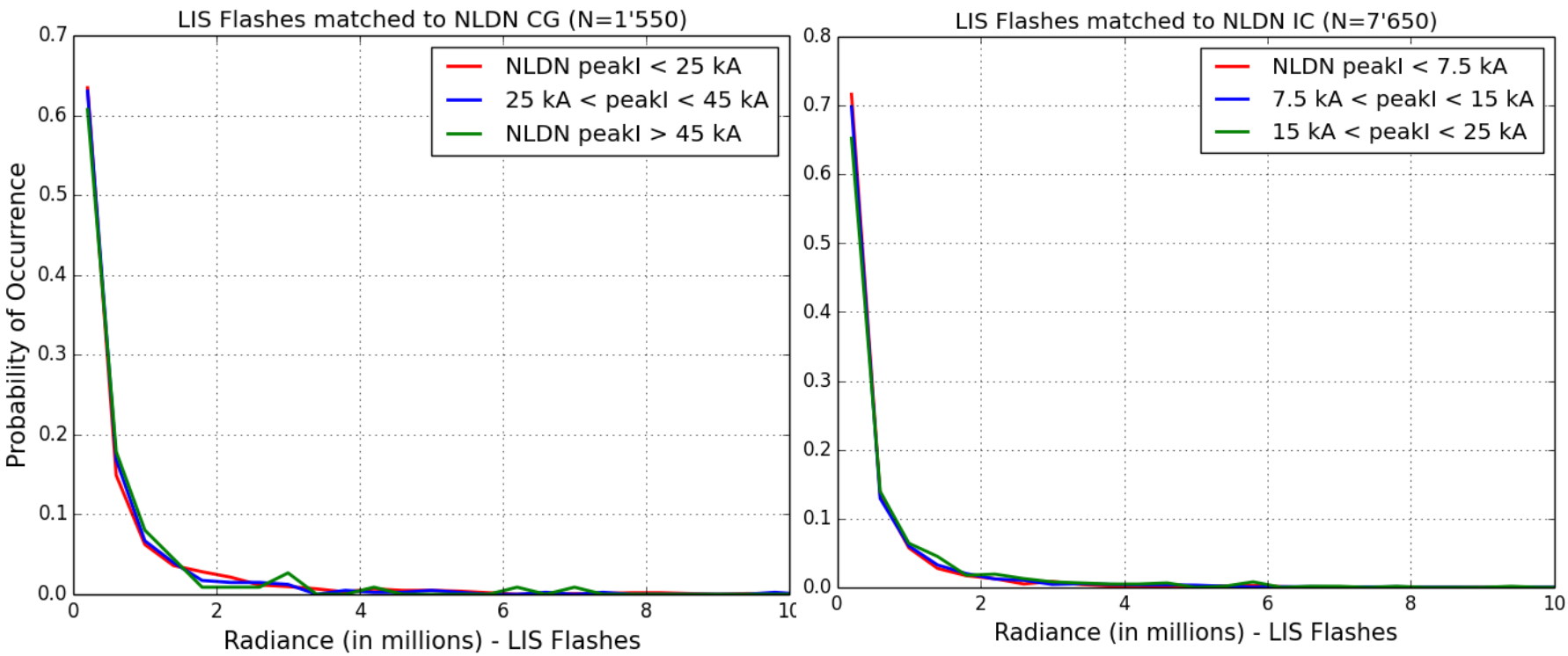
Lightning Imaging Sensor (LIS)

- Oceanic and Land Radiance



http://thunder.msfc.nasa.gov

LIS and NLDN



- No correlation between LIS Radiance & NLDN peak Current

Ron Brown Results

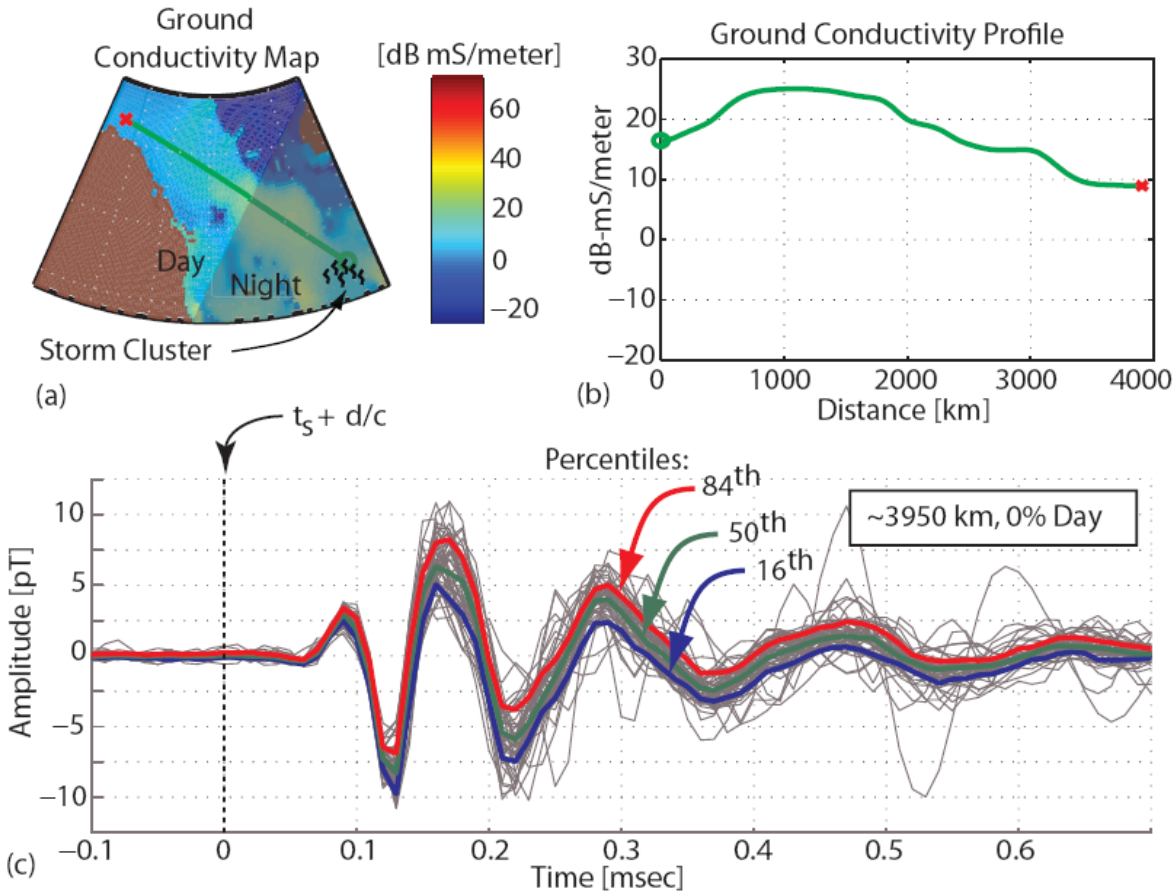
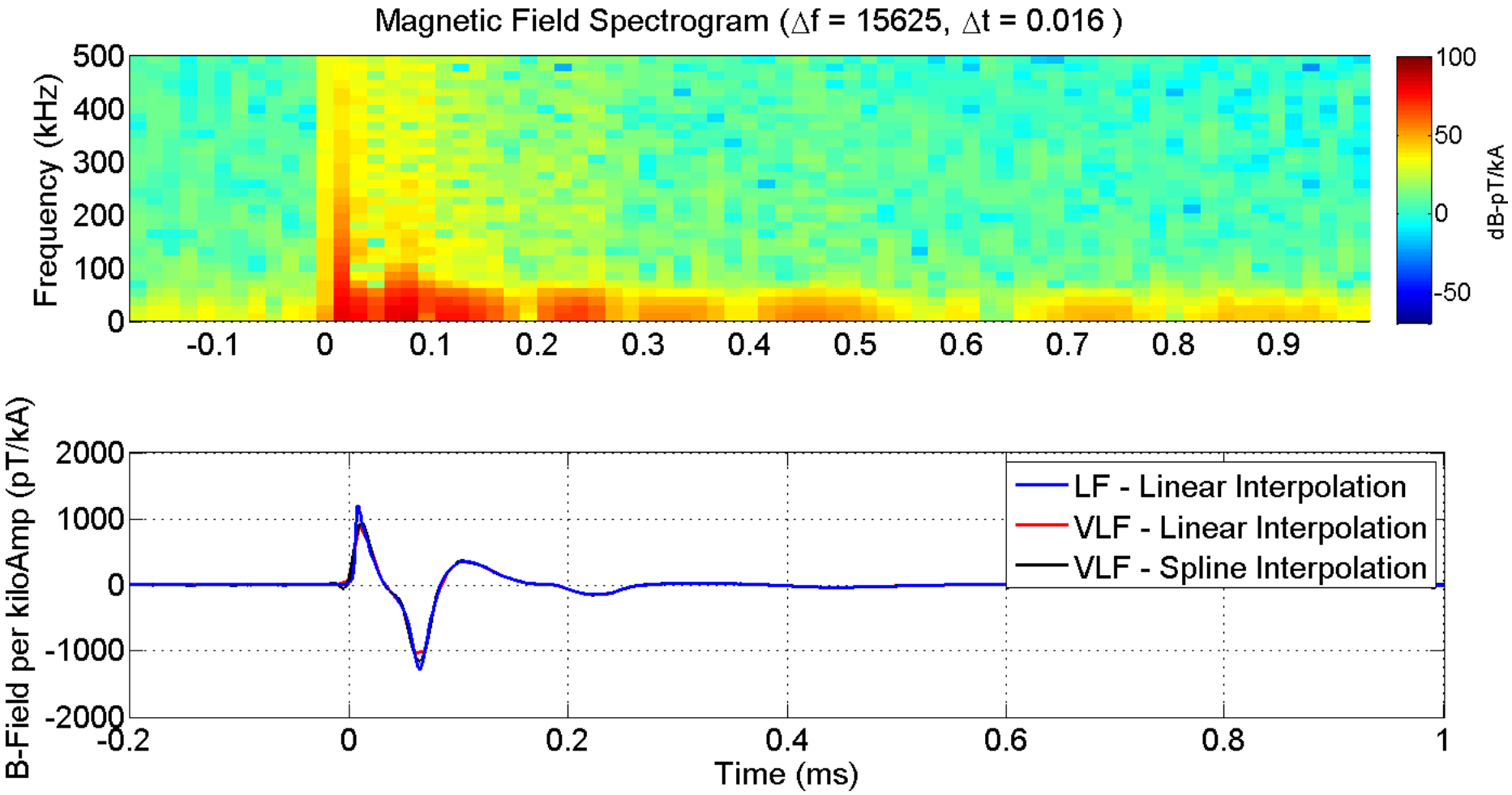


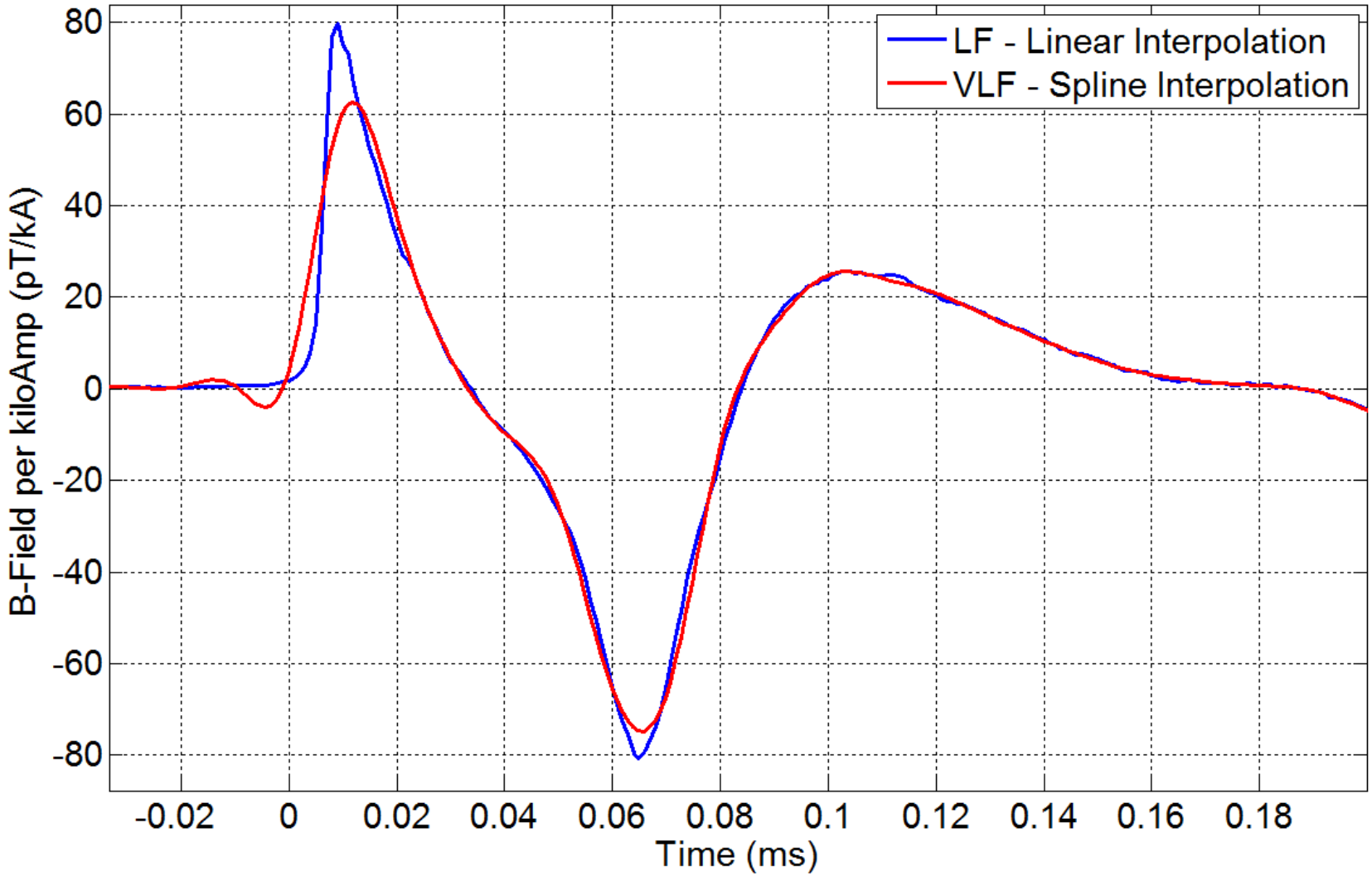
Figure 4.1: Process for measuring an averaged waveform. (a) Storm cluster with a specific propagation path profile to the receiver. (b) Ground conductivity profile between the storm cluster and the receiver. (c) The locus of received waveforms defines a canonical waveform. The shown sferics are from a 100% nighttime path.

LF Canonical Waveforms



- 600-700km – 408 neg-CG strokes

Zoomed In Look at VLF vs. LF



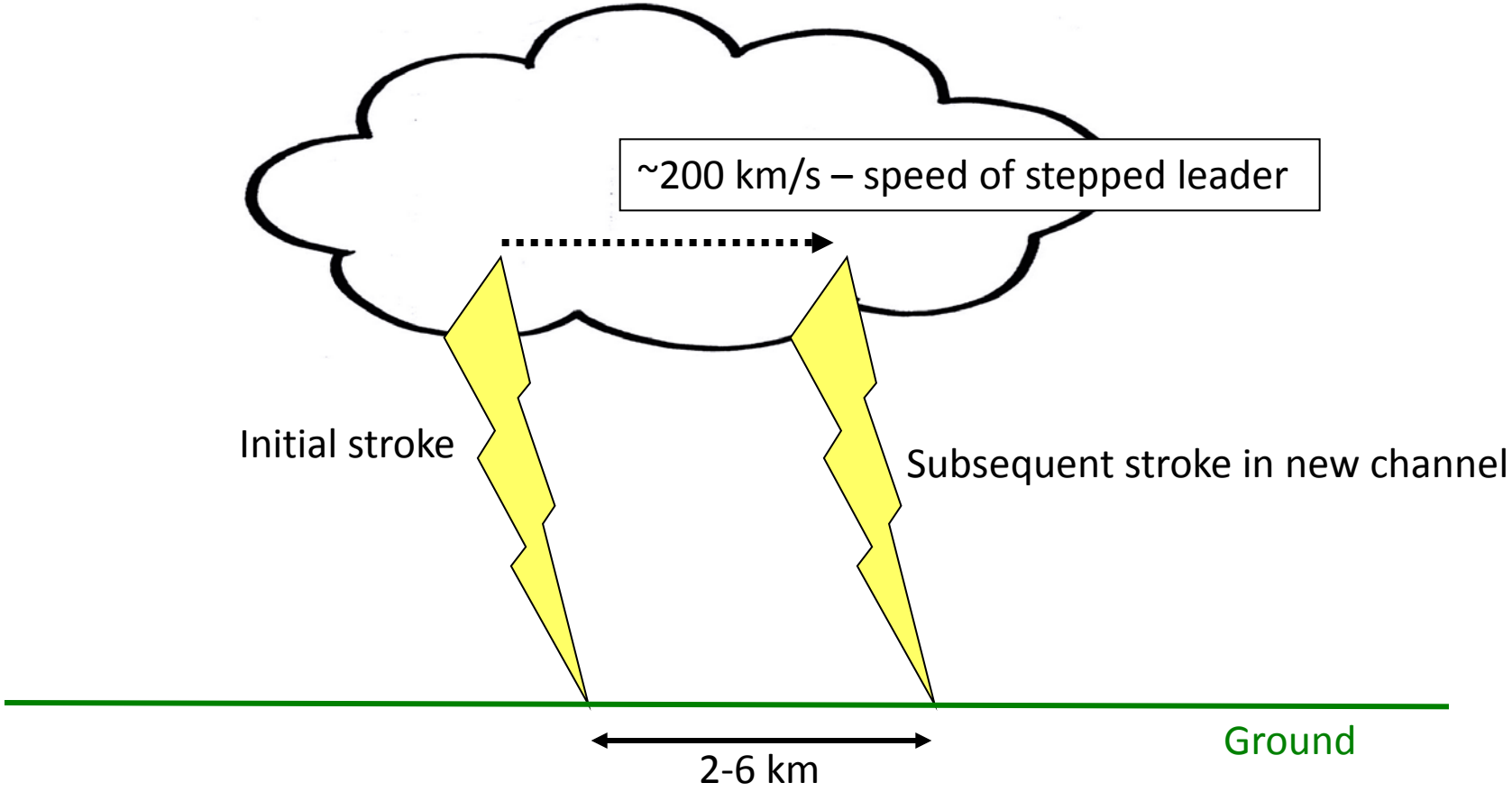
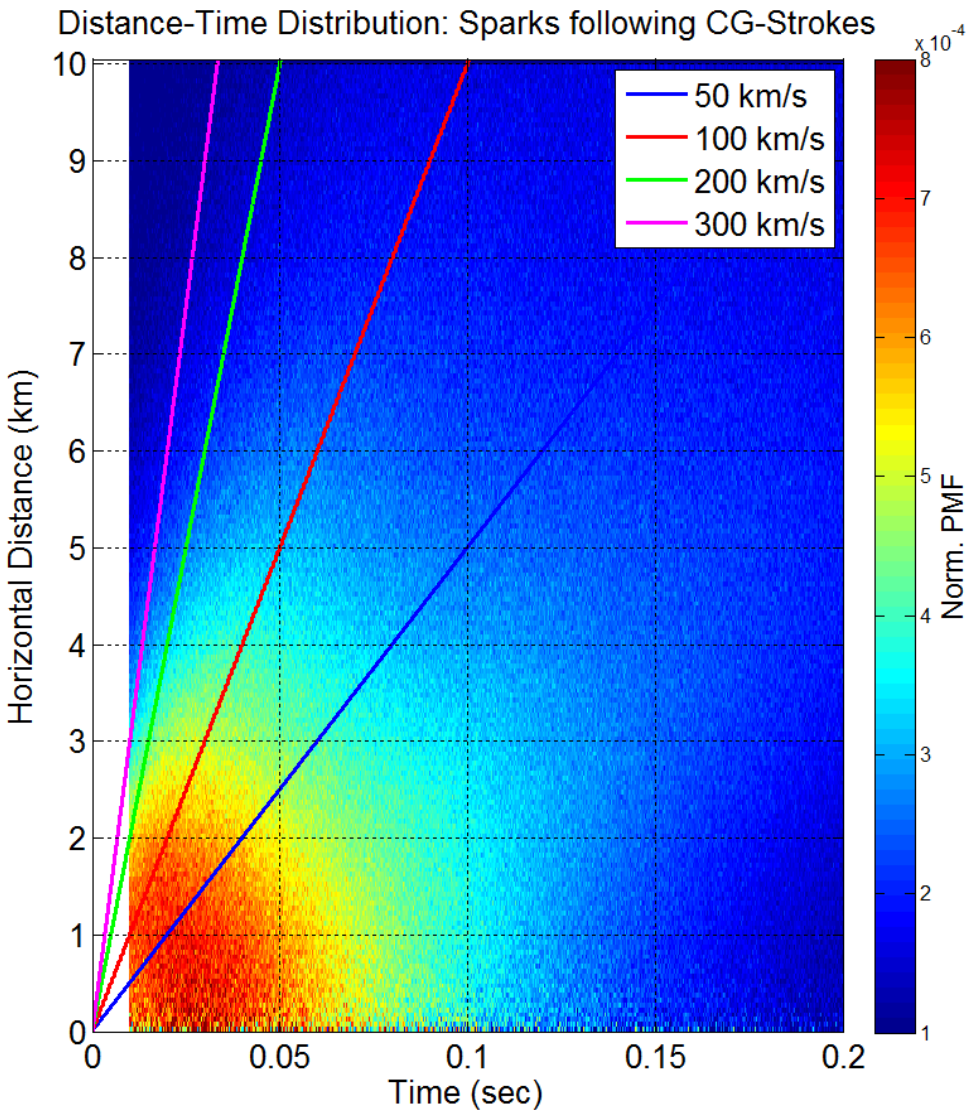
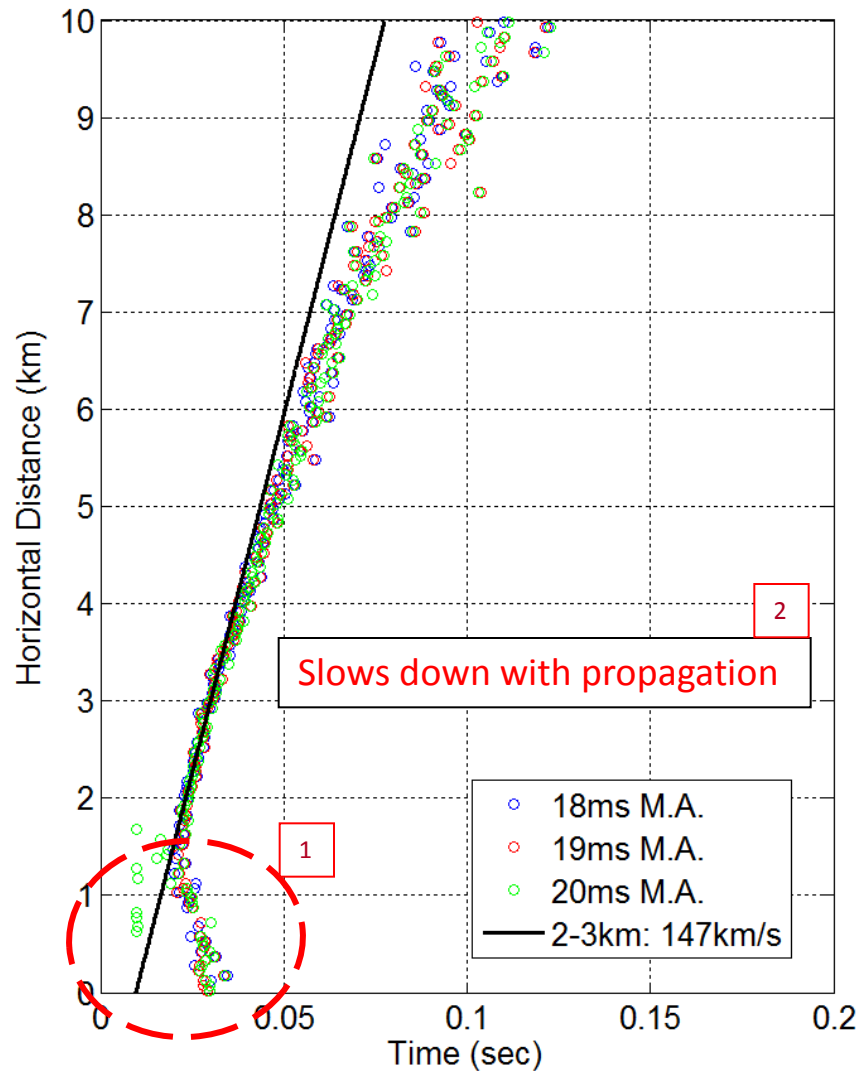
References & Contact Information

- Said, R. K., M. B. Cohen, and U. S. Inan. "Highly intense lightning over the oceans: Estimated peak currents from global GLD360 observations." *Journal of Geophysical Research: Atmospheres* (2013).
- Cohen, Morris B., Umran S. Inan, and Evans W. Paschal. "Sensitive broadband ELF/VLF radio reception with the AWESOME instrument." *Geoscience and Remote Sensing, IEEE Transactions on* 48.1 (2010): 3-17.
- Said, R. K., U. S. Inan, and K. L. Cummins. "Long-range lightning geolocation using a VLF radio atmospheric waveform bank." *Journal of Geophysical Research: Atmospheres (1984–2012)* 115.D23 (2010).
- Zoghzoghy, F. G., et al. "Statistical patterns in the location of natural lightning."*Journal of Geophysical Research: Atmospheres* (2013).
- Said, Ryan Khalil. *Accurate and efficient long-range lightning geo-location using a VLF radio atmospheric waveform bank*. 2009.

<u>Contact Information</u>

Fadi Zoghzoghy fadiz@stanford.edu

Extra Slide 1: Cartoon - Evolution of neg-CG Flash



Extra Slide 2: LMA-NLDN Distance-Time