



Morris Cohen¹

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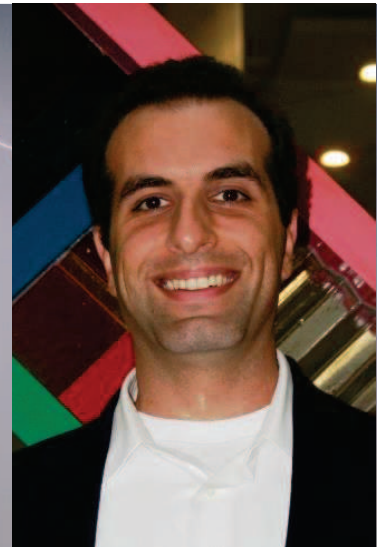
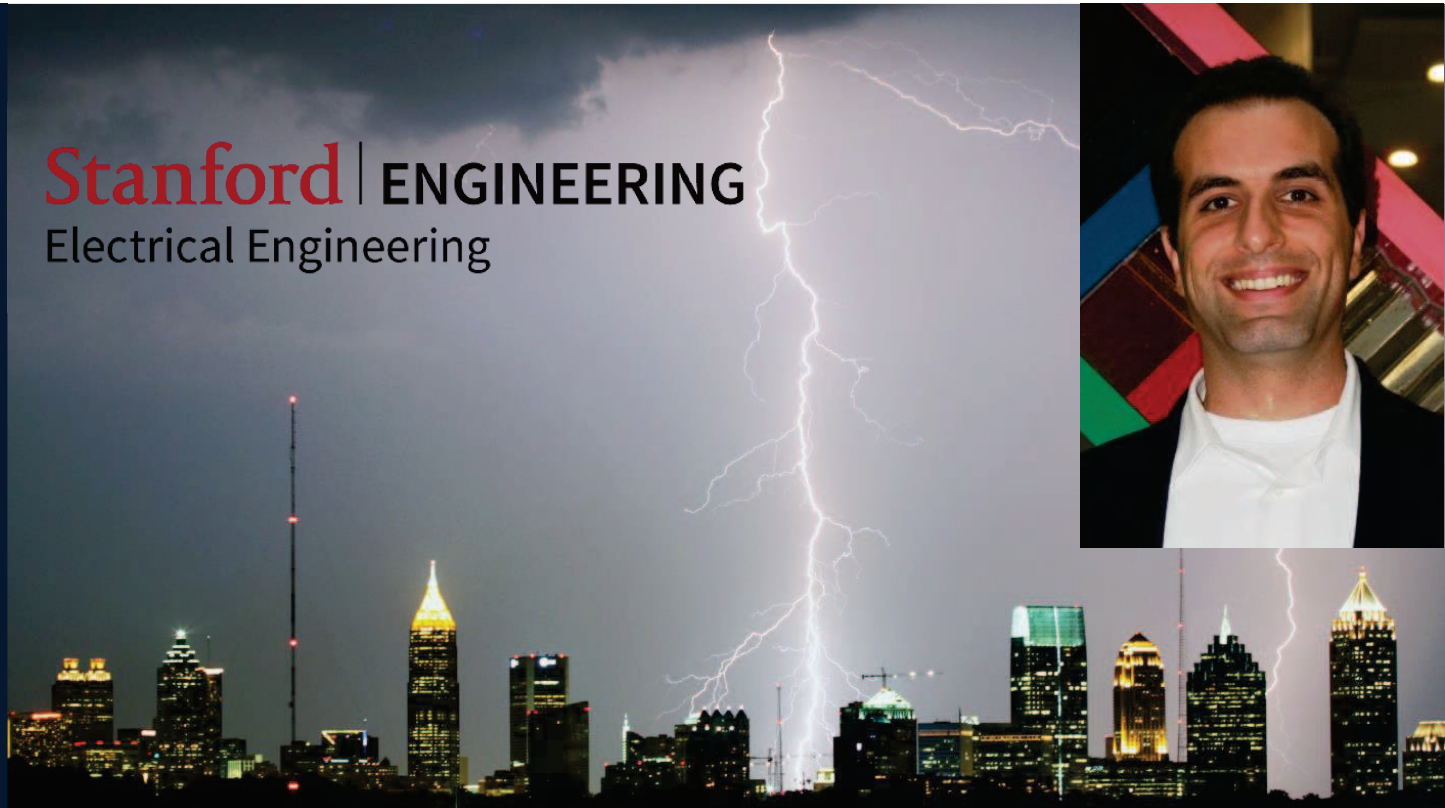
Wednesday, August 2

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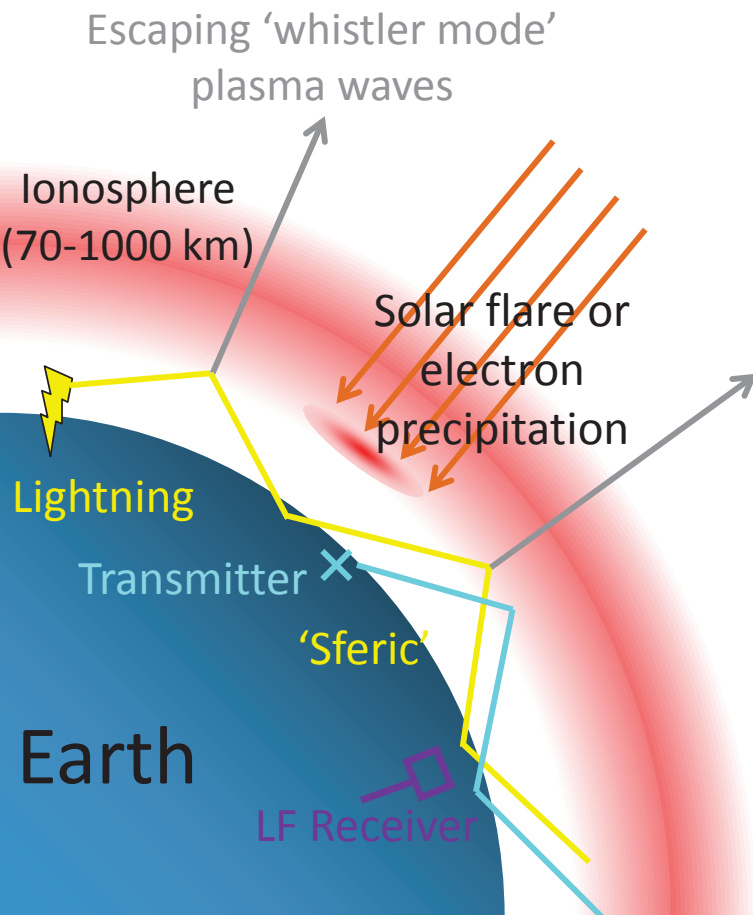
Stanford | ENGINEERING
Electrical Engineering



The AWESOME Program

VLF/LF Remote Sensing of the Ionosphere and
Magnetosphere: From IHY to ISWI and Beyond

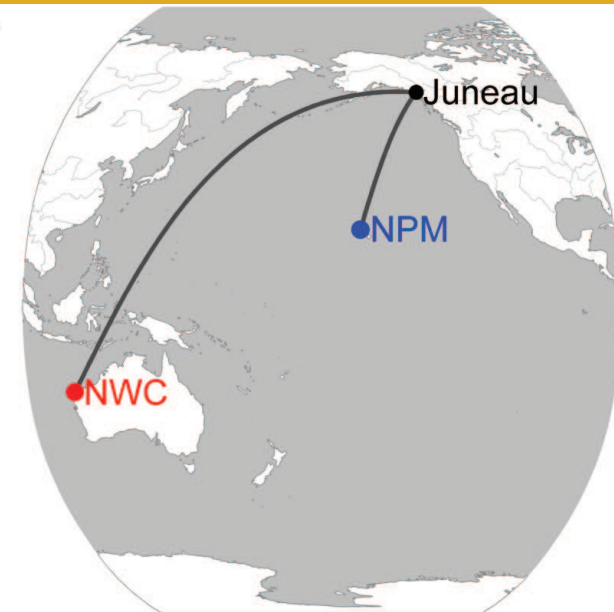
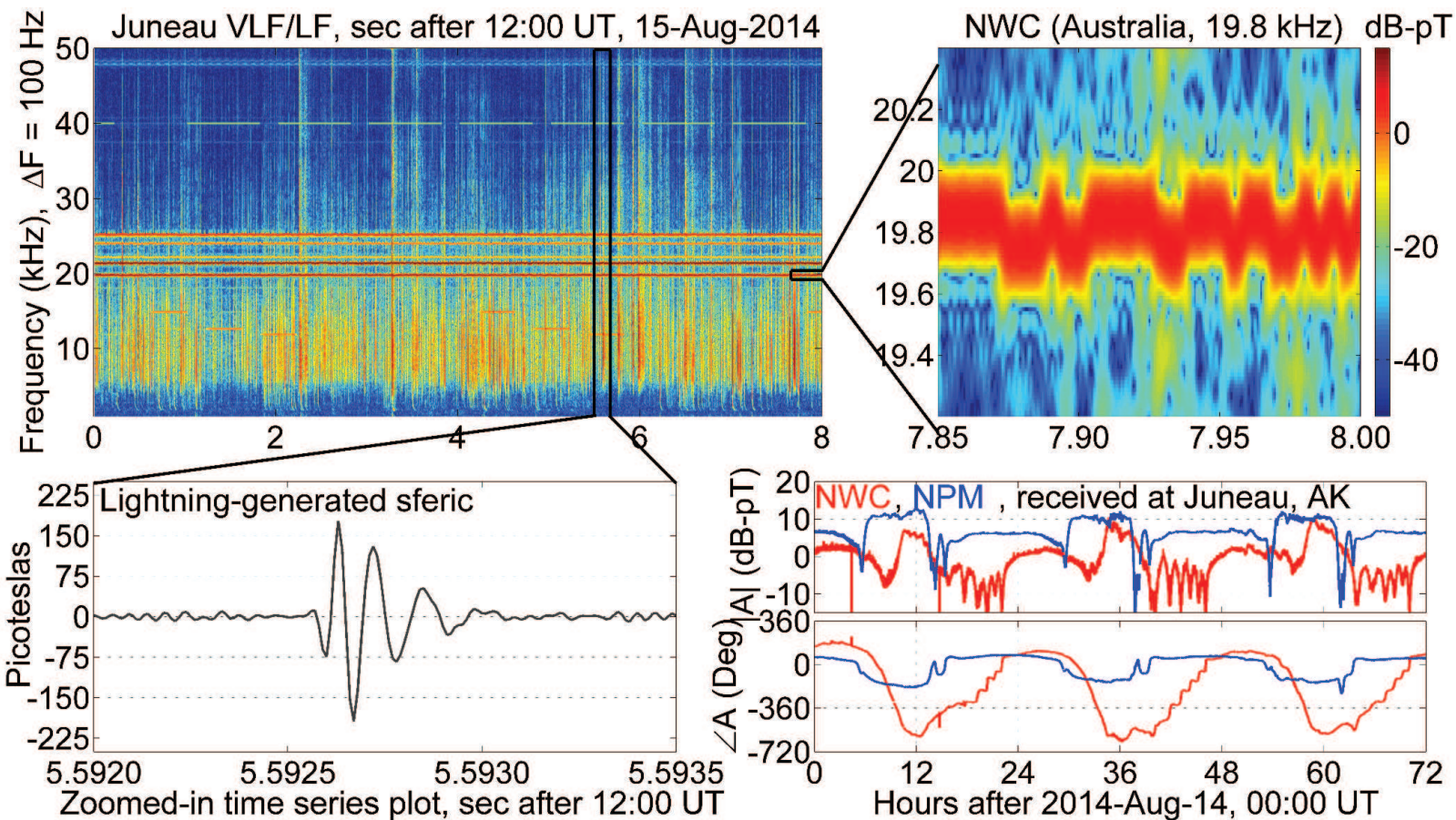
VLF/LF in Geophysics: Summary



- Sun's x-rays ionize atmosphere above ~ 70 km
- 'Ionosphere' acts like a metal
- Lightning generates powerful LF waves which propagate in Earth/ionosphere waveguide
- Navy transmitters for global submarine comm
- Global navigation before GPS
- Monitor lightning strokes
- Detect ionospheric outages
- Impacts on radiation-belt electrons
- We focus on **generation**, **propagation** and **detection** of VLF/LF waves

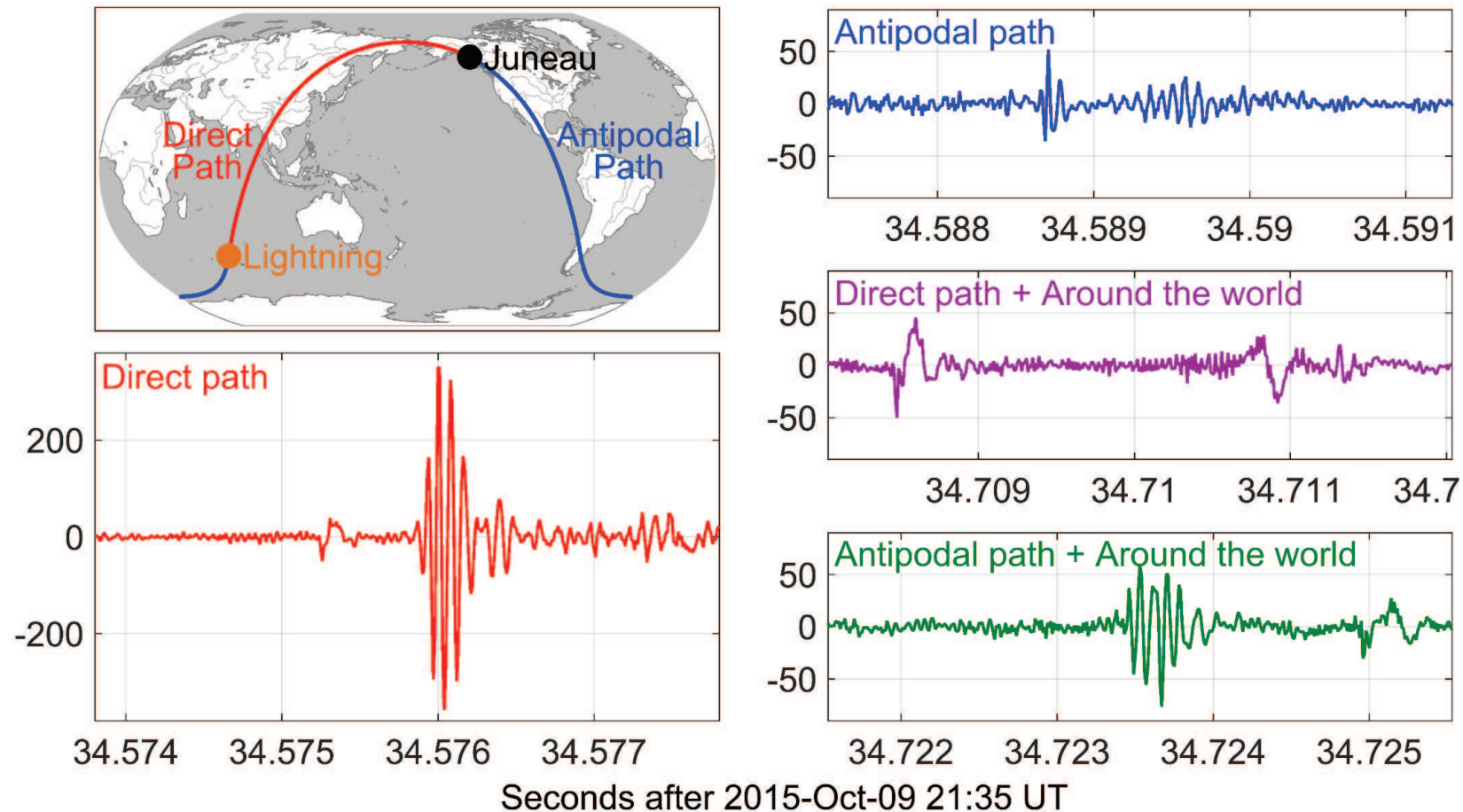


The Low Frequency Radio Environment



- LF data dominated by “sferics” from lightning, and naval radio stations

Multiple Lightning Echoes Around the World



VLF Radio Sferics Can Be Used to Geolocate Lightning

VAISALA

www.vaisala.com

Vaisala Global Lightning Dataset GLD360

Instantly detect lightning and convective activity anywhere over land and sea. Delivered as a dedicated data stream – no investment in hardware necessary.

Vaisala Global Lightning Dataset (GLD360) is a service which provides real-time lightning data for accurate and early detection and tracking of severe weather. Unbeatable long-range data precision and location accuracy.

Improve early warnings and operational effectiveness

Currently, long-range severe weather detection is limited by data gaps. These significant data gaps lead to late or no warnings for people, ships and planes.

The data provided by the GLD360 is generated by a Vaisala owned and operated world wide network. Fill the gaps in your radar coverage. Greatly enhance your forecasting and early warnings capability for high seas, thunderstorms and cyclones. Besides safety, this improves for example transportation route optimization.

Better than satellites

With the GLD360 there are no data gaps. Get complete uniform global coverage – unlike satellite or radar. Cloud-to-ground lightning is detected instantly, and data is delivered in less than two minutes.

Benefits

Detect in real-time, everywhere:

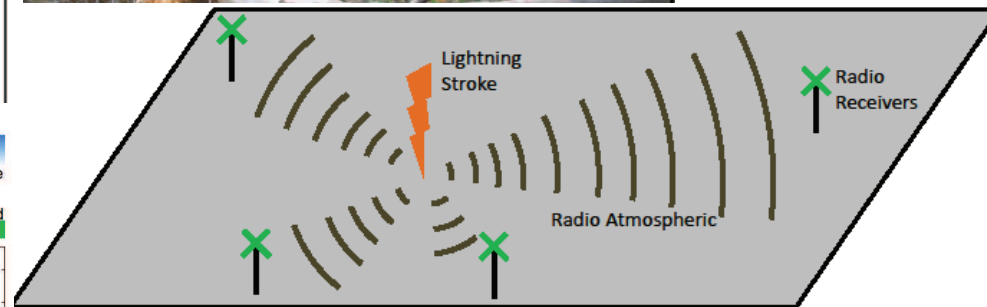
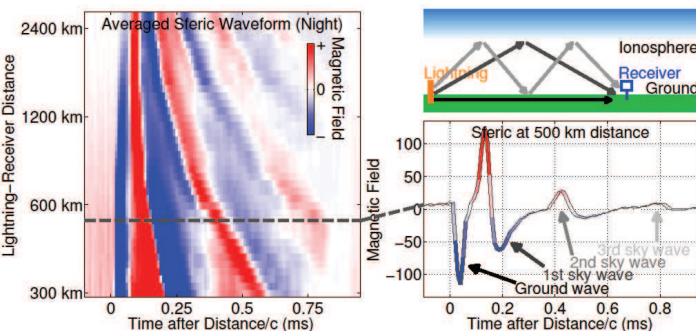
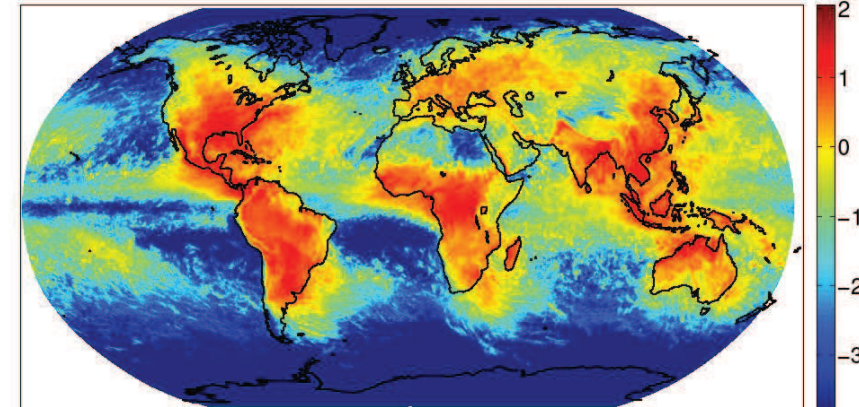
- First truly global and accurate lightning coverage.

No investment in hardware:

- The GLD360 is offered as a service. There is no need to own equipment and no maintenance concerns.

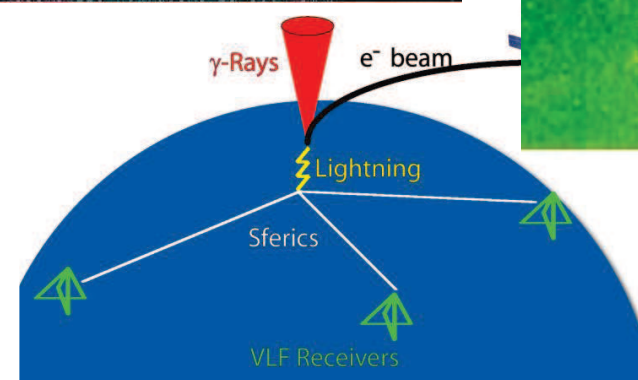
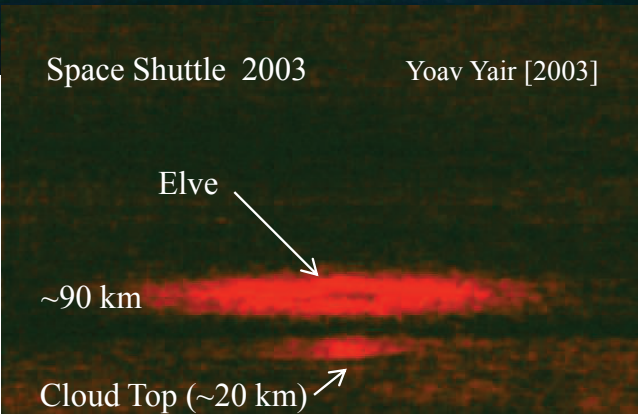
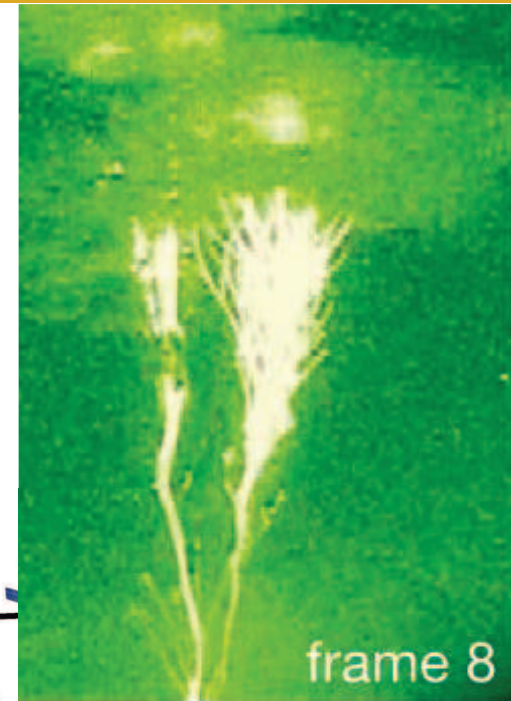
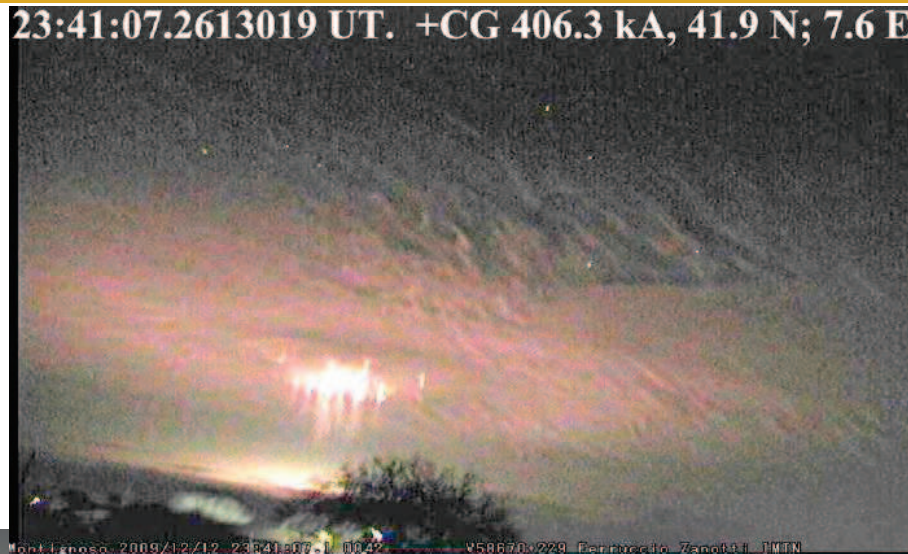
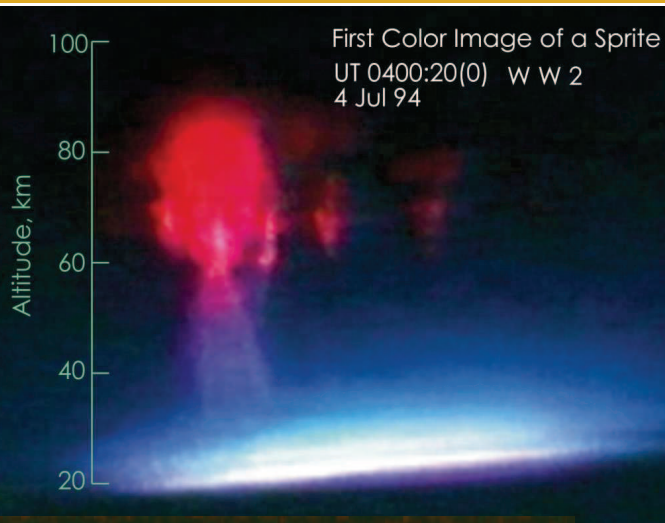
Delivery within a week:

- Begin receiving data within a week, which enables you to quickly provide better a service to your end-users.

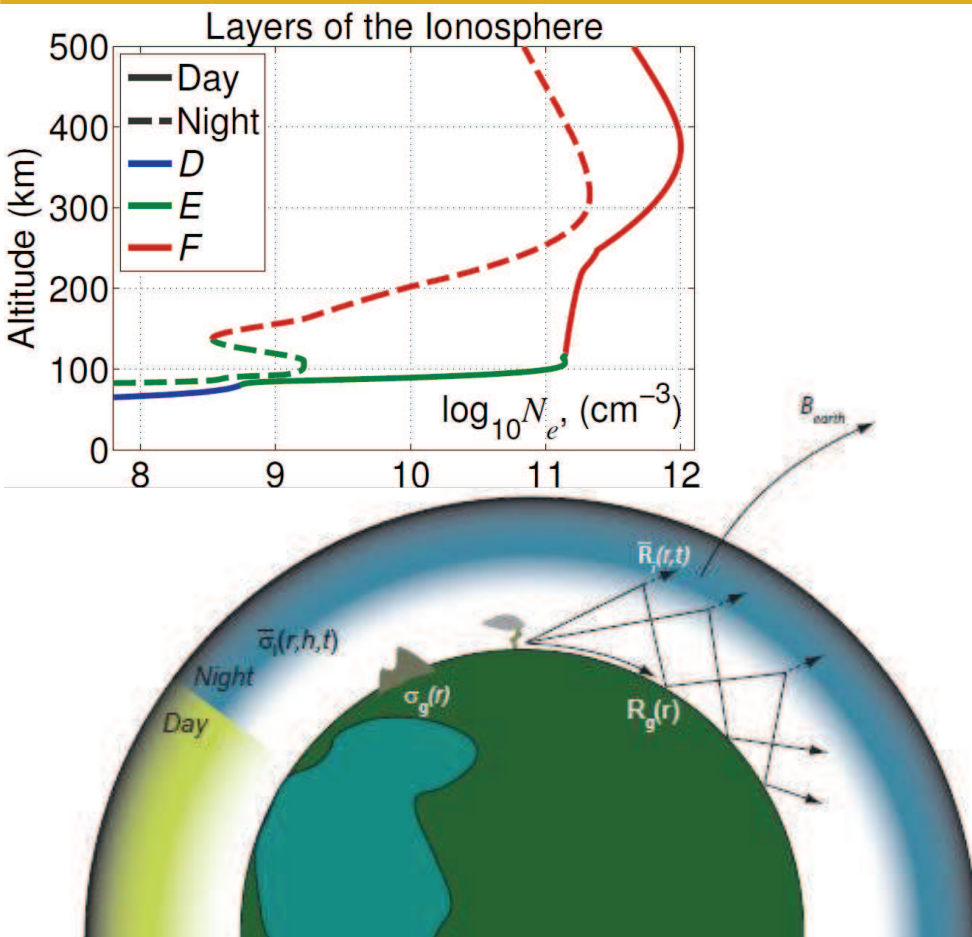


- Live lightning data important for power grid reliability, aviation safety, weather forecasting, and more

High Altitude Effects of Lightning

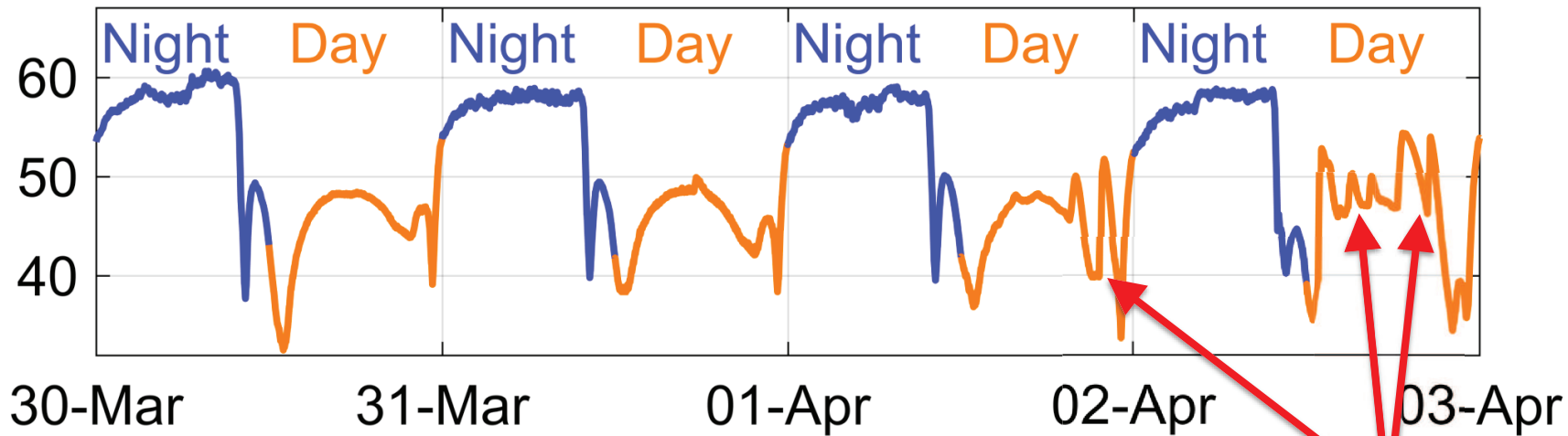
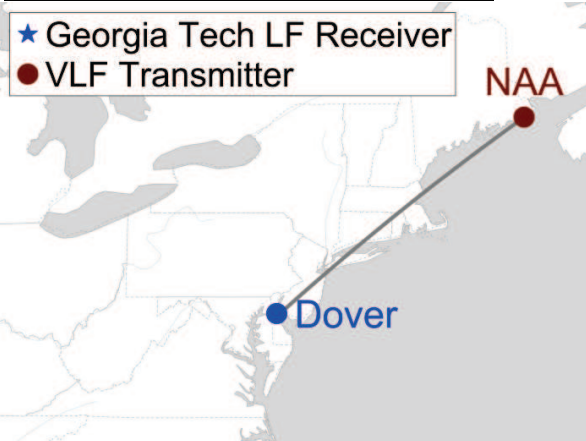
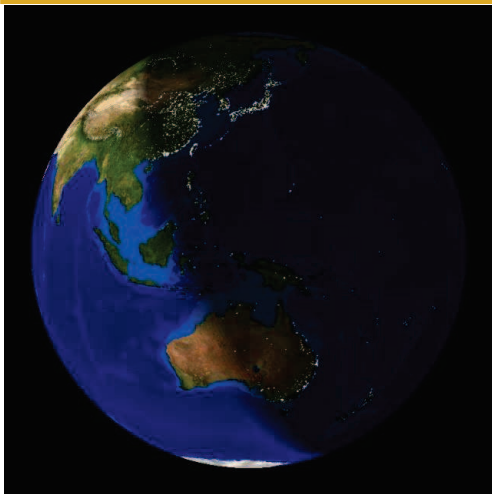


Remote Sensing of the Upper Atmosphere

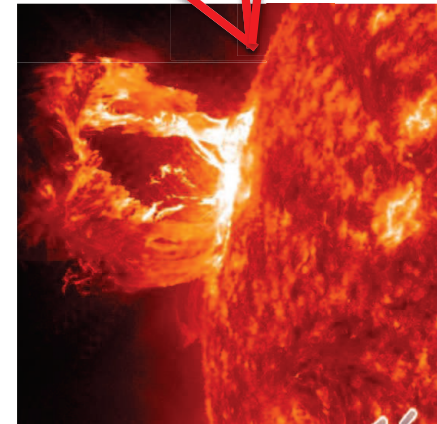


- The ionosphere is too high for balloons, too low for satellites
- VLF/LF radio stations (operated by navies) act as probe signal
 - It's our best way to study the ionosphere
- Ionospheric reflections are affected by even small changes to ionosphere
- Monitoring LF transmitter signal is intrinsically a *diagnostic tool*

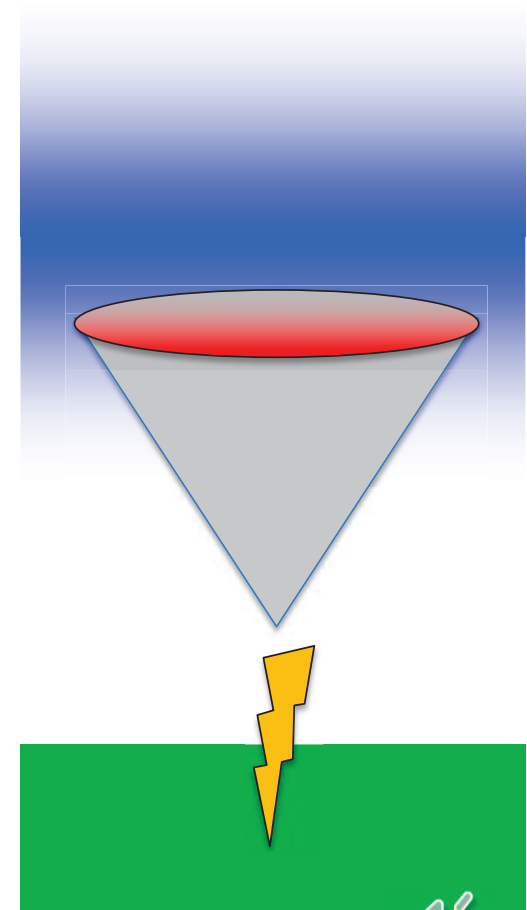
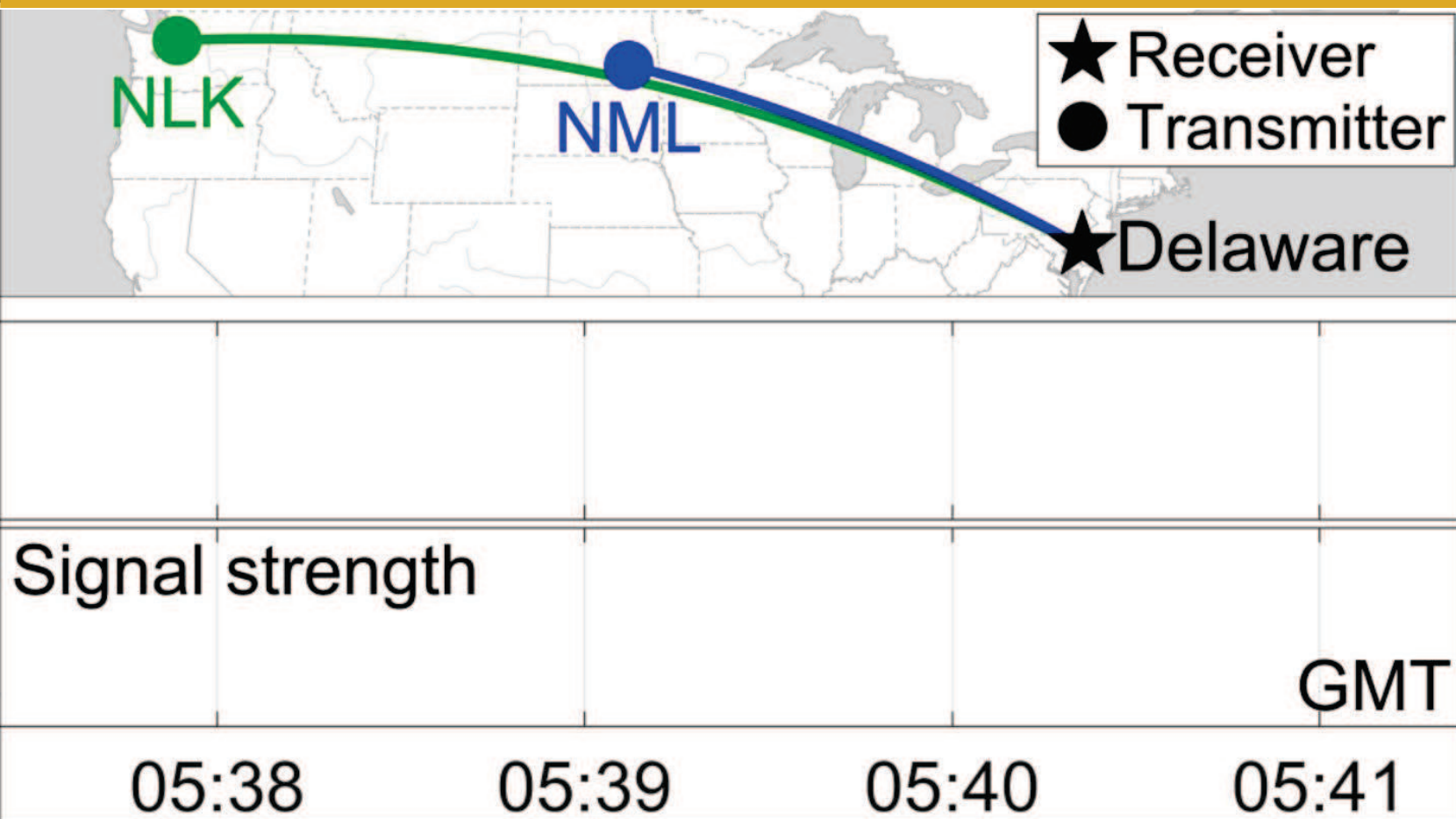
Diurnal Variations and Solar Flares



- LF Radio signals reach very long distance (1000s of miles)
- Signal levels change significantly at day/night boundary
- Solar flares disturb ionosphere

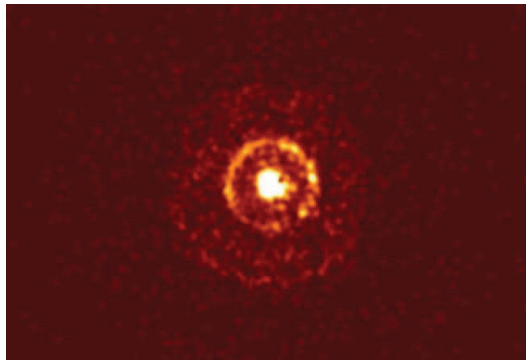
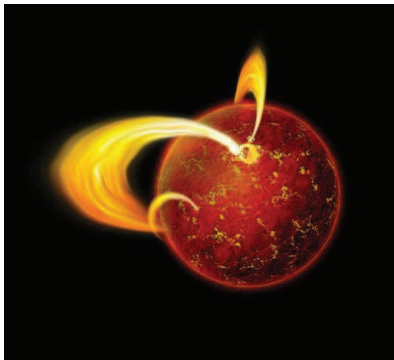


A “Patch Disturbance” from Lightning

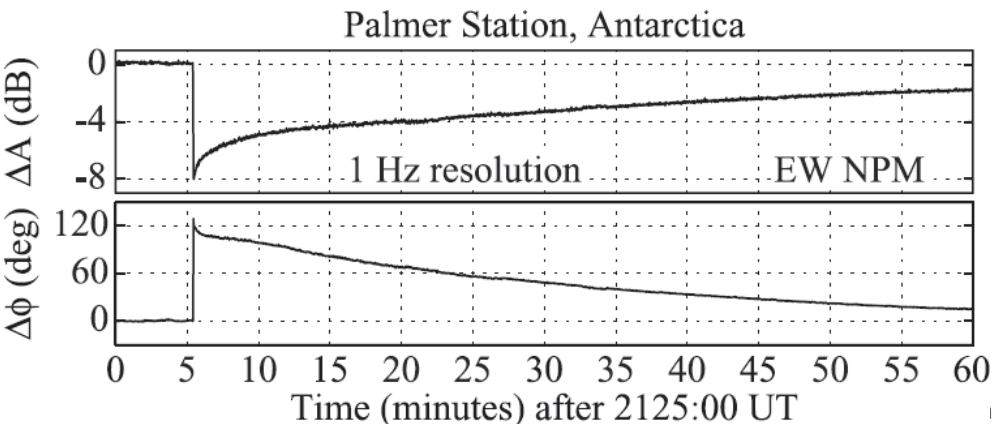


Soft Gamma Repeater (SGR)

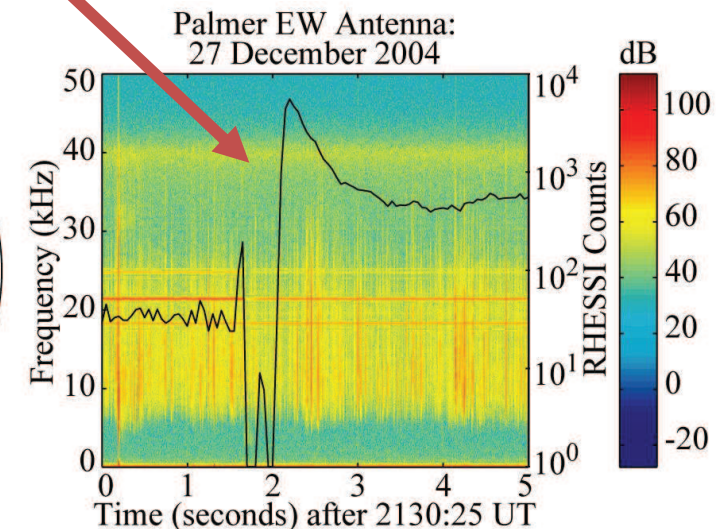
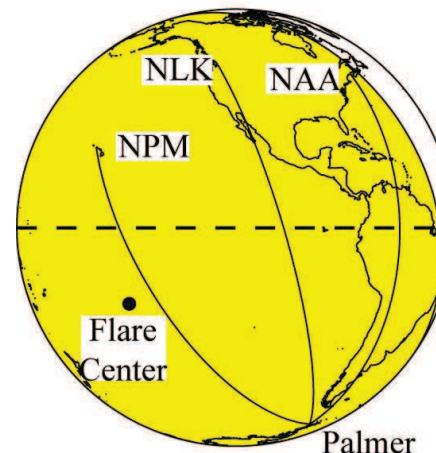
Neutron star emitting gamma-ray burst. Event onset clearly evident in broadband spectra, as amplitude reduction on all signals, including VLF transmitters and radio atmospherics



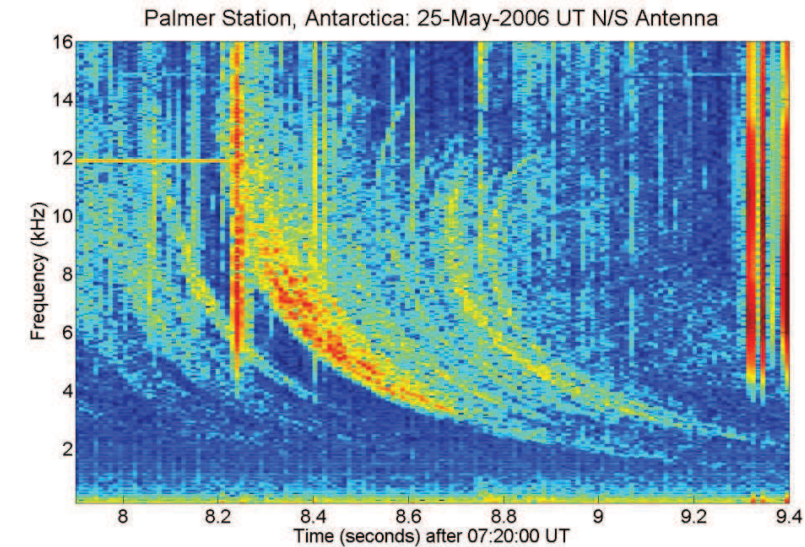
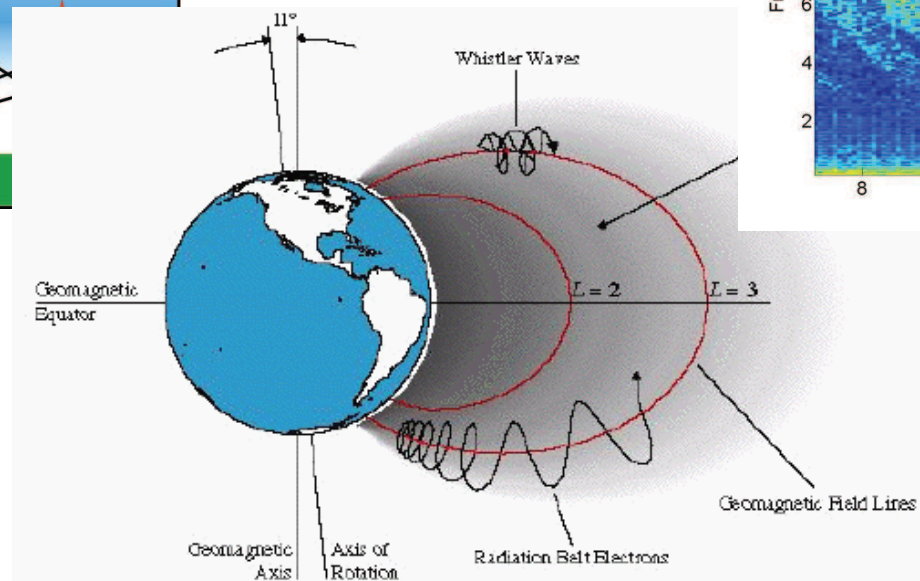
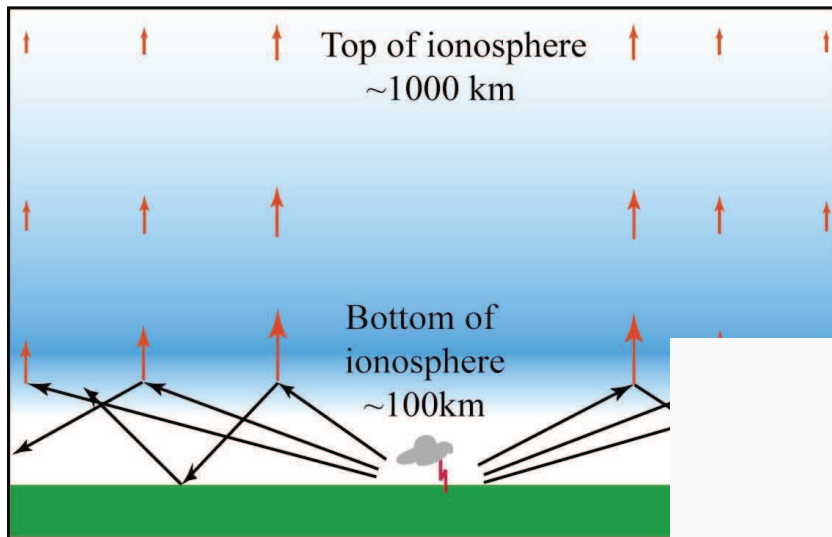
RHESSI satellite detectors saturate and stop counting



in et al. [2007, GRL]



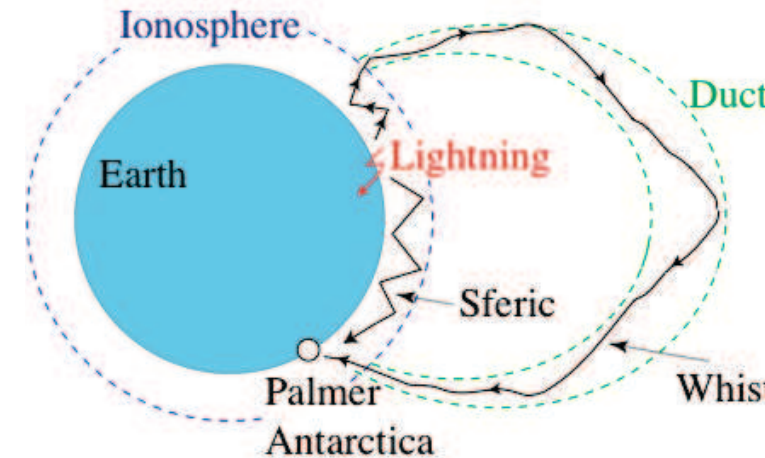
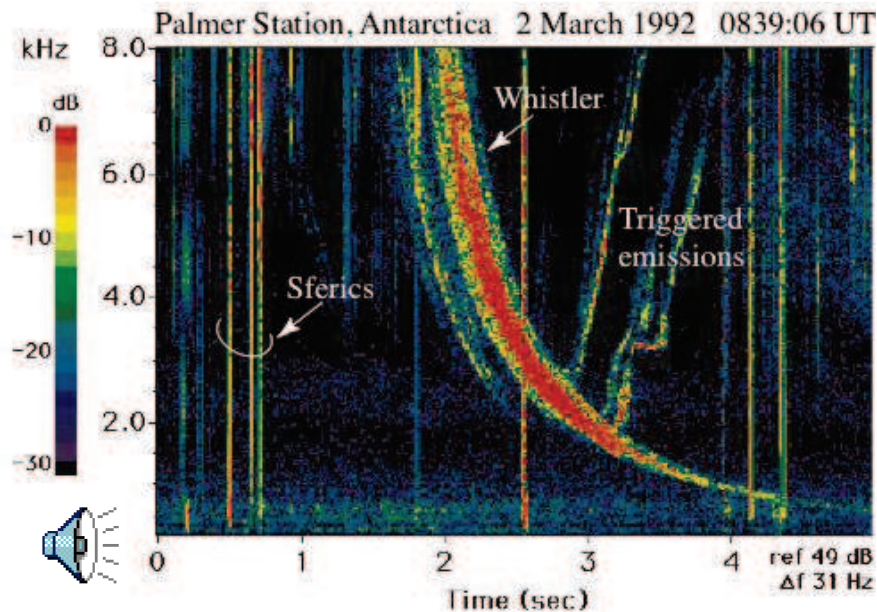
The Rest of the VLF Energy



Space is a Big Amplifying Tube for LF

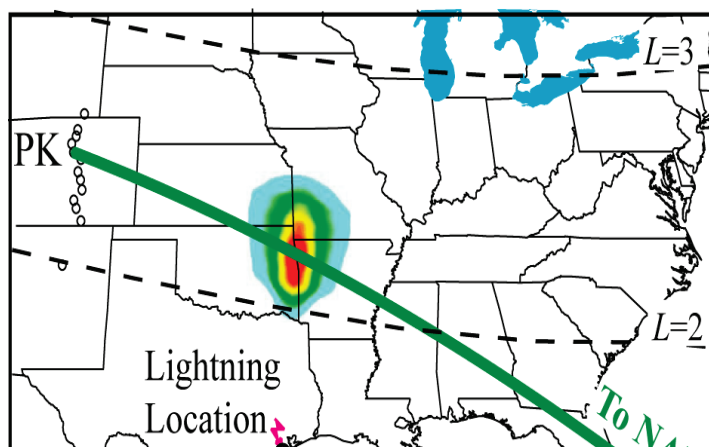


ELF/VLF waves can be ***amplified*** by trapped electrons, taking energy

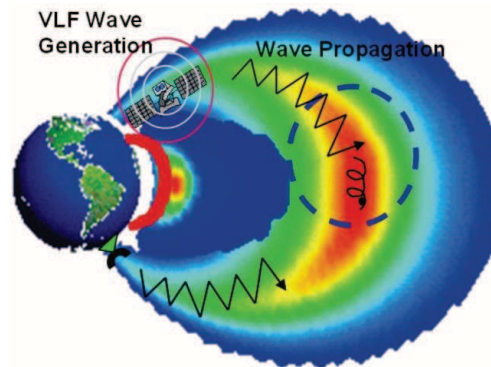
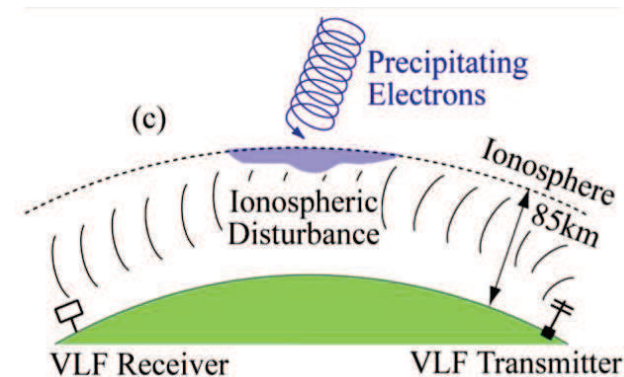
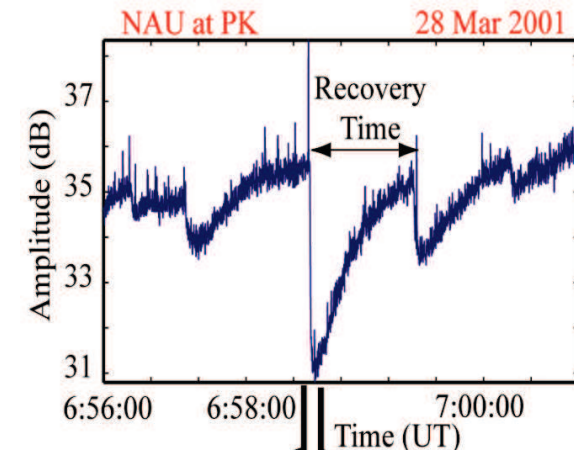


Nonlinear wave-particle interactions can ***trigger*** free-running emissions

VLF/LF Waves Drain the Radiation Belts



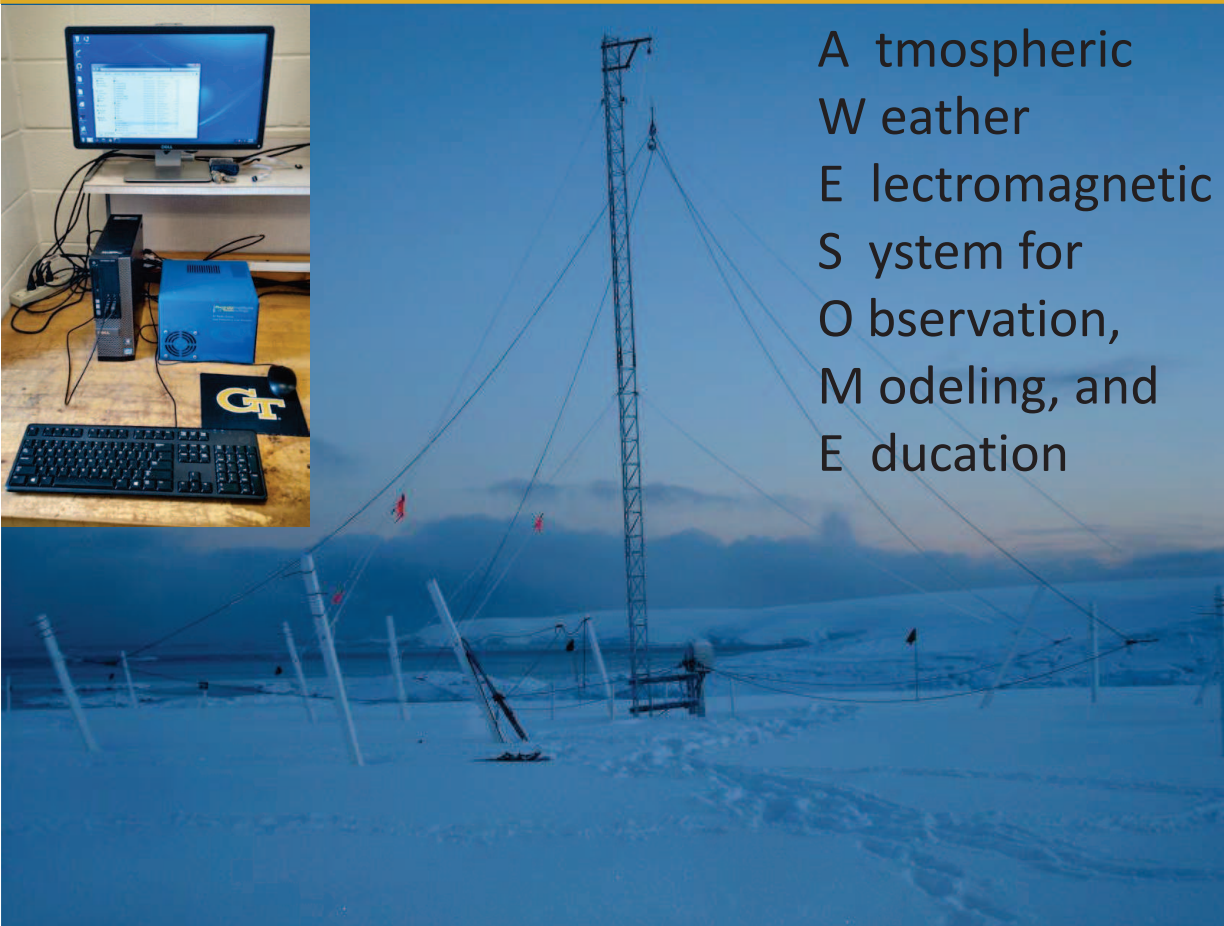
ELF/VLF waves can ***scatter*** trapped energetic particles



Scattered particles **precipitate** onto atmosphere

Ionosphere is **disturbed** by precipitation

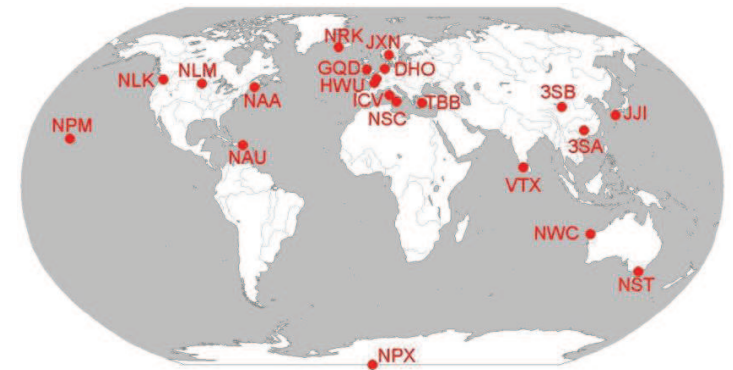
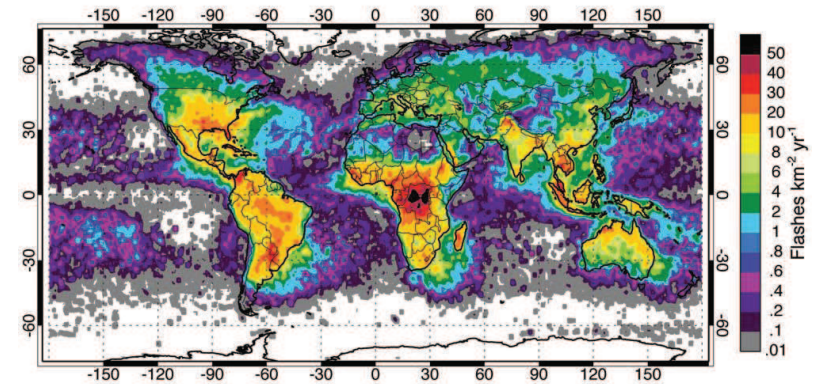
The AWESOME VLF Receiver



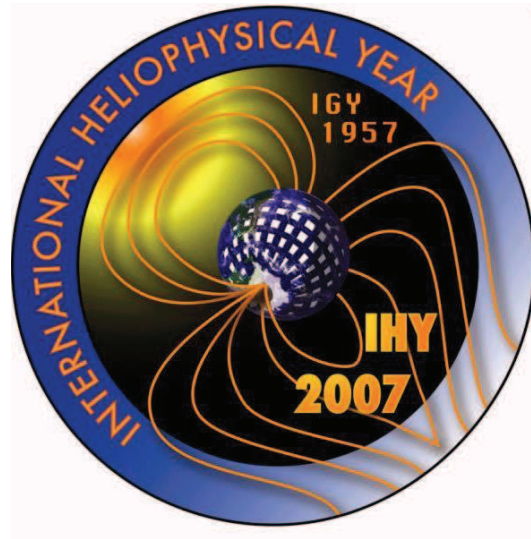
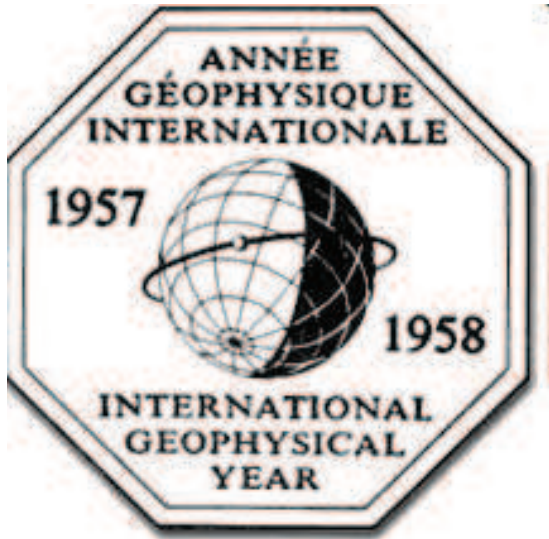
- 1 MHz sampling
- 1-450 kHz band
- Two orthogonal wire loop channels
- 15-20 ns timing accuracy
- 96 dB dynamic range
- Excellent sensitivity
 - ~ 0.03 fT/rt-Hz (30 kHz)

VLF is Intrinsically a Global Field¹⁵

- Lightning occurs globally
- VLF waves travel around the world
- Impacts effects of lightning vary with location
- Global observation system needed to understand VLF impacts
- Strong worldwide collaborations needed



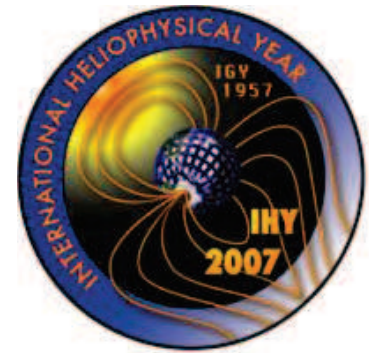
IGY (1957) → IHY (2007) → ISWI (2011)



- Program Goals
 - Global nature of science encourages regional and international collaboration
 - Broad science topics allows appeal to many different backgrounds, projects for students
 - Low-cost instrument advances and computational power allows global distribution of measurements

The AWESOME Network: 2007-2012

- Install VLF receivers globally under UN/NASA supported IHY/ISWI program
- Tutorials/data exercises available online
- Sharing of data globally
- Encourage publications by users
 - Many already published
- Develop regional collaborations
- International workshop series



Original Worldwide AWESOME Sites

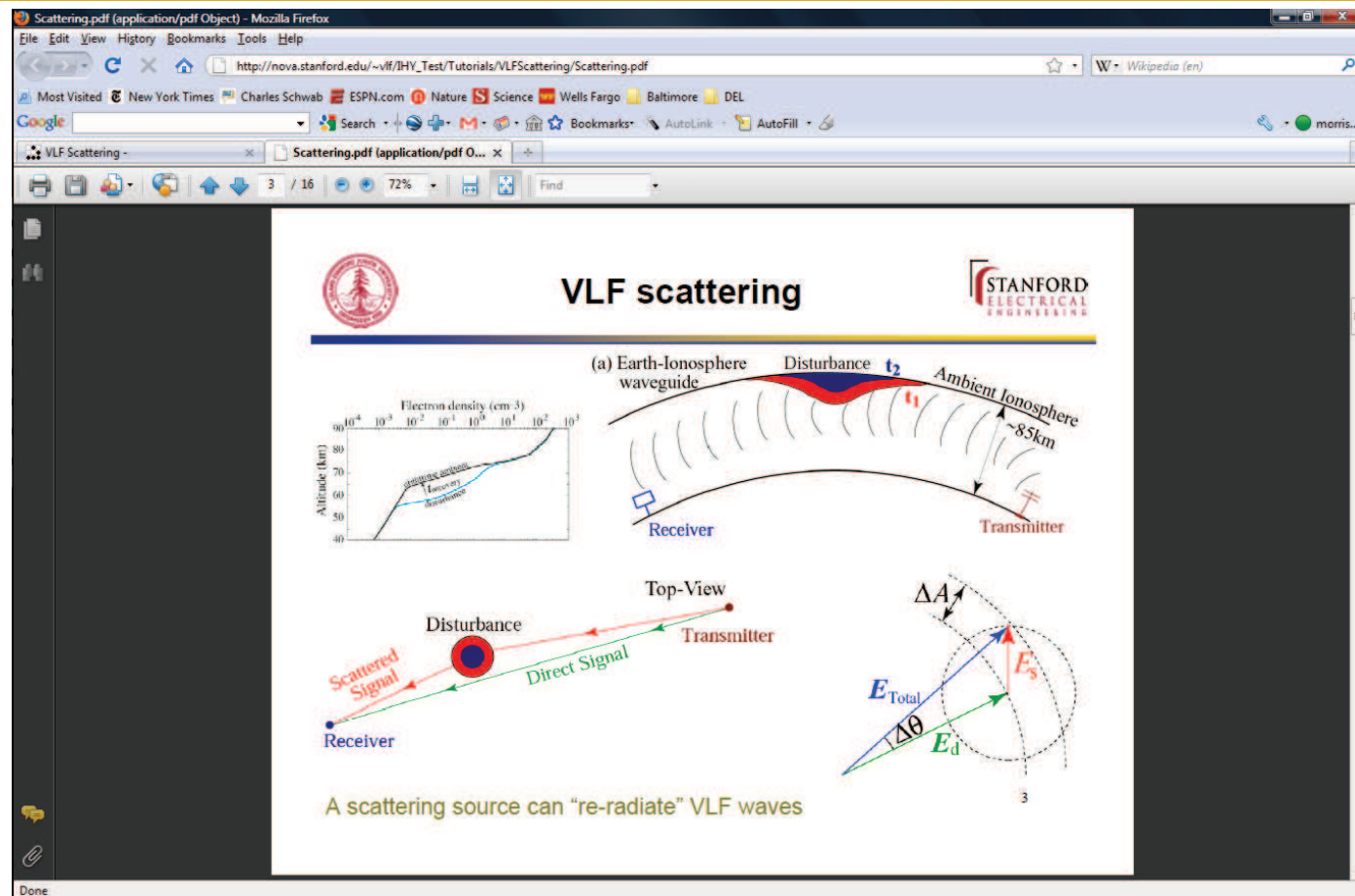


From Receivers to a Receiver *Network*



Online Tutorials

- Originally developed by Stanford VLF group, 2007-2008
- Distributed at 3 IHY/UNBSS/AWESOME workshops
- About to be re-released publicly after some updating



Data Sharing and Collection

- Data were collected on a large server at Stanford
 - Peak collection 2007-2011
- Server is no longer operating but data have been transferred to Georgia Tech
- Online access to be re-established again soon
- Future site hosts must allow sharing of data with public



Three International IHY/VLF Workshops

- Regional workshop August 2008, Bahir Dar, Ethiopia
- May 2009: Tunis, Tunisia
- February 2010: Sharjah, UAE
- November 2011: Goa, India
- 30-40 participants from 15-20 countries

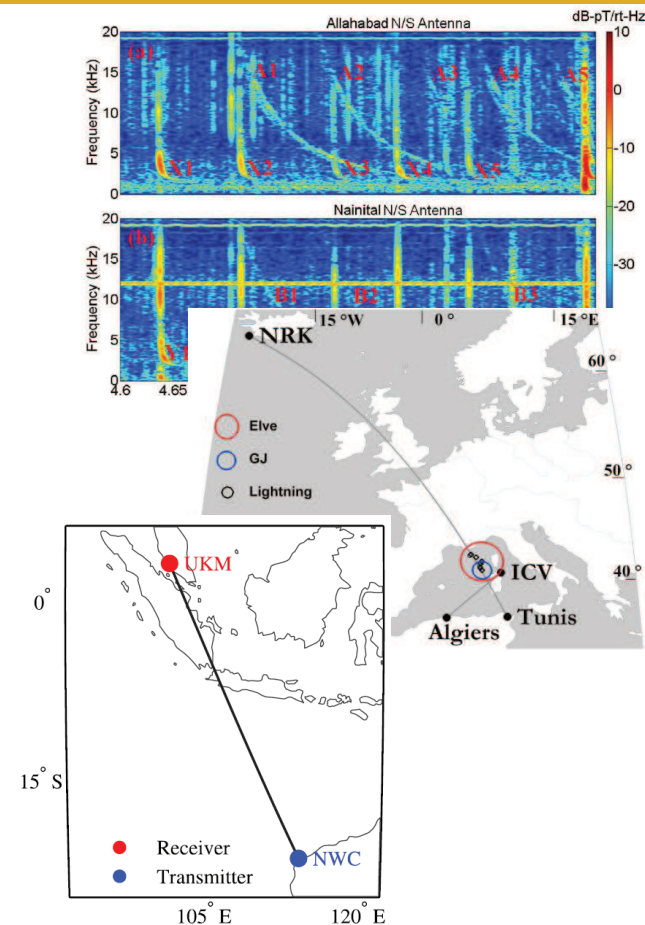


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Selected Success Stories

- VLF Group at Indian Institute of Geomagnetism (Rajesh Singh, B Veenadhari, Ajeet Maurya)
 - Broadband and narrowband VLF ionospheric remote sensing
 - Revitalized study of low-latitude whistlers
 - Several papers published, A. Maurya wins Fulbright Fellowship
- North African network (led by Samir Nait Amor, Algeria)
 - Geographic and peak-current dependence of early/fast events
 - Collaboration with groups in Greece, Libya, Tunisia
 - Now key collaborator in European EUROSPRITE/TEA-IS network
 - Part of ground observations to support multiple ESA satellites
- Malaysia VLF group
 - Two published papers on sea-based early/fast events
 - Student author now PhD student at Georgia Tech

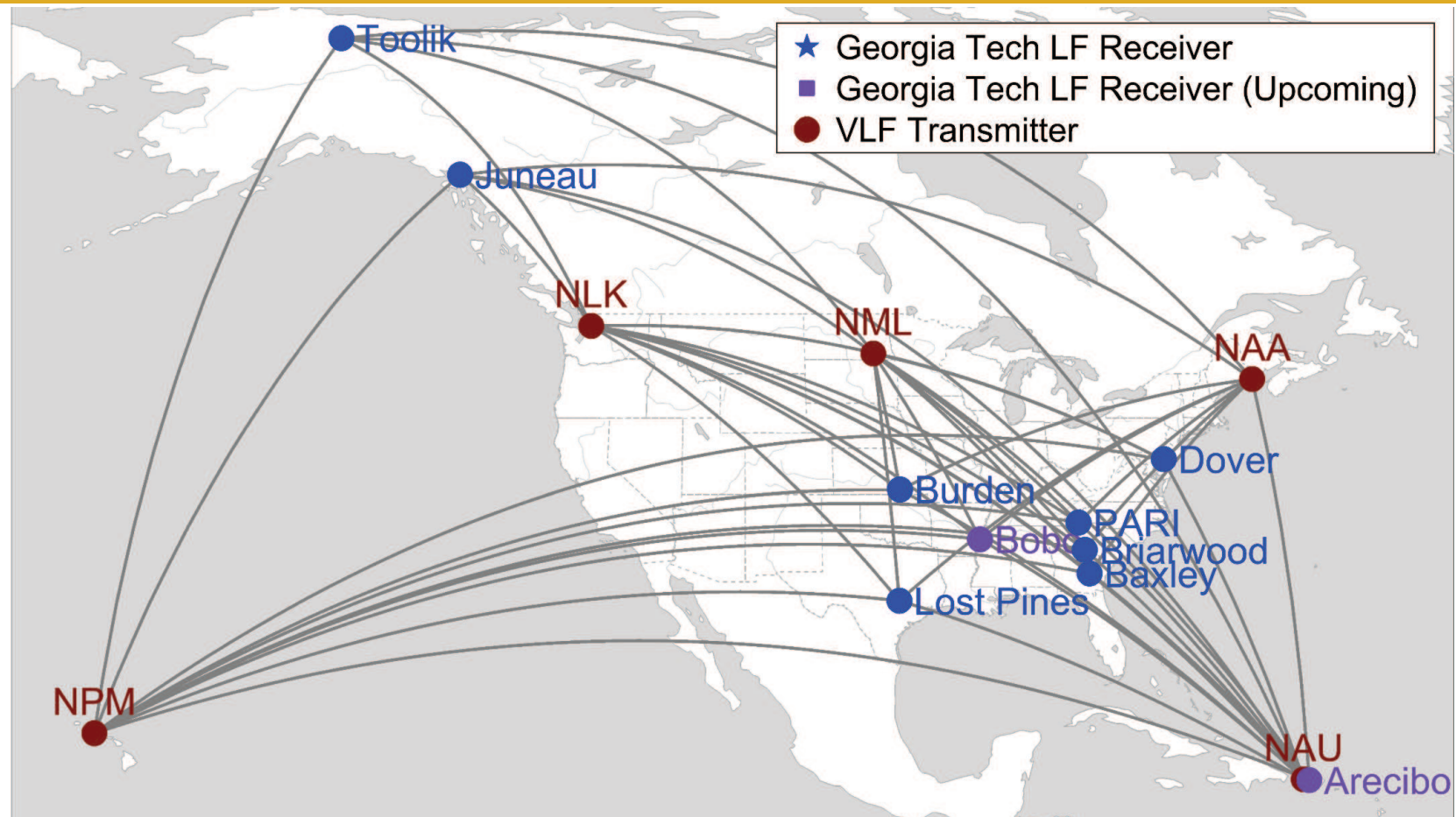


The AWESOME Network: 2013-Present

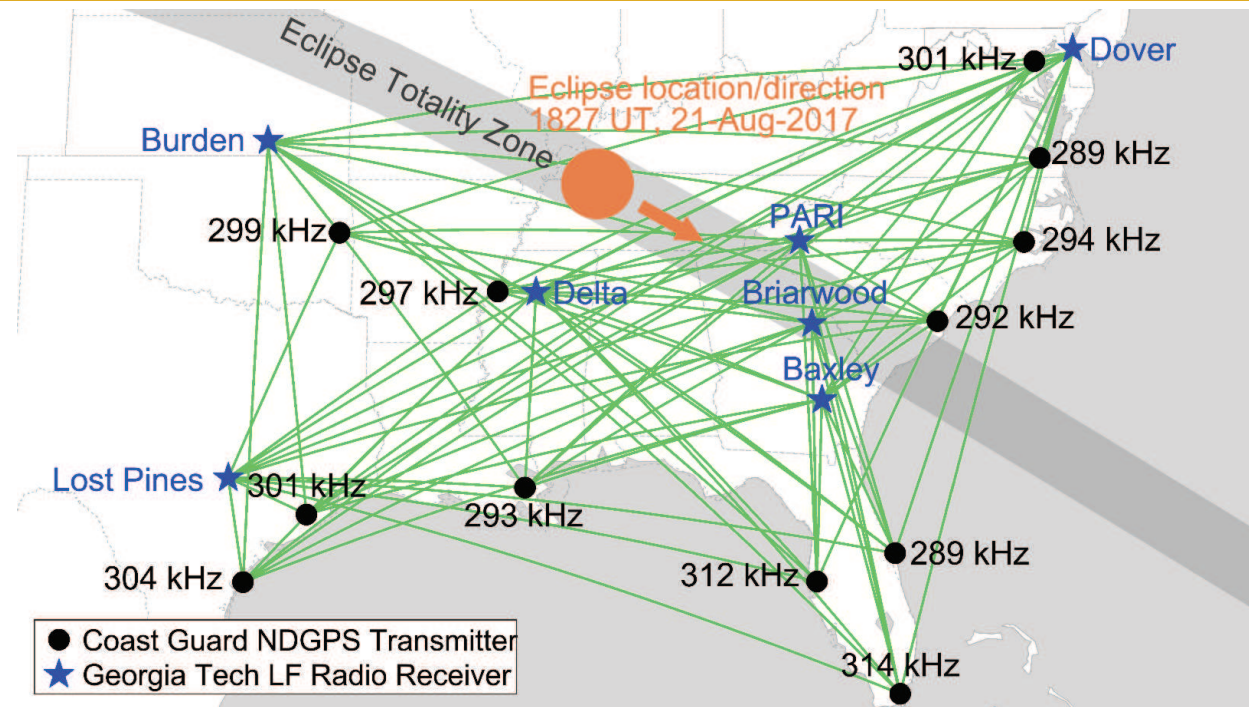
- Stanford VLF group no longer able to support VLF network following departure of Co-PI Umran Inan (now President of Koc University, Turkey)
- Existing sites continue to be maintained, regional collaborations continue
 - Long-recovery early/fast events
 - Low-latitude whistlers
 - Earthquake VLF precursor signals
 - Tweeks as ionospheric diagnostic
- Co-PI of VLF/AWESOME network, Morris Cohen, now at Georgia Tech (top-5 ranked engineering school) to continue collaborations
 - Tutorial/workshop materials being refurbished to be re-released
 - Receiver refreshed, now able to re-establish selected international sites



Grid of VLF Transmitter-Receiver Paths



Tracking Impact of Solar Eclipse with LF



- Eclipse forms moving patch of “night”, surrounded by day
- Radio scattering problem using web of transmitters/receivers at 300 kHz
- Funded by NSF/CAREER program

Low frequency radio science and engineering...

... the sky is no limit!

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