Characterizing traveling ionospheric disturbances using passive HF observations from lightning sources

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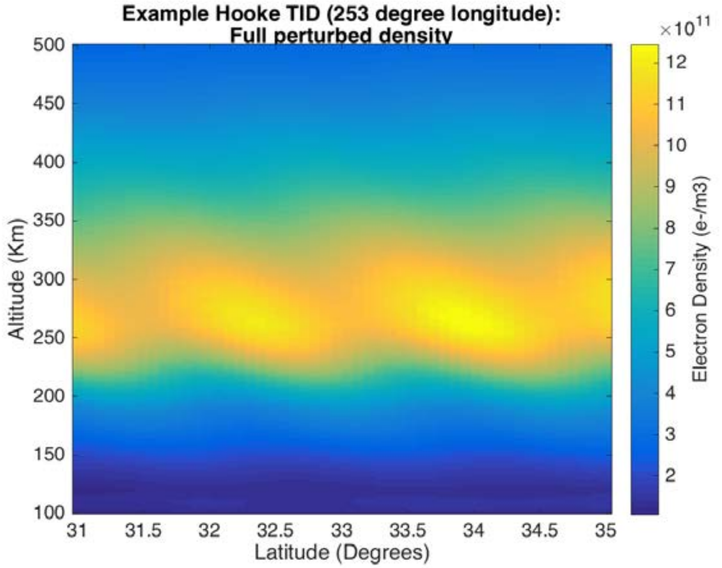
Motivation

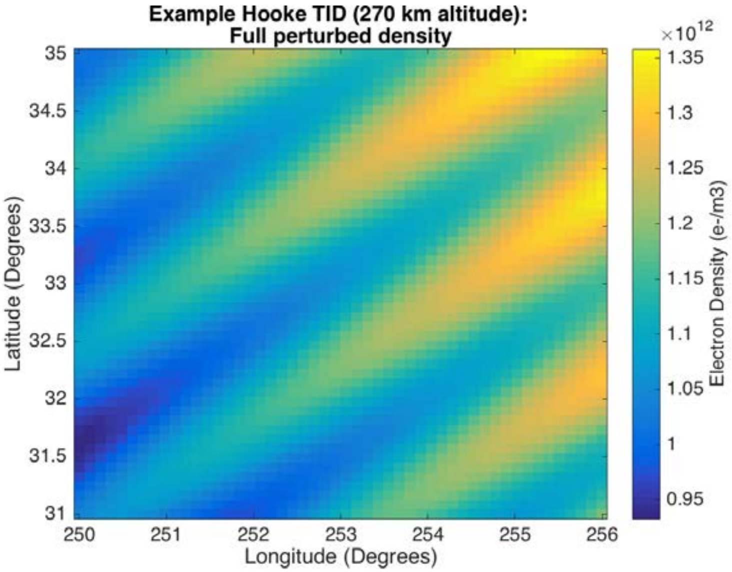
- **Geolocation**
  - **Geo-location of transmitters via sky-wave propagation has been a problem of interest for the scientific community for a number of years, from the 1990s to current times**
    - *Bust, et al., Application of ionospheric tomography to single-site location range estimation, Int. J. Imag. Syst. Technol.,5,160-168 (1994)*
    - *Pagani et al., A Study of HF Transmitter Geolocation Through Single-Hop Ionospheric Propagation,, EuCAP 2014)*
  - **The dynamically changing ionosphere can cause significant challenges to HF geolocation – particularly traveling ionospheric disturbances (TIDS) on the bottom-side of the ionosphere.**
- **Scientific studies of bottom-side TIDS**
  - **Measure TIDS over wide geographical region, times of day, geophysical conditions**
  - **Characterize physical parameters of TIDS**

Bottom-side TIDS

Example TID model:

- Hooke physics – based model of TIDS
- Physical parameters:
  - Horizontal wavelength 160 km
  - Wave direction (horizontal) southeast
  - Vertical wavelength 200 km
  - **Amplitude 7 m/s along magnetic field**





Measuring TIDS

- **Most techniques used to measure TIDS only measure certain aspects of the TID**

- **For example ionosondes measure time delay but it is hard to interpret that in terms of spatial TID parameters**
  - **Need several spatially distributed systems to measure all parameters**

- **GNSS measures TEC - integrated density over all altitudes. Good for detecting presence of TIDS , but less sensitive to bottom side density variations**

- **Ground oblique HF can measure angles of arrival, time delay and Doppler.**
  - **But only 1 frequency typically – limited altitude information**
  - **Need multiple systems paths to measure spatial structure.**

- **Satellites could have broad-band HF transmitters.**
  - **But requires deploying multiple HF receivers**

- ***Broad band receivers on satellites - Use lightning as broad band sources***

Advantages of Lightning

- **Its akin to having an oblique sounder in space with a broad band HF ground transmitter that gives TOA over a broad band of HF frequencies**

- **Because the lower HF band, ray bends as it goes through the ionosphere**
  - **we get all the advantages of an HF ground to ground Oblique HF except the receiver is in space**

- **Over a single Satellite pass we will measure a large number of such soundings from differing ground positions**

- **Previously demonstrated detection of broad-band lightning with Los Alamos FORTE satellite mission**

- **Waves in D-region previously studied from multiple ground-based lightning stations**
  - *Lay, E. H., and X.-M. Shao (2011), Multi-station probing of thunderstorm-generate D-layer fluctuations by using time-domain lightning waveforms, Geophys. Res. Lett., 38, L23806, doi:10.1029/2011GL049790.*

Lightning questions

- **Do strikes occur often enough for a LEO/GEO satellites?**
  - **Pick case of 20 strikes/km^2/yr**
  - **Take 300km x 300km square ~ 3.5 strikes / minute**
  - **Confirmed by FORTE (Los Alamos) satellite lightning registrations. Often 3-4 / minute**

- **How sensitive is the received time of arrival (TOA) versus frequency to bottom side TIDS?**
  - **10 micro-second resolution of delay corresponds to 100 kHz bandwidth – use as limit**

- **What frequency band and resolution for optimum detection of TIDS?**

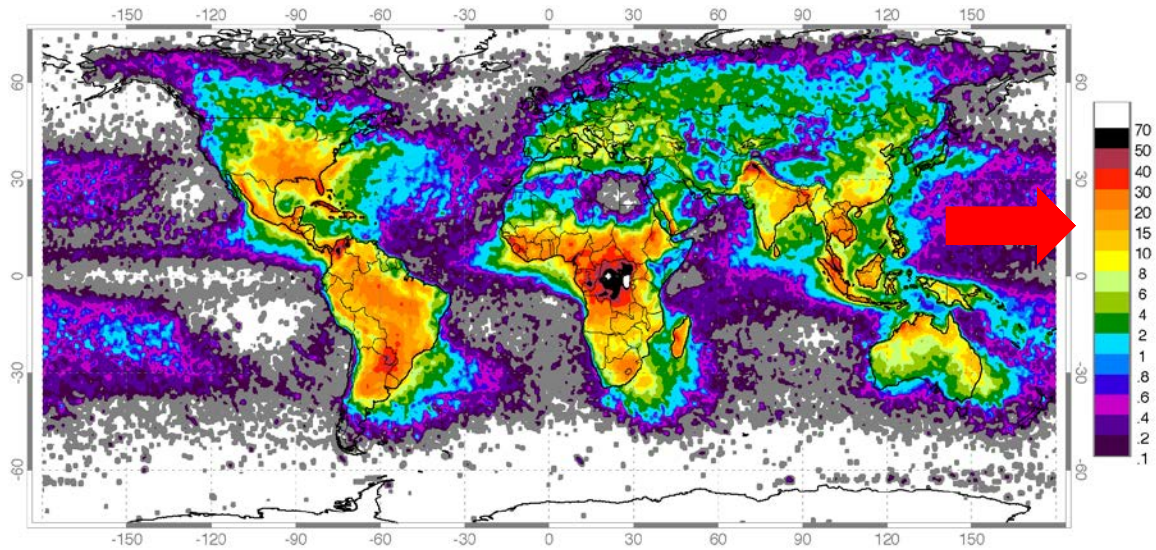


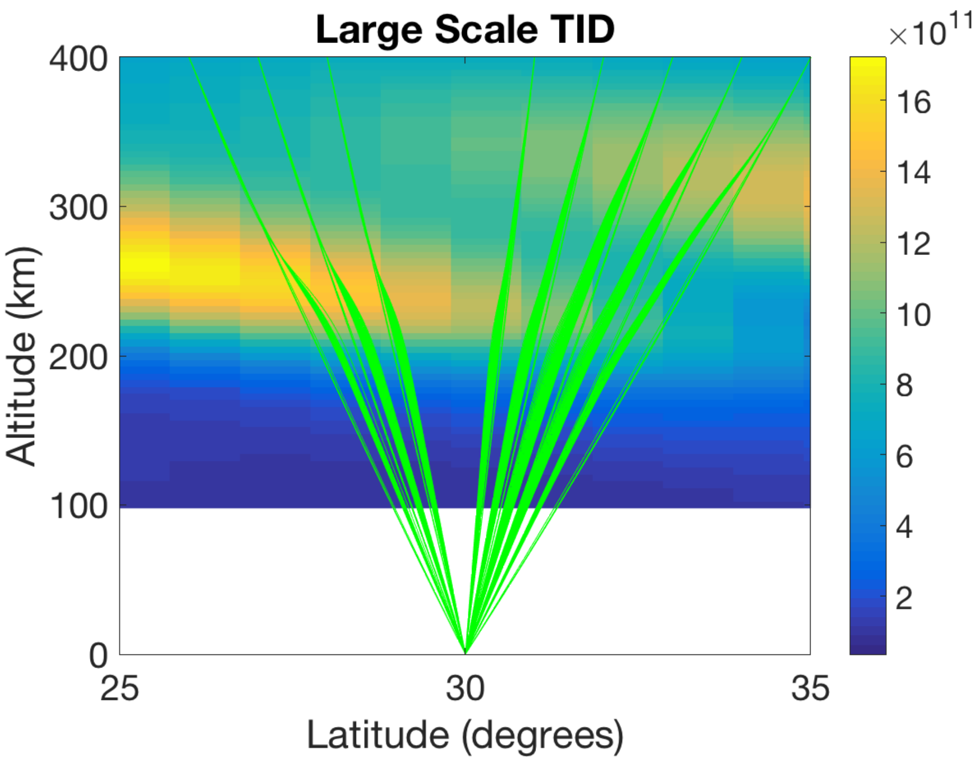
Figure attributed to NASA/GHRC/NSSTC Lightning Team - http://www.nasa.gov/centers/goddard/news/topstory/2004/0621lightning_prt.htmhttp://visibleearth.nasa.gov/view_rec.php?id=2264, Public Domain, https://commons.wikimedia.org/w/index.php?curid=208039

Simulations

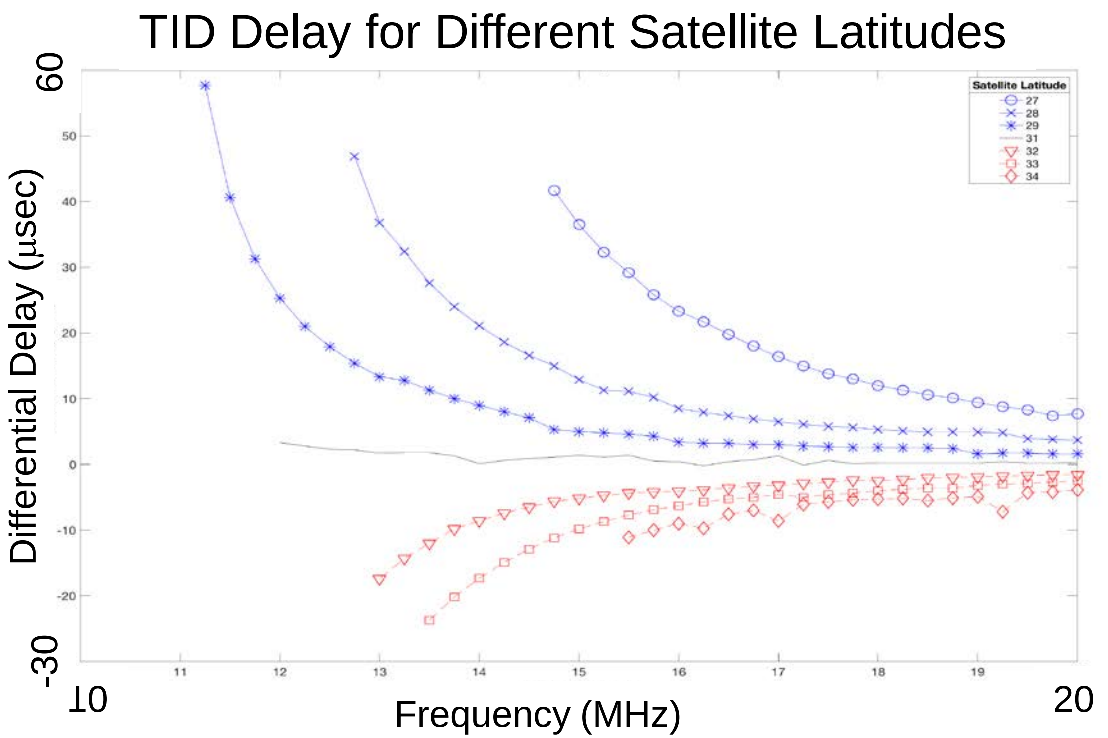
- **Wave simulations:**
  - **Background IRI**
    - **2014 mid latitude, day time**
  - **LSTID: 1000 km horizontal wavelength; 200 km vertical wavelength; 1 hour period; southeast propagation**
  - **MSTID: 160 km horizontal wavelength; 200 km vertical; 20 minute period; southeast propagation**

- **Lightning simulations**
  - **Pulser located at around 30 degrees latitude, 110W longitude (New Mexico)**
  - **Pulsing every 30 seconds**
  - **10-20 MHz with 0.25 MHz sampling, 40 and 80 MHz**
  - **Raytrace from lightning source to satellite using Strider raytracer (provided for our use courtesy of ARL:UT)**

- **Satellites**
  - **LEO at 400 km altitude**
  - **GEO**

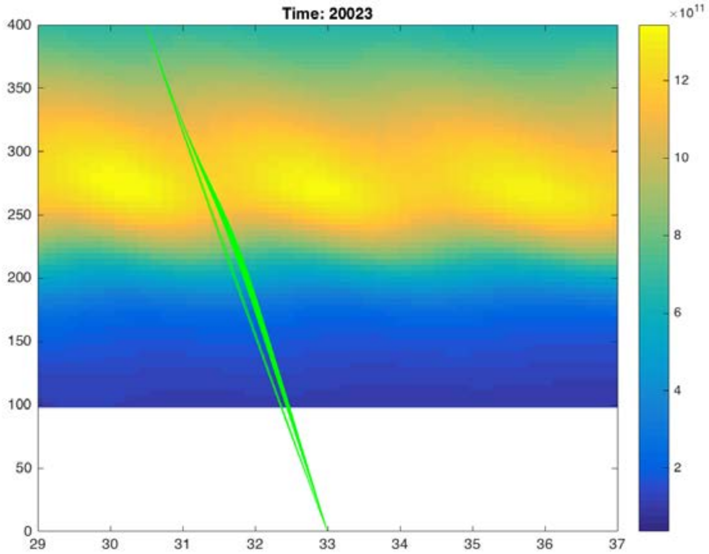


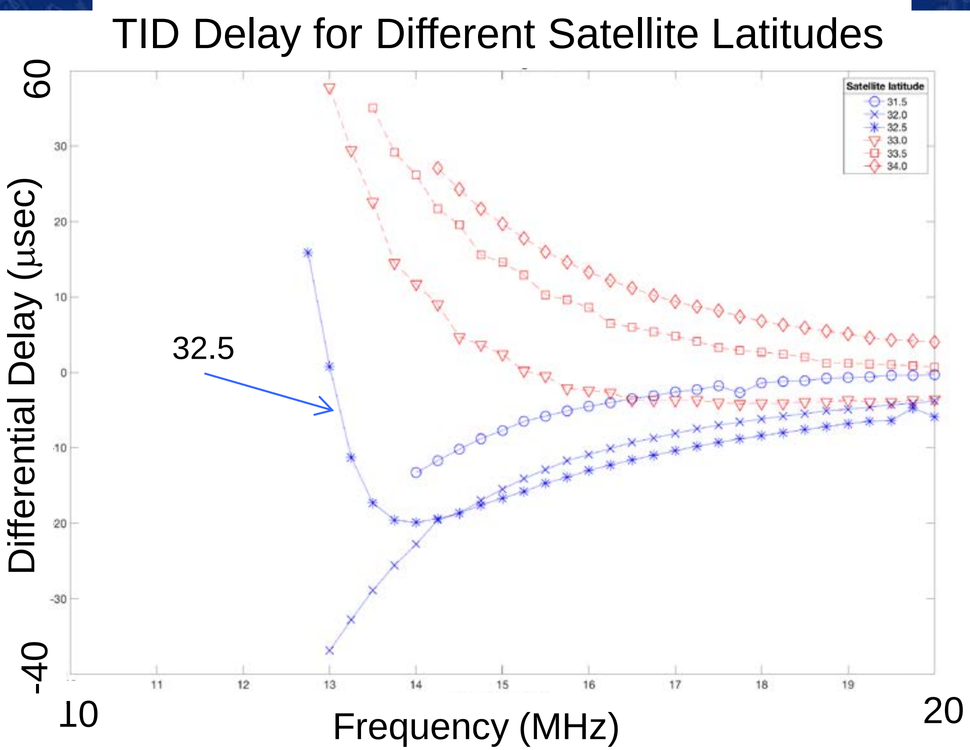
LEO Results: Large Scale TID (LSTID)



- Plot shows the differential delay versus frequency for a number of different satellite positions
- Blue for ground-satellite trajectories along TID phase front. Red across phase front
- Delays are clearly detectable for most frequencies < 20 MHz
- Sensitive to structure of the waves

LEO Results: Medium Scale TID (MSTID)



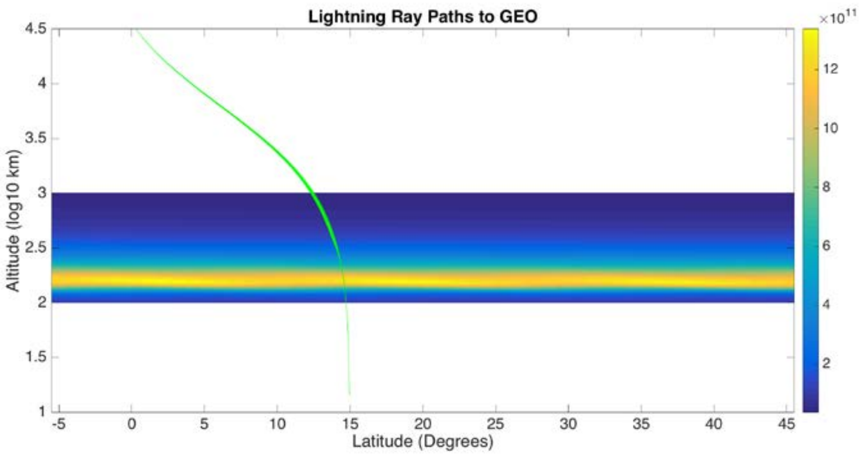


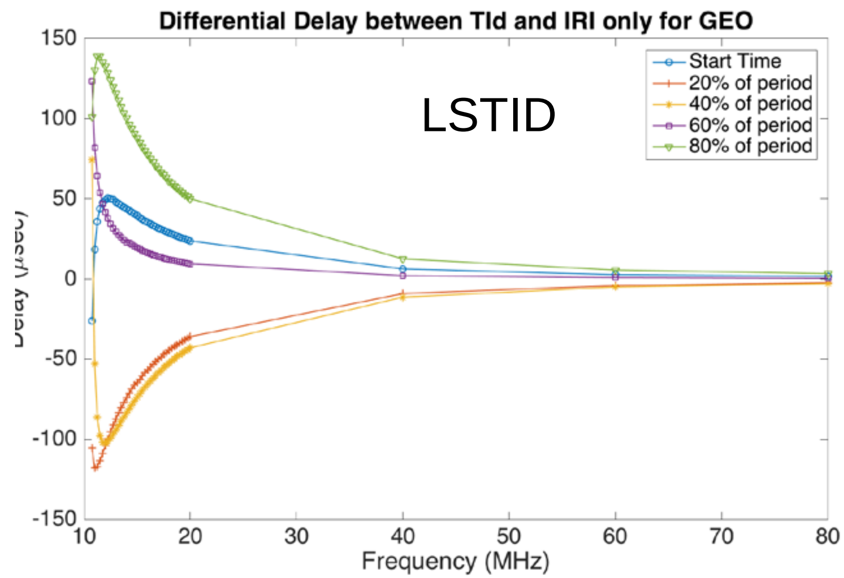
- Left hand plot shows variations in ray paths as different frequencies propagate through wave field
- Right hand plot similar to the large scale TID simulation
- Note the 32.5 satellite latitude plot (near vertical propagation) has a lot of structure about the wave.

GEO Results: Large Scale TID (LSTID)

Why GEO?

Los Alamos RFS instrument on SENSOR. launch 2019. 5-55 MHz lower band





GEO LSTID produces results similar to LEO.

Simulations show encouraging results towards GEO broadband HF transmitters to detect and characterize TIDS

- **What additional distortions and/or signal variations would structures like plasmaspheric waves cause?**

Summary

- We have shown through simulations that is is feasible to detect and characterize TIDS using lightning sources
- There are enough lightning strikes:
  - Over most land masses except high latitudes
  - ~3-4 strikes per minute in many places
- For LEO/GEO focus lower part of HF band with good resolution in frequency:
  - As low frequencies as environment and geometry allow for transionospheric propagation
- Large bandwidths – good time resolution
  - For 100 kHz, or 10 micro-seconds delays, LSTIDS and MSTIDS are detectable
- Structure differences in delay versus frequency plots for different times suggest spatial / time structure of TID can be extracted

Scientific Applicability

- A single LEO satellite could measure TIDS over a large range of latitudes and longitudes, all seasons and solar conditions
- A GEO satellite could continuously make measurements of TIDS from all lightning sources within its field of view
- A constellation of LEO and GEO satellites could allow measurement of TIDS over almost the entire globe every few hours.
- This will provide improved understanding of the physical sources are that cause TIDS, how those source vary geographically, diurnally, seasonally, and with solar-geomagnetic conditions.

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