Investigation of earthquake-related signals using geomagnetic data from ground-based sensors, GPS ionospheric soundings, and space-based measurements

Eric Calais
Purdue University – West Lafayette, IN
ecalais@purdue.edu

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Collab. Tom Bleier
QuakeFinder – Palo Alto, CA

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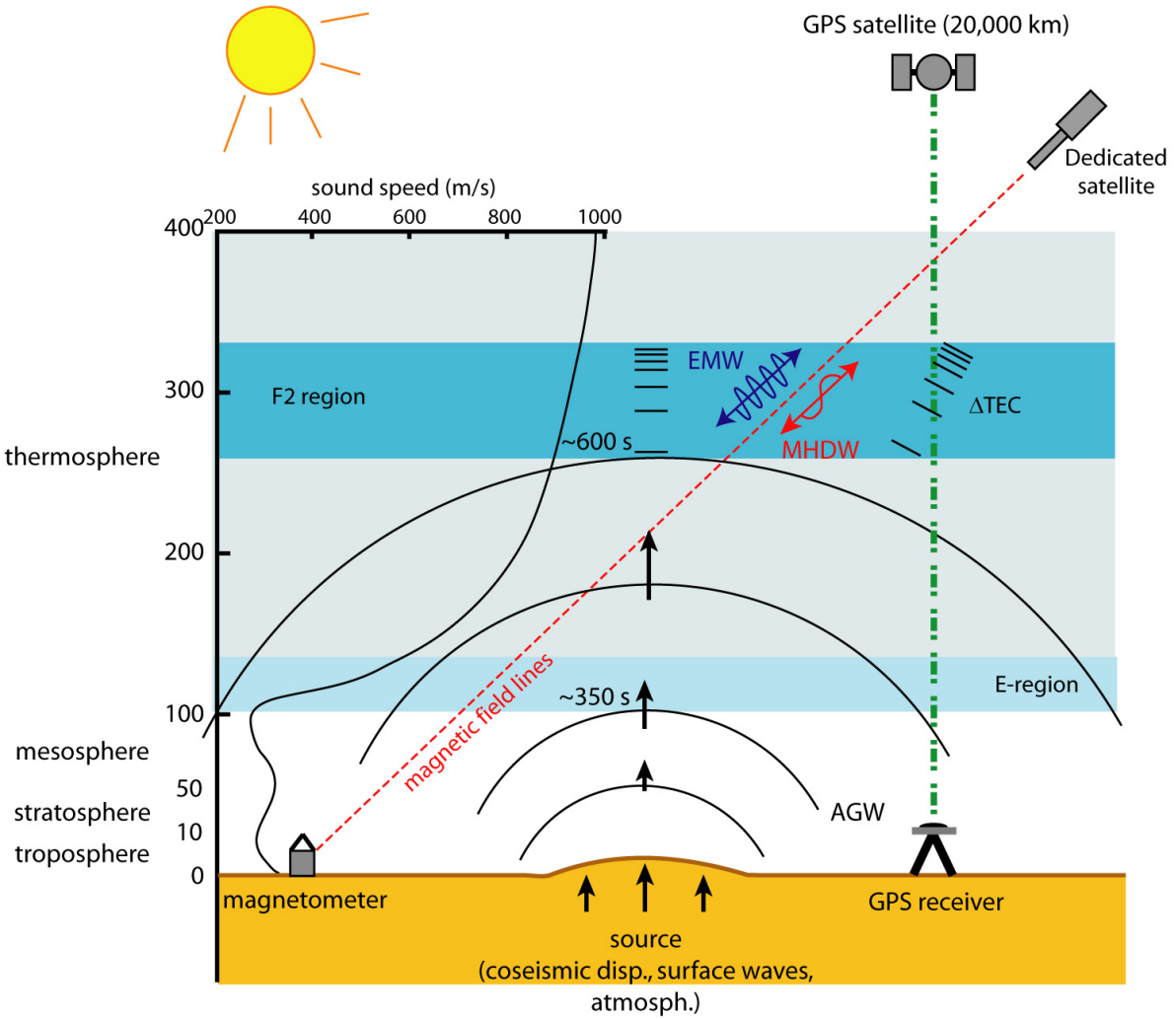
Background



Ground motion / atmospheric source:

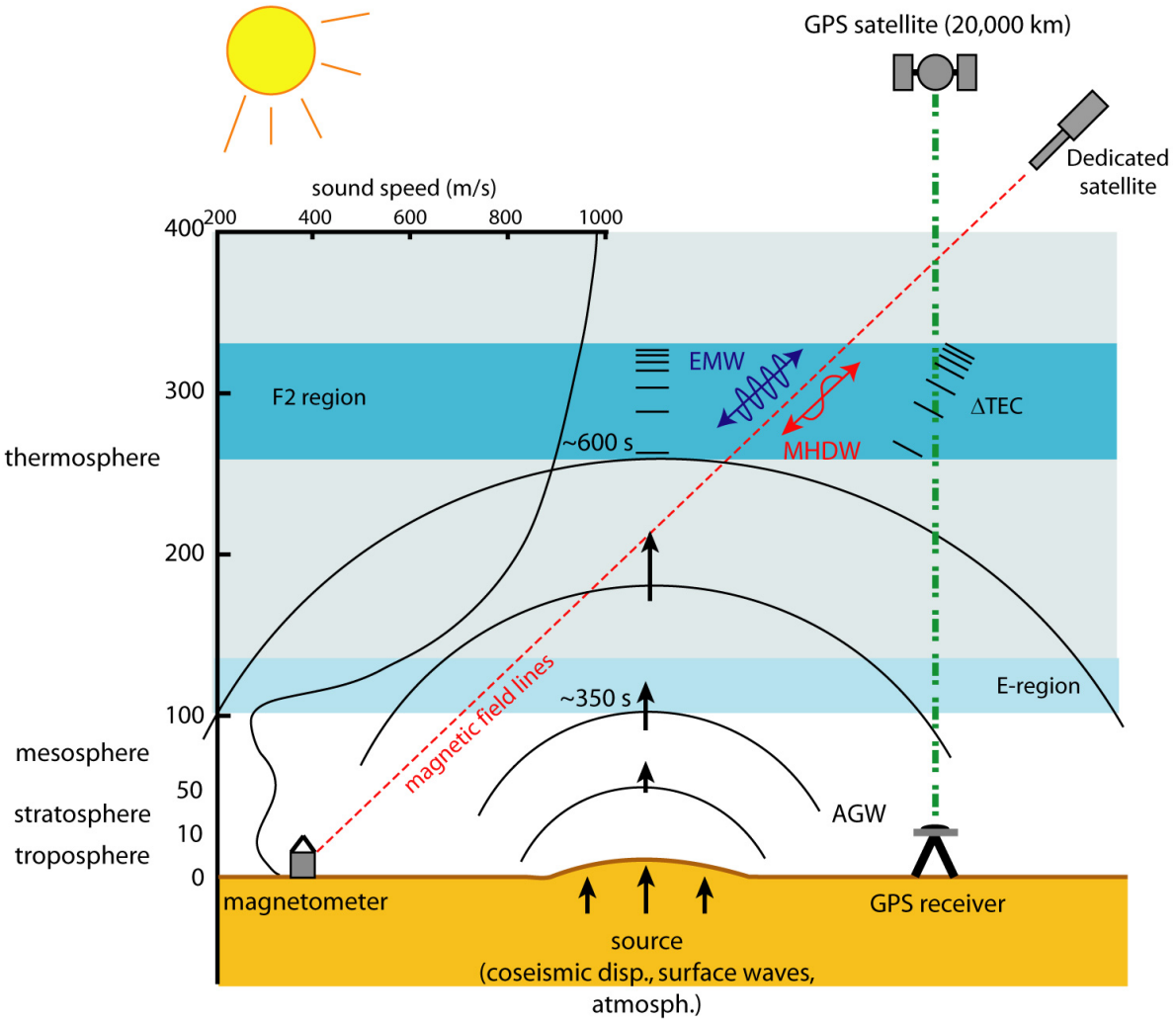
⇒ Acoustic Gravity Waves (AGW) = neutral pressure wave

⇒ Electron density variations (ΔTEC) from drag forces between neutral/ionized medium

⇒ Induced currents in conductive layers

⇒ Magnetohydrodynamic (MHD) and electromagnetic (EM) waves

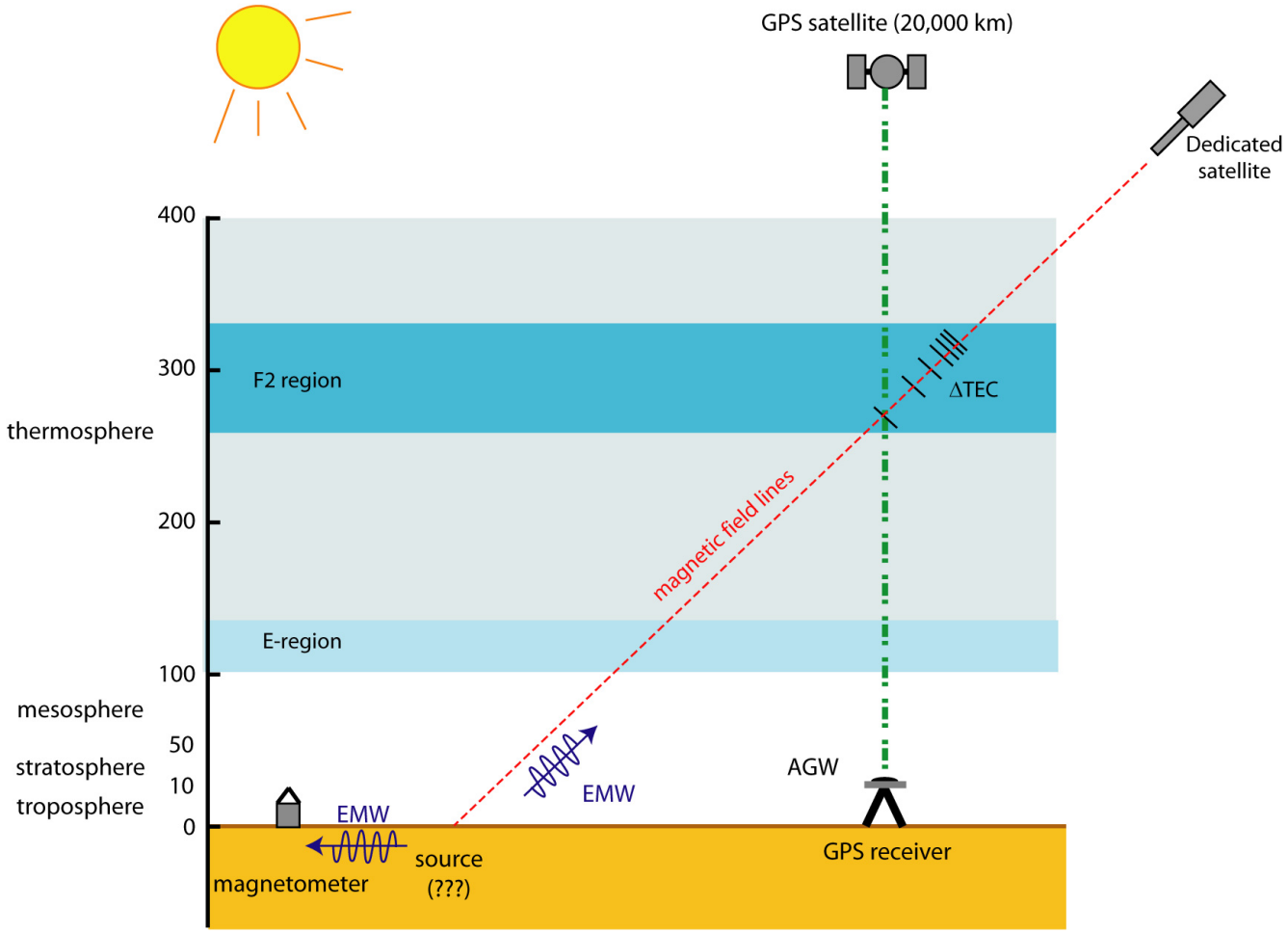
Background



Potentially detectable from ground and space:

- Magnetometers:
  - EM: F = ULF [3 Hz] ELF [3 kHz] VLF [30 kHz] / $v = c$
  - MHD: F = 0.1 – 10 Hz / v ~300,000 m/s (below 500 km)
- GPS:
  - AGW: P = 300 – 1,000 s / v = 300 – 1,200 m/s

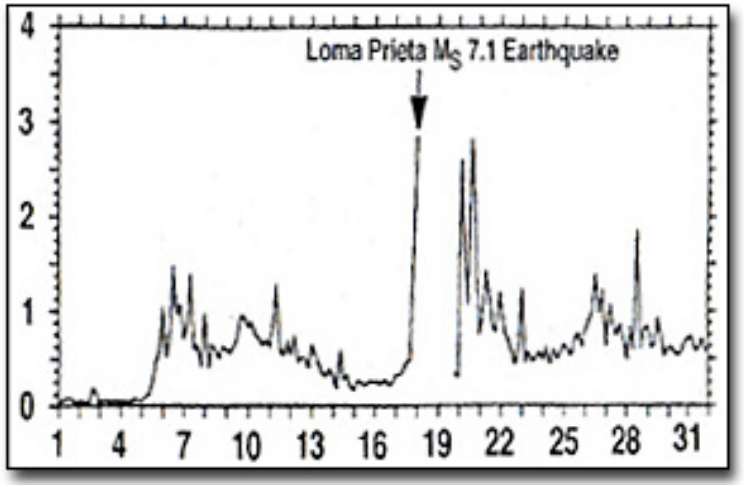
Background



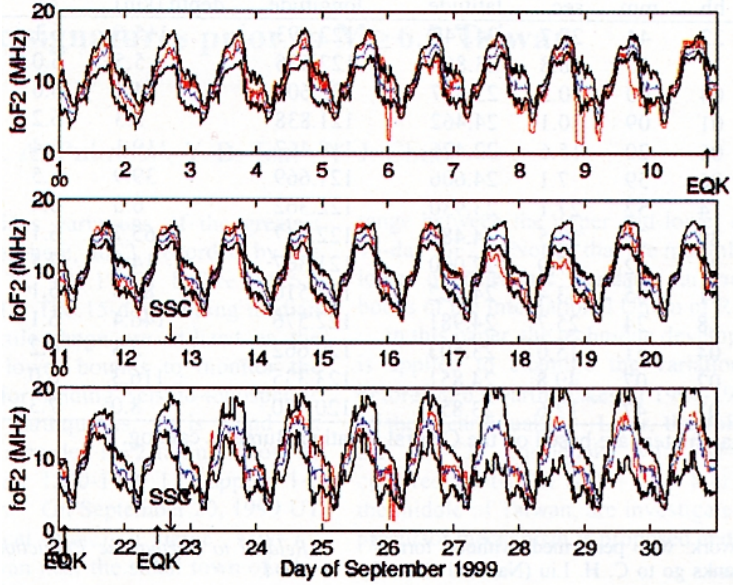
Pre-earthquake signals?

- EM from ground-based sensors
- EM from space-based sensors
- Electron density variations (ΔTEC) from currents generated by EM perturbations

Background



nT vs. hours in 0.01–0.02 Hz band; Fraser-Smith et al., 1990



Decrease in foF2 3 days before M_w7.3 ChiChi eq; Liu et al., 2000

Electromagnetic emissions related to earthquakes have been reported in various tectonic settings:

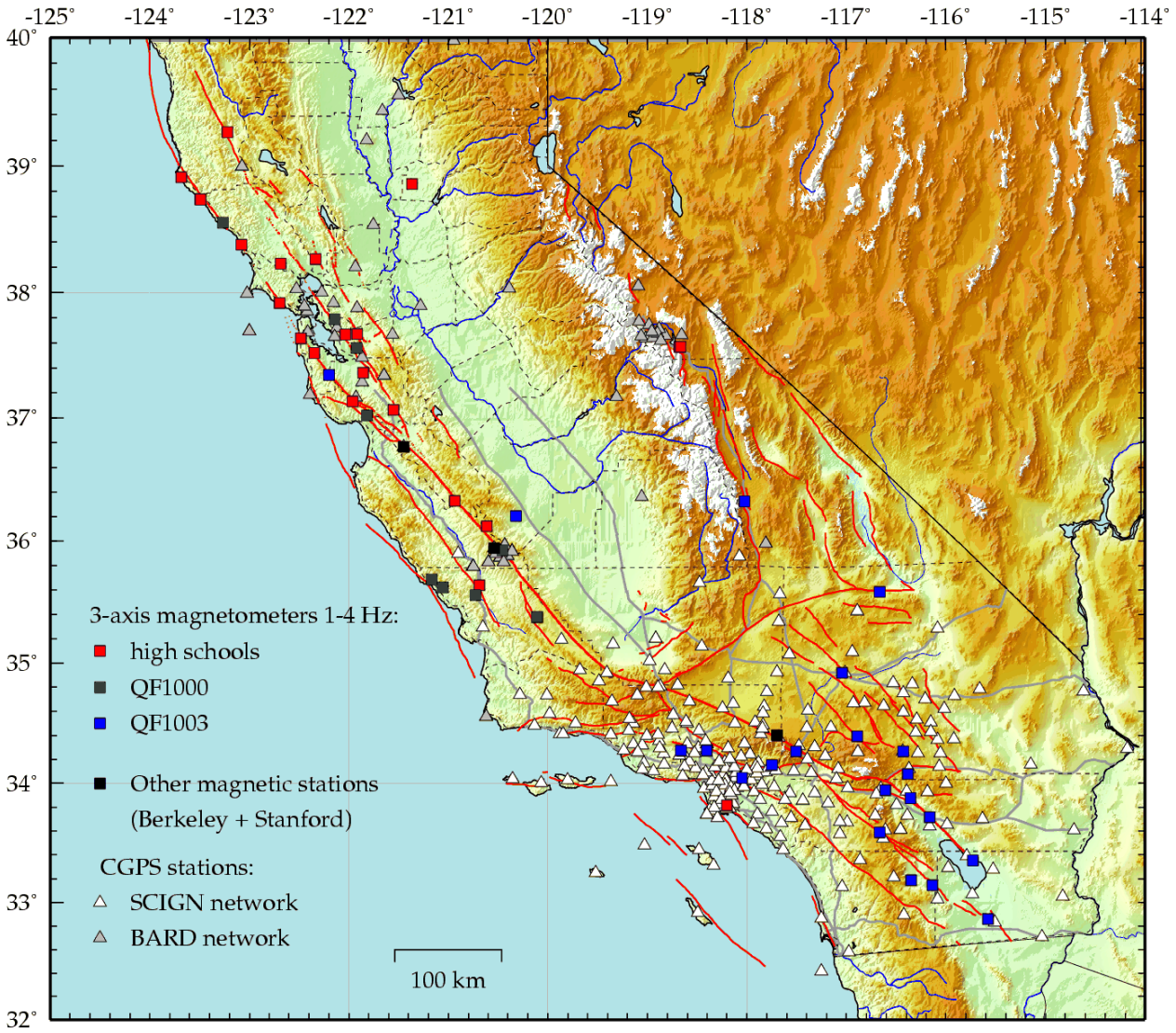
- Ground electromagnetic measurements (*e.g.,* Gokhberg, 1982; Fraser-Smith et al., 1990)
- Space-based measurements:
  - Phase shift in VLF (3-30 kHz)/ULF (<3 kHz) signals from Omega transmitters: observed a few days before Kobe earthquake (Hayakawa et al., 1996, 1999, 2000)
  - Decrease in ionospheric plasma critical frequency (foF2): observed 1-6 days before M>6 earthquakes in Taiwan (Liu et al., 2000; Chuo et al., 2002)
  - Increase of Total Electron Content (TEC): observed within 48 hours of M>5 earthquakes worldwide in 34% of cases (Zaslavski et al., 1998, using Topex-Poseidon)

Background

- Several of these studies raise suspicion:
  - Causative relationship between earthquakes and ground or space signals usually not demonstrated
  - Statistical significance sometimes weak
  - Observations not easily reproducible, consistency unclear
  - Background noise often not quantified, in particular over long-term
  - Source mechanism not clearly established: piezoelectric, electrokinetic, microfracture electrification, etc.
  - Many other possible sources: anthropogenic (*e.g.,* industrial, military), extra-terrestrial (*e.g.,* solar flares, magnetic storms), atmospheric (*e.g.,* internal waves, lightning)
- Many reasons to be suspicious, but one reason to be interested: **unexplained** EM and ionospheric signal exist $\Rightarrow$ worth studying regardless of their temporal relationship to earthquakes
  - Source? Propagation?
  - Background noise in EM or TEC time series?
- Need for a systematic study in a well-monitored, seismically active, region.

Combining ground- and space-based data

- ELF Magnetic Field Sensors:
  - 0.05–5 Hz, 3-axis, picoTesla (Stellar Solutions)
  - 0.001–10 Hz, 3-axis (EMI, operated by Berkeley and Stanford)
  - (+ USGS magnetometers)
- Space-based Measurements:
  - DEMETER (CNES, launch 2004)
  - QuakeSat (1–1,000 Hz)
- Ground-based measurements with GPS



Objectives

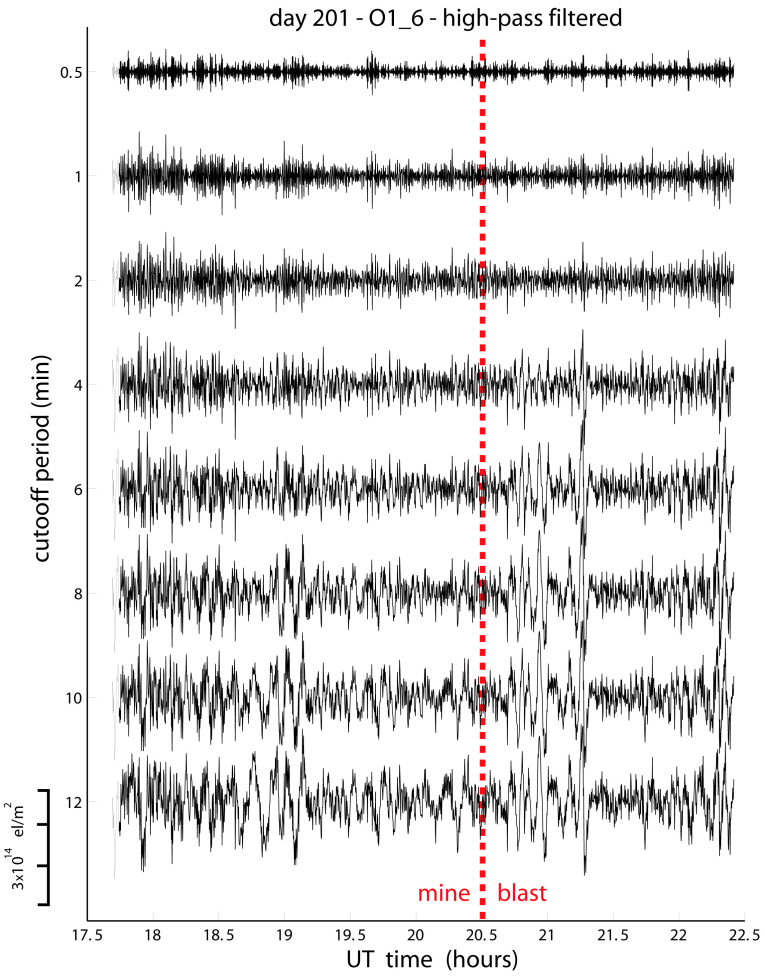
- **Investigate the detectability level** of co- and preseismic signals: Obtain reliable ionospheric and geomagnetic time series prior, during, and after earthquakes.

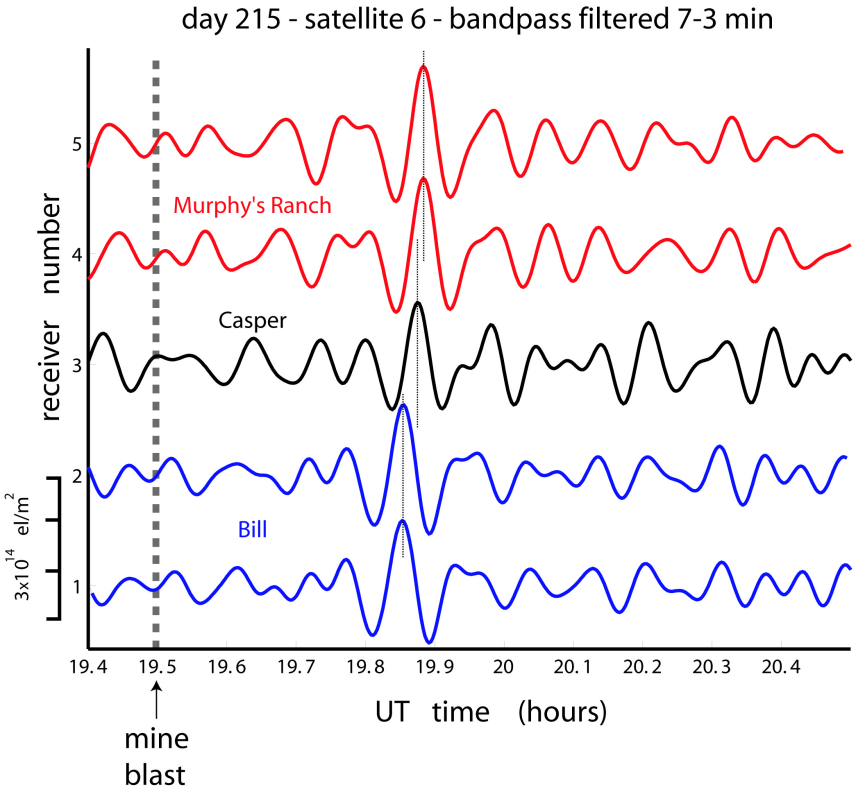
- **Better understand the noise characteristics** of the measurements: Systematic comparisons between GPS-derived ionospheric data and ground and space-based magnetic

- **Establish long-term continuous time series** to allow for a robust statistical analysis of the correlation between EM ULF/ELF energy activity and earthquakes.

- **Investigate non-seismic sources** of ionospheric perturbations to better separate them from seismic sources.

A 1.5 Kt Mine Blast in Wyoming

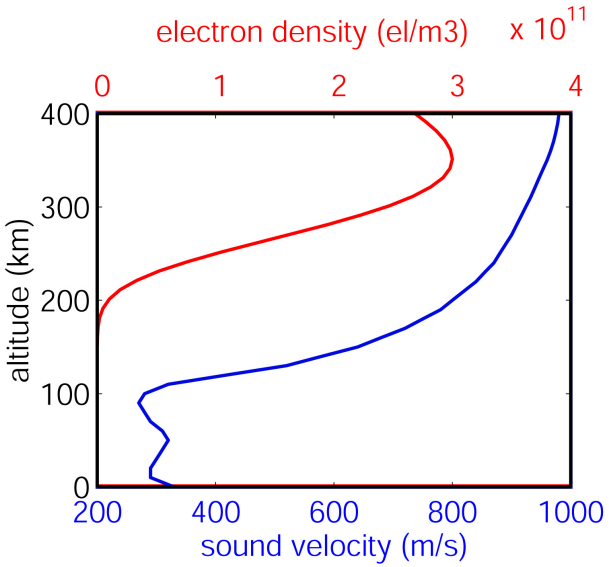


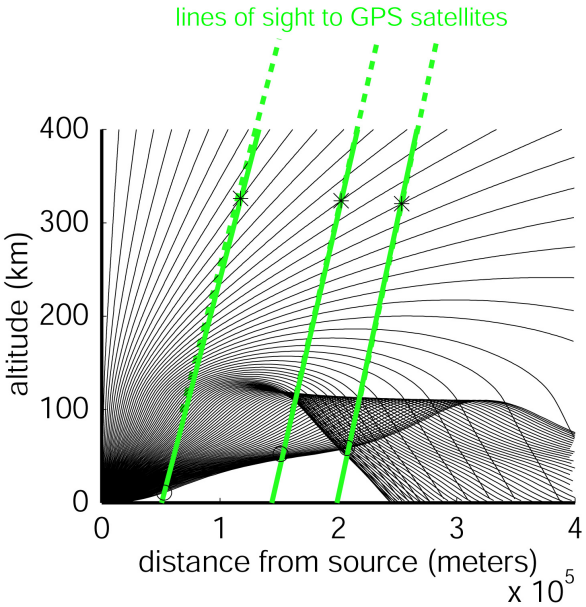


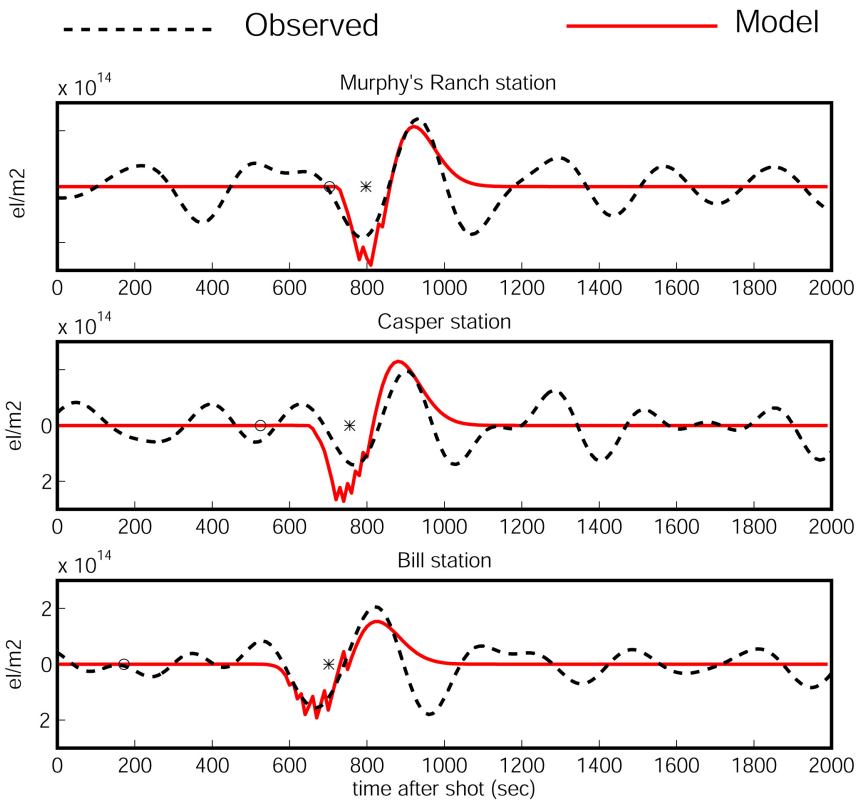
⇒ Energy concentrated at periods greater than 2 minutes

⇒ Outward propagation is visible

A 1.5 Kt Mine Blast in Wyoming





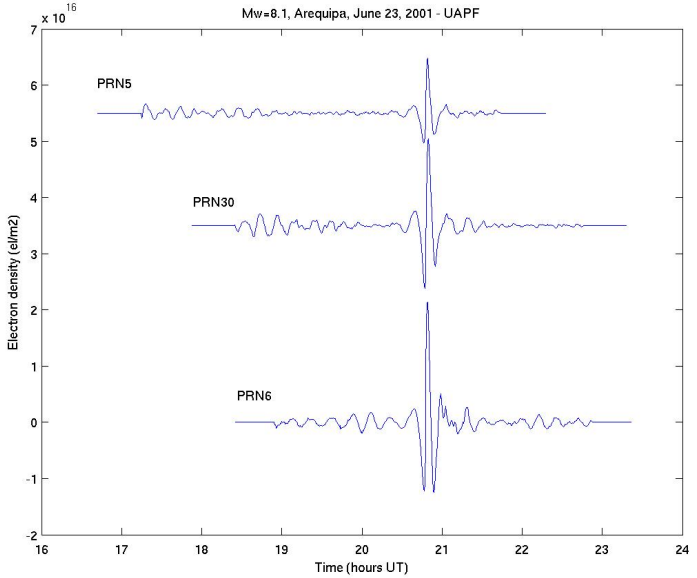


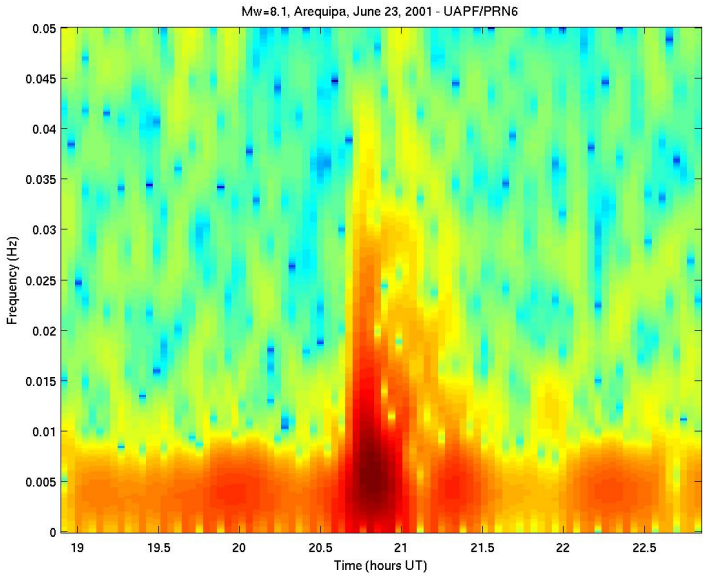
- Linear-acoustic ray theory ⇒ simulate the propagation of a pressure wave in a 1-dimensional, horizontally stratified, atmosphere
- Ionospheric charged particles follow the motion of neutral atmosphere, preferentially along magnetic field lines
- Source function = N-wave scaled to match observed perturbations

Similar observations, other sources

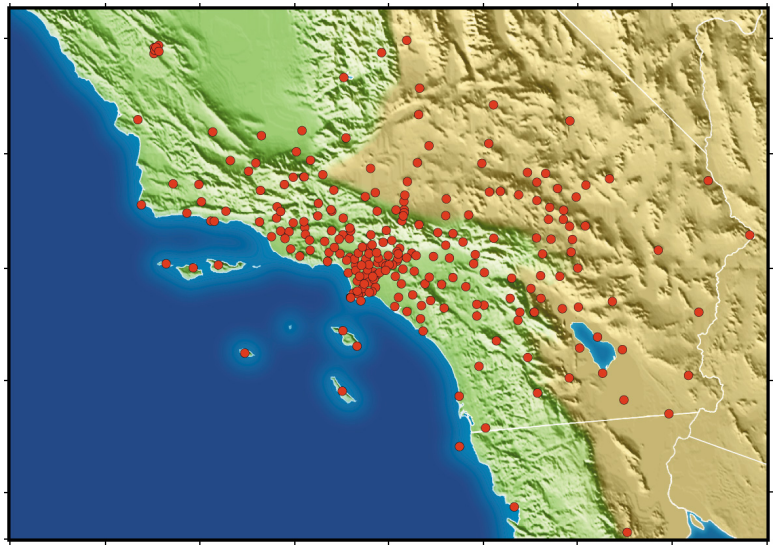
- After earthquakes:
  - ⋆ Triggered by ground motion (*e.g.,* Leonard and Barnes, 1965; Wolcott et al., 1984; Calais and Minster, 1995; Afraimovitch et al., 2000)

    Right: GPS detection of the ionospheric perturbation following the M_w8.1 Arequipa earthquake
  - ⋆ Triggered by surface waves (*e.g.,* Yuen et al., 1969; Weaver et al., 1970; Artru et al., 2003)
- After rocket launches (Jacobson et al., 1994; Calais et al., 1998), during solar eclipses, around heavy military operation areas, etc.

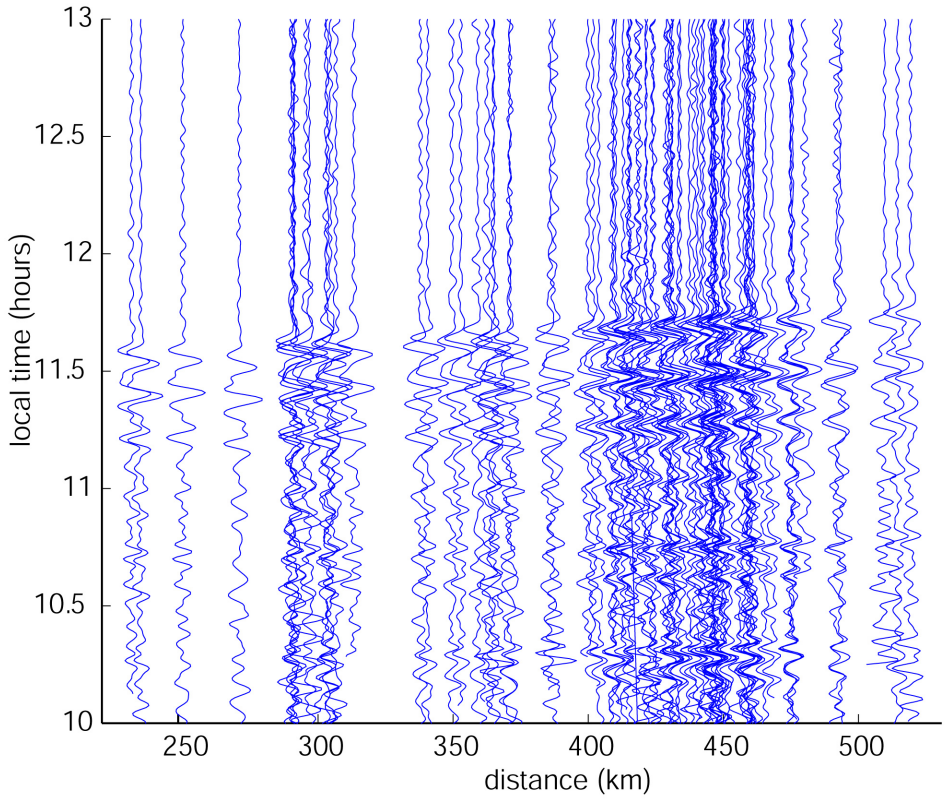




Using the SCIGN array

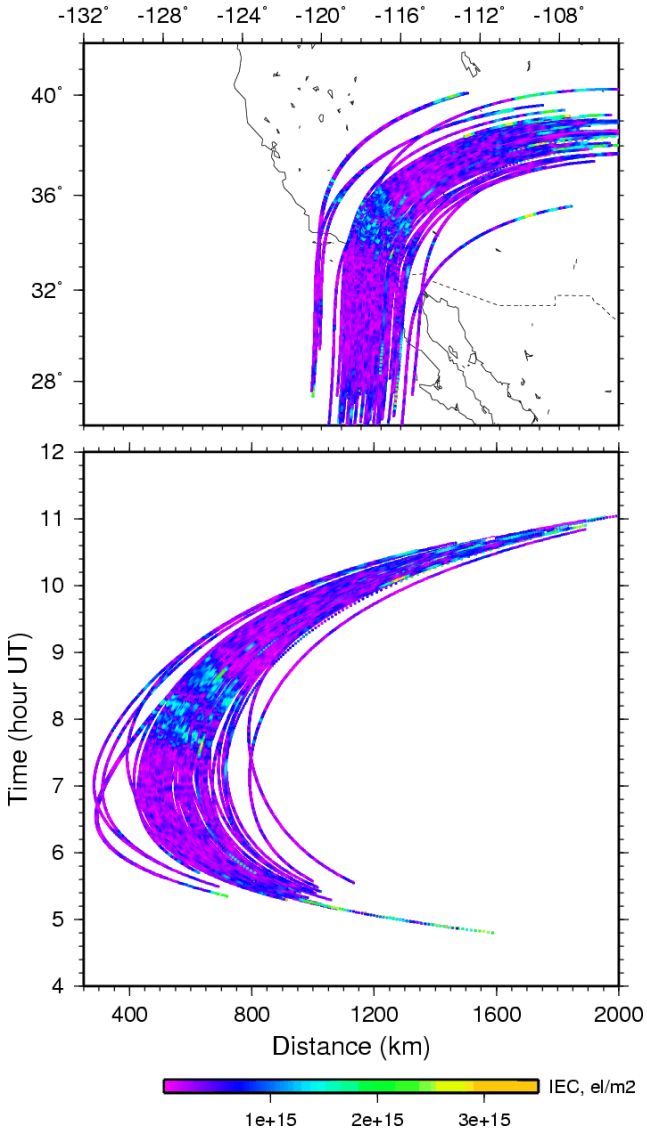


- Southern California Integrated GPS Network = SCIGN
- 250 continuous GPS stations, sampling @ 30 sec, some at 1 sec
- Installed primarily for crustal deformation applications

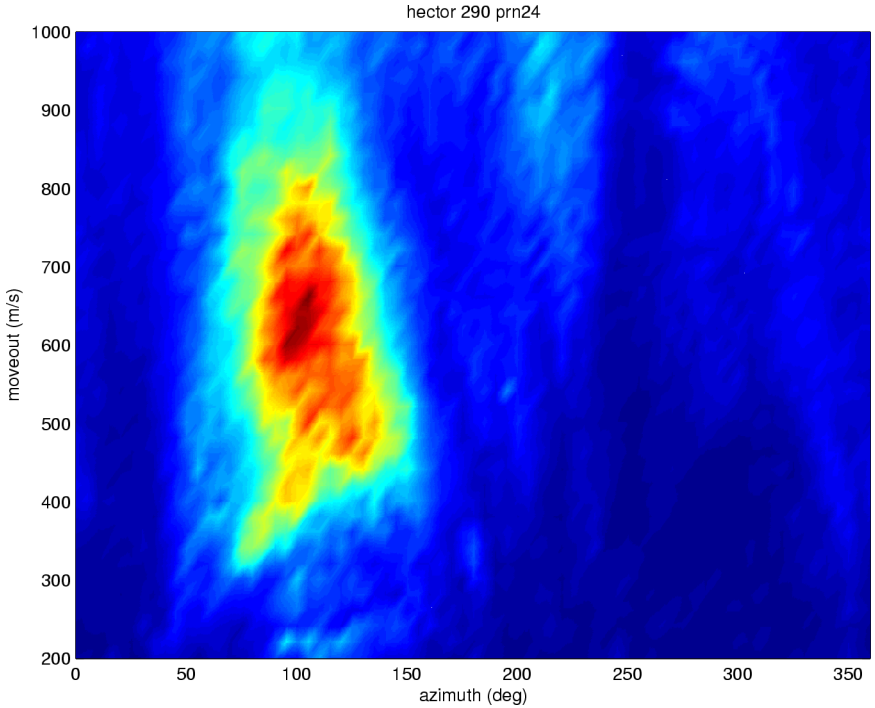


TEC times series bandpass filtered between 3 and 10 minutes, shown as a function of distance to the eastern edge of the array.

Using the SCIGN array



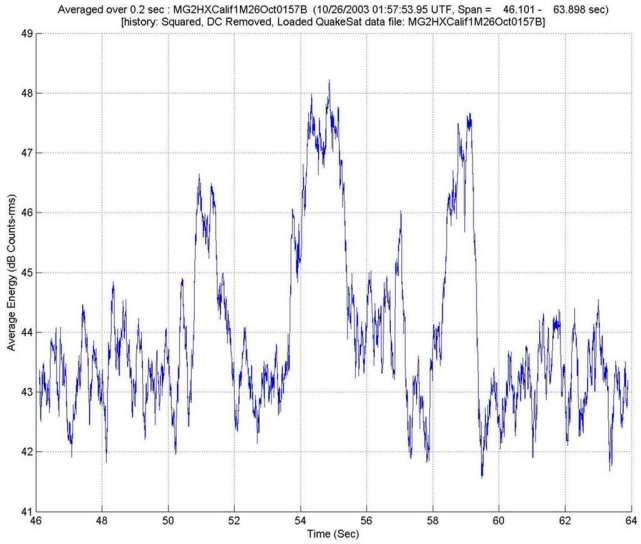
TEC amplitude: top = in map, bottom = Time-Dist space. Traces do not plot as straight lines because of the GPS satellite motion.



Search for the best-fit propagation speed and direction ⇒ v = 650 m/s, azimuth = N100E

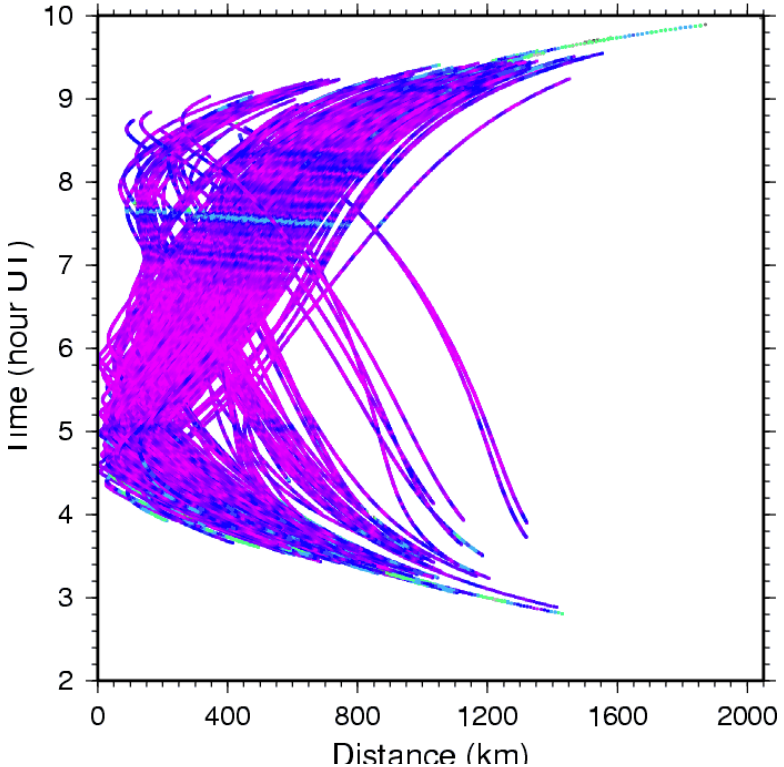
M_w6.5 San Simeon earthquake - 12/22/2002 @ 19:16 UT

Satellite magnetometer (QuakeSat), October 26, 2003



- After eliminating known noise/signal sources, $\sim$20 unexplained perturbations above seismically active regions
- Seem to originate from ground, but no statistically significant temporal relationship with earthquakes
- More sophisticated signal processing is being applied to teh data

GPS-TEC in time-distance space, 12/22/2003



TEC perturbation recorded by SIGN 11 hours before the event (PRN15): infrasonic + not in ground EM record + similar waveforms repeat every day $\Rightarrow$ not related to the earthquake

Conclusions

- Current effort to monitor EM and GPS-TEC signals from ground and space in California
- Signals have been detected that are not related to earthquakes and remain unexplained (lower atmospheric origin?)
- No evidence for EM or GPS-TEC signals has been found for the 2003 San Simeon and 2004 Parkfield earthquakes
- Great potential of dense GPS network together with EM sensors (ground and space-based) to contribute to the study of solid Earth-atmosphere-ionosphere couplings and energy transfers