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Title:	Understanding the Atmospheric and Ionospheric Response to Bolides and Hypersonic Objects in the Atmosphere (Update Talk, 4/7/2016)
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Understanding the Atmospheric and Ionospheric Response to Bolides and Hypersonic Objects in the Atmosphere

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Intelligence and Space Research Group (ISR-2)

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Overview

Introduction
- Motivation: objective, science focus

Description of new analysis tools

Validation of new analysis tools

Application to bolide cases

Summary

Science Motivations

***Primary research objective**:*

To advance knowledge of phenomena and characteristics associated with bolides by exploring the atmospheric and ionospheric responses from verifiable incoming objects.

Current science focus:

To develop and use analysis tools to identify bolide signatures in GPS-TEC (locally and globally).

Specific attributes (for each event) necessary to observe are:

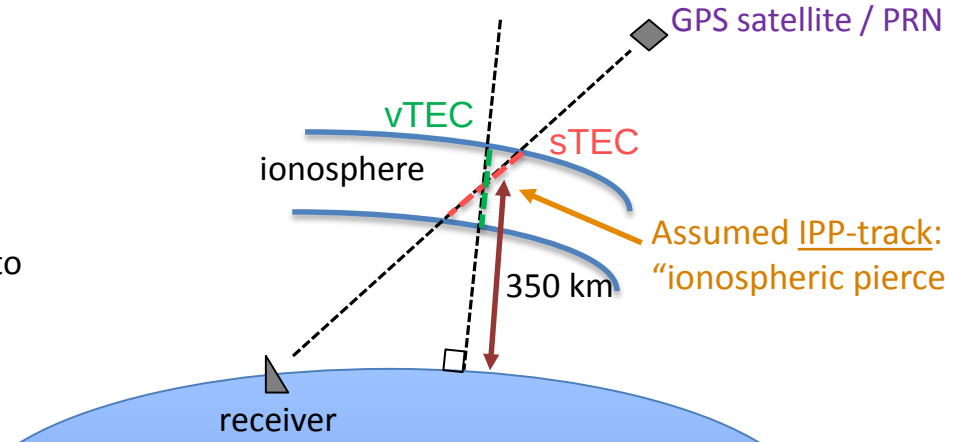
- geographic location / time
- velocity / propagation direction
- strongest periods and wavelengths in spectrum.

GPS Total Electron Content (TEC)

How TEC is measured:

- Signals between ground stations and GPS satellites are analyzed.
- GPS frequencies:
  L1: 1.22 GHz
  L2: 1.57 GHz
- Measure phase delay and group delay due to the ionospheric plasma.
- Determine total integrated electron density based on those delays.
- Unit: 1 TECU = 1 x 10^{16} electrons/m^2
- Always > 3 GPS satellites in line of sight of any ground station.

sTEC: Projected "Slant TEC"
vTEC: Projected "Vertical TEC"



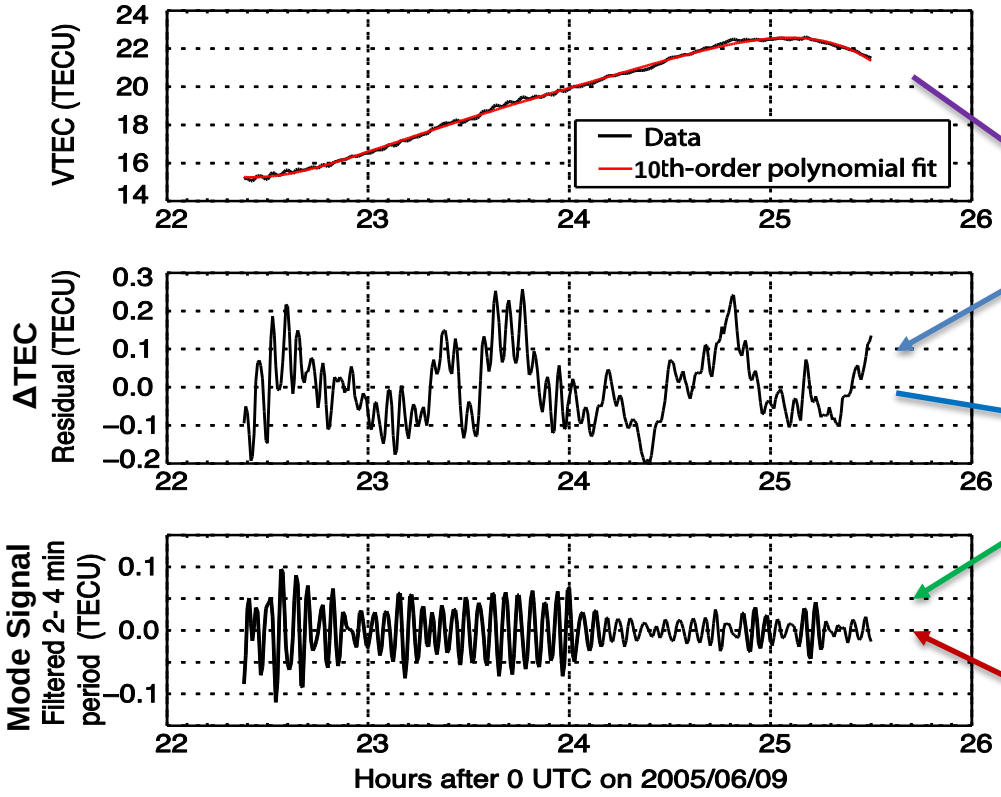
$$TEC = \int_{ground}^{satellite} N_e \, ds$$

Electron density (electrons/m^3)

Total Electron Content (TEC):
Integrated electron density along line-of-sight from ground receiver to satellite [in electrons/m^2].

GPS Total Electron Content (TEC)

Goal: detect wave modes in TEC:



Remove satellite motion effects:

Subtract TEC from 10th order polynomial fit.

Isolate mode in ΔTEC:

Band-pass filters and *wavelet analyses* isolate modes:

- acoustic wave: < 6 min
- gravity wave: > 6 min

Limitations:

- minimum ΔTECU = .01
- minimum Δt = 30 seconds

Effective Noise Floor

New Analysis Tools

For high-rate RINEX data (1-sec):

- Why?: Required to consider 1-min GPS-TEC signatures
- What?: - use new black box codes (i.e. newest TEQC / UNAVCO)
  - completely original code

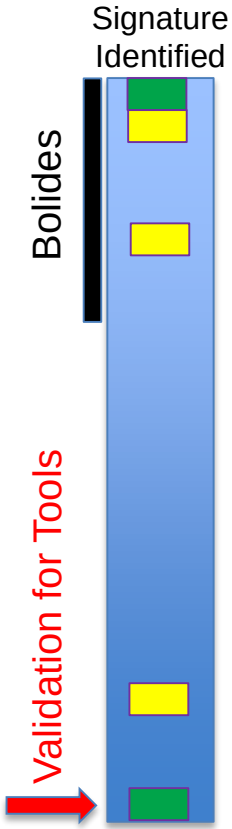
Simple tools:

- Why?: Existing methods often miss key signature attributes
- What? - arrival time estimation: atmospheric acoustic wave model
  - bi-directional bandpass: BP amplitudes without time offset.
  - normalized spectrum: pulse detection
  - N-station-phase: instantaneous direction / velocity

Time-lapse (TL) tools:

- Why?: Complementary tools to deal with low SNR
- What? - TL TEC tool: Combining GPS-TEC from available stations (frames at 30-sec).
  - TL band-phase tool: Identify absolute BP phase in signal.
  - TL arrow tool: N-station velocity / direction

Validate and Evaluate Signatures of Bolides



Ind	Events of Interest:	Location (near)	Event Class	Type/Class/Group	[Abs Mag]	[kt]
1	Chelyabinsk 2013	Chelyabinsk, RU	Superbolide	Ordinary Chondrite LL5	-27.0	>400
2	Sutter's Mill 2012	Sutter's Mill, CA	Superbolide	Carbonaceous Chondrite CM2	-20.0	4
3	Novato 2012	Novato, CA	Bolide/Fireball	Ordinary Chondrite L6	-13.8	0.003
4	Ger/Sw/Aus/Bel 2015	Munich, Germany	Bolide	Not Recovered	-16.0	?
5	San Antonio 2014	San Antonio, TX	Bolide/Fireball	Not Recovered	-14.0	0.055
6	Northern Florida 2015	North of Olando	Bolide	Not Recovered	-16.0	?
7	Peekskill 1992	Peekskill, NY	Fireball	Stony Iron H6 Monomict	-13.0	?
	From JPL's Extended Fireballs/Bolide list:					
8	Japan Pacific (2010)	East of Japan, Pacific	Bolide	-	?	33.0
9	Tuli Meteor (2009)	Tuli Safari Area, Zimbabwe	Bolide	-	?	18.0
10	Gulf of Boni (2009)	Gulf of Boni, Indonesia	Bolide	-	?	33.0
11	Antarctica (2014)	Southern Ocean, Antarctica	Bolide	-	?	7.6
	Comparisons:					
12	Atlantis (STS-125) Launch	Kennedy LC-39A, FL	*Fireball*	Launch	-	-
13	Columbia (STS-107) Reentry	~Abilene-West-Lufkin, TX	Fireball	Reentry-breakup	-5.0	?
14	Mir De-orbit 2001	SE of Fiji, Pacific	Fireball	Reentry-breakup	-5.0	?
15	West Fertilizer Explosion	West, TX	Fertilizer Explosion	Explosion	-	.001-.005
16	Mount Asama Eruption	Karuizawa, Japan	Volcano Eruption	Explosion	-	47.8
17	G4 March 2015	Earth	Geomagnetic Storm	G4	-	-
18	Japan Tsunami 2011	Offshore of Sendai, Japan	Earthquake/Tsunami	seismic = 9.0	-	45000

*Simple Physics Model: Est. Acoustic Wave Travel

Method:

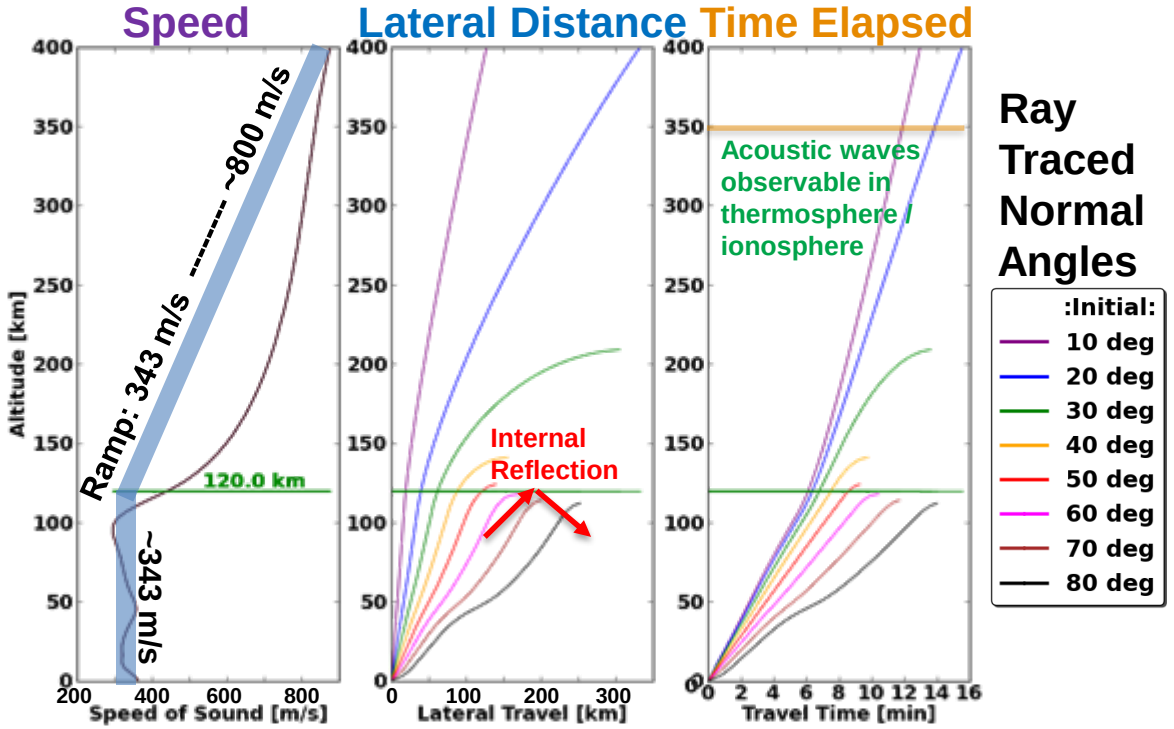
1. Consult MSIS model for thermospheric densities
2. Use basic dispersion relation for AW/GW
3. Find velocities with thermodynamic identifies
4. Trace propagation in the atmosphere

Note:

Acoustic wave speed:

$$c_s = \sqrt{\frac{\gamma k_B T}{M_n}}$$

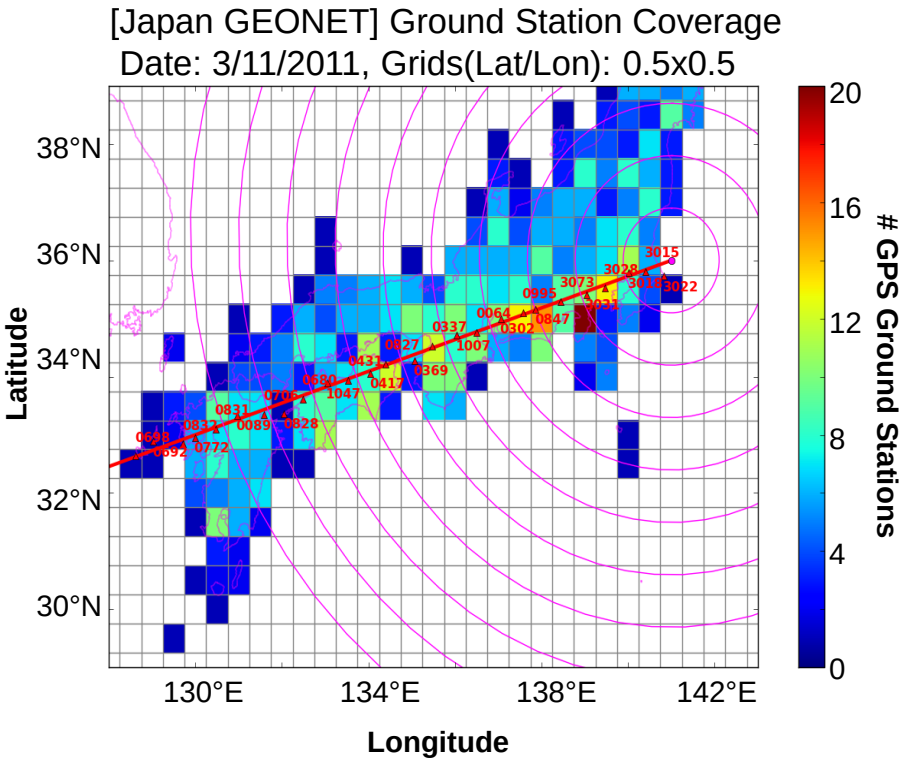
Though density decreases, temperature increases and extended mean free paths allow for faster travel of an acoustic front.

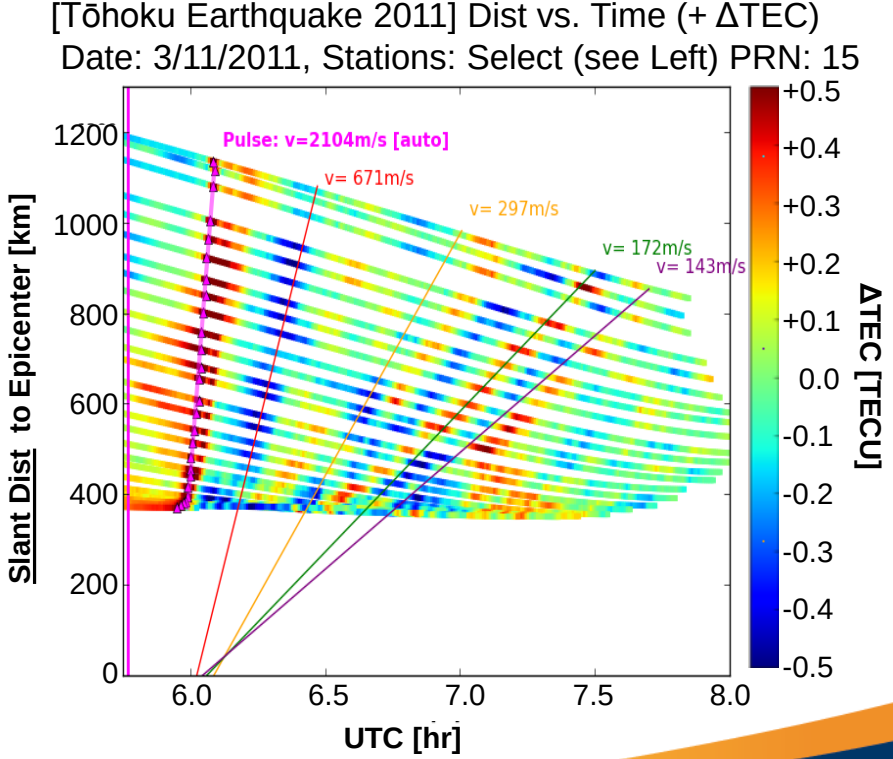


*For better results, collaboration with JHUAPL / R. Bruntz is essential.

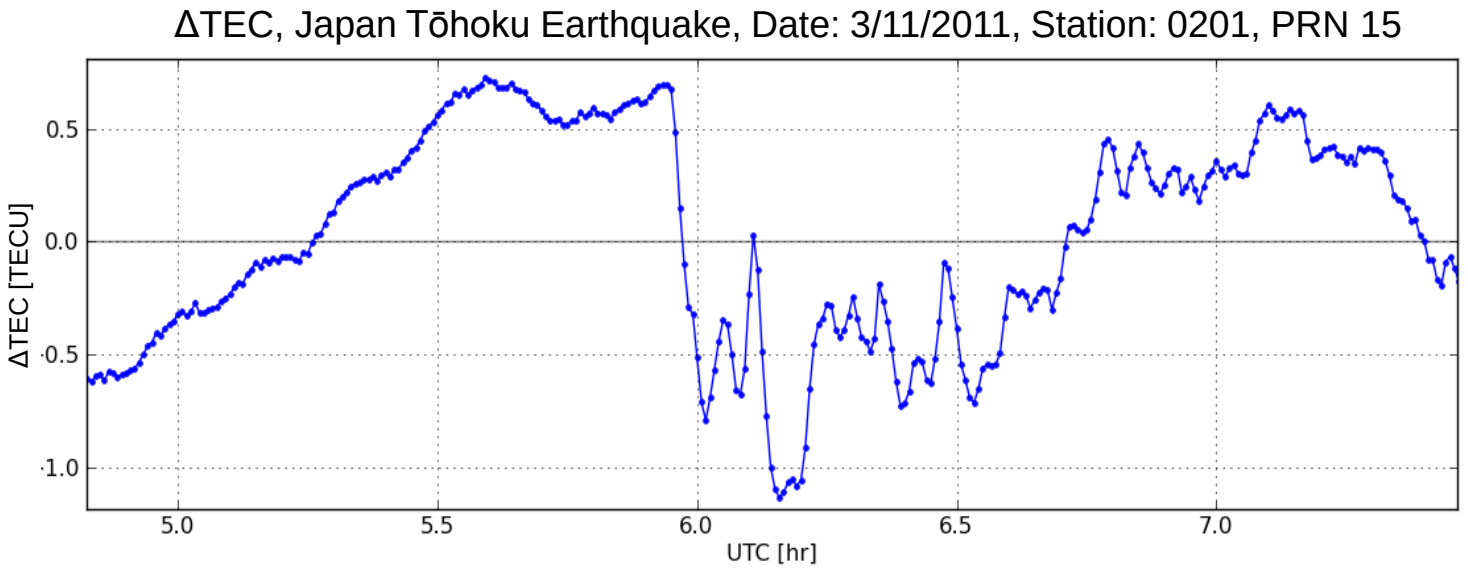
Validation: Tōhoku Earthquake 2011

ΔTEC fluctuations at increasing distances:





Validation: Modes in Earthquake Pulse



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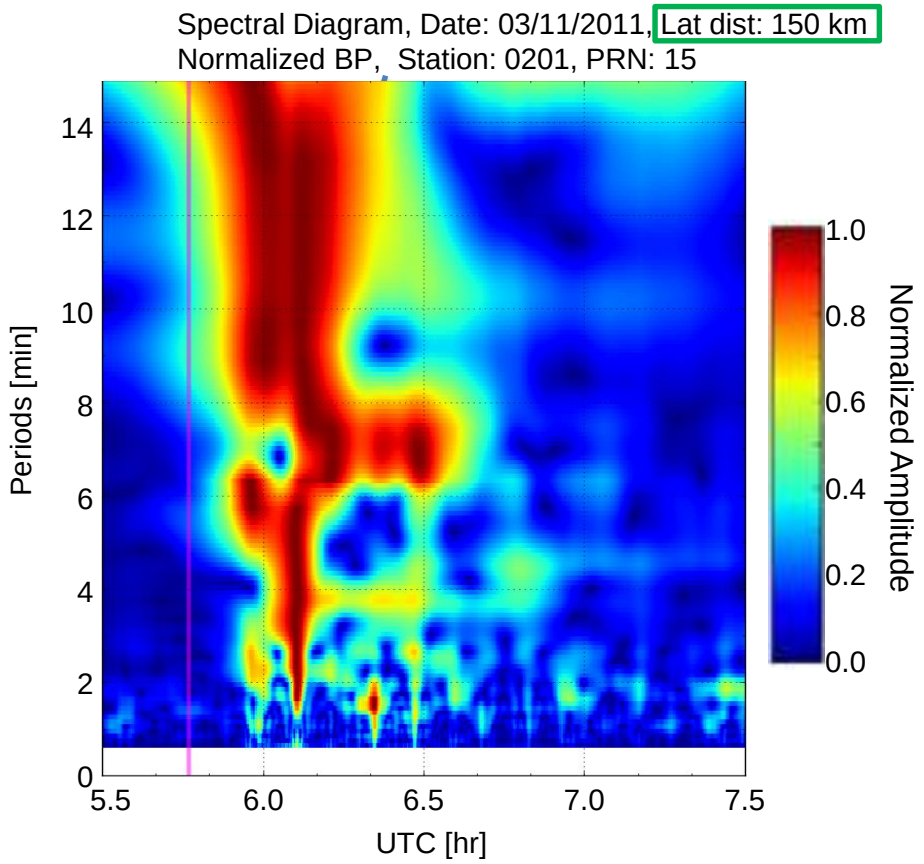

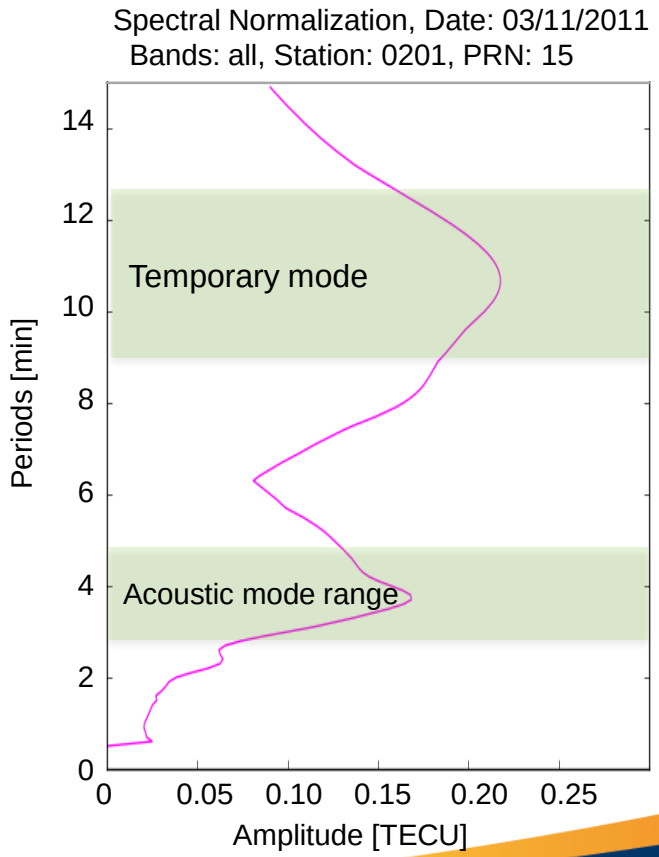

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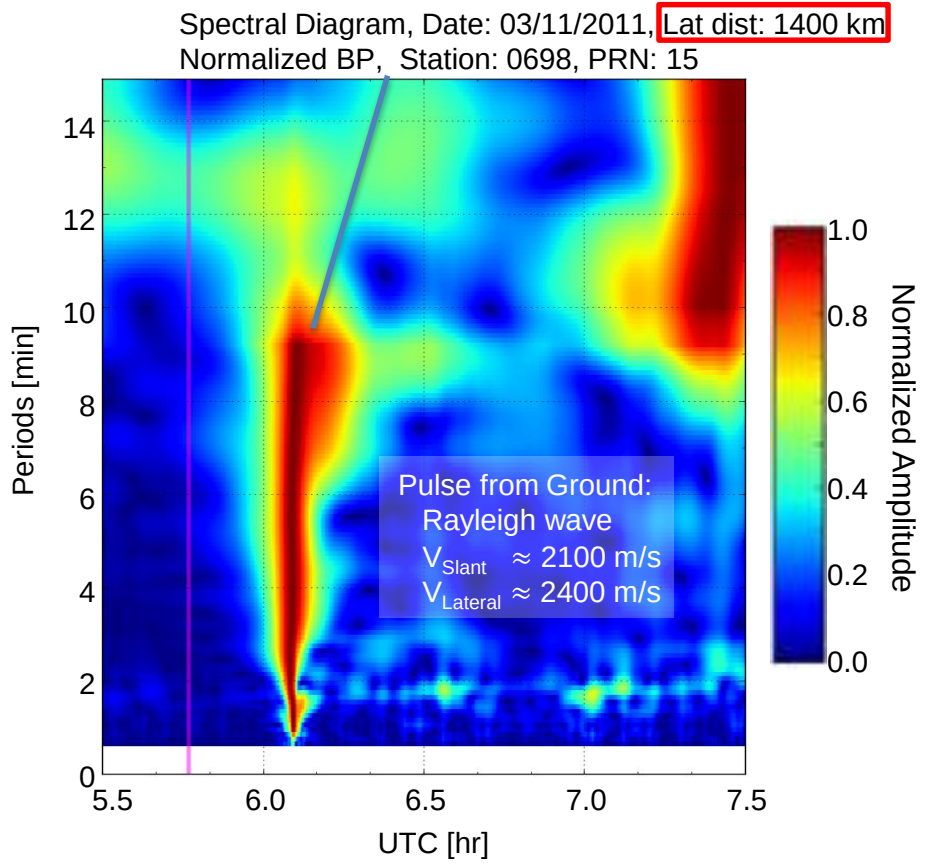
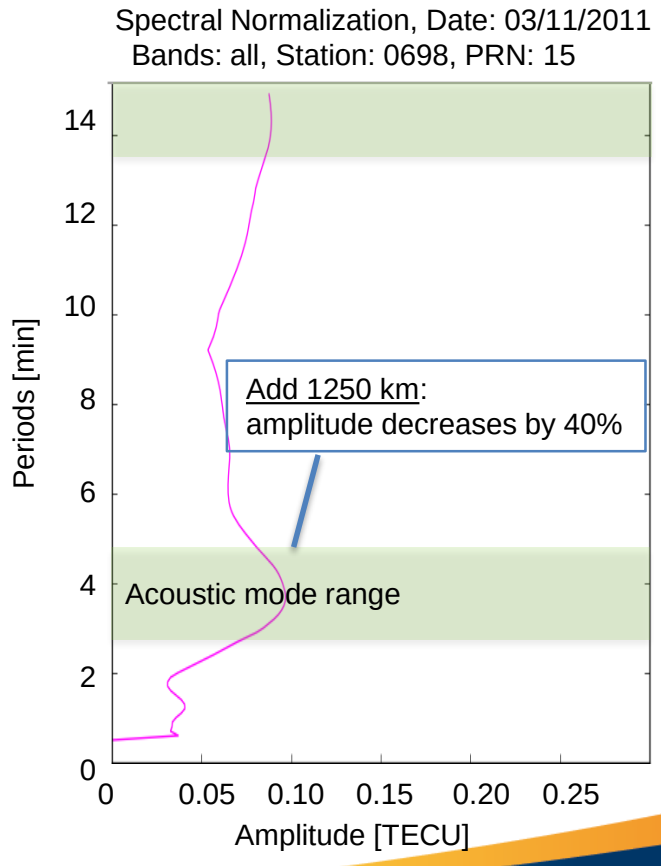


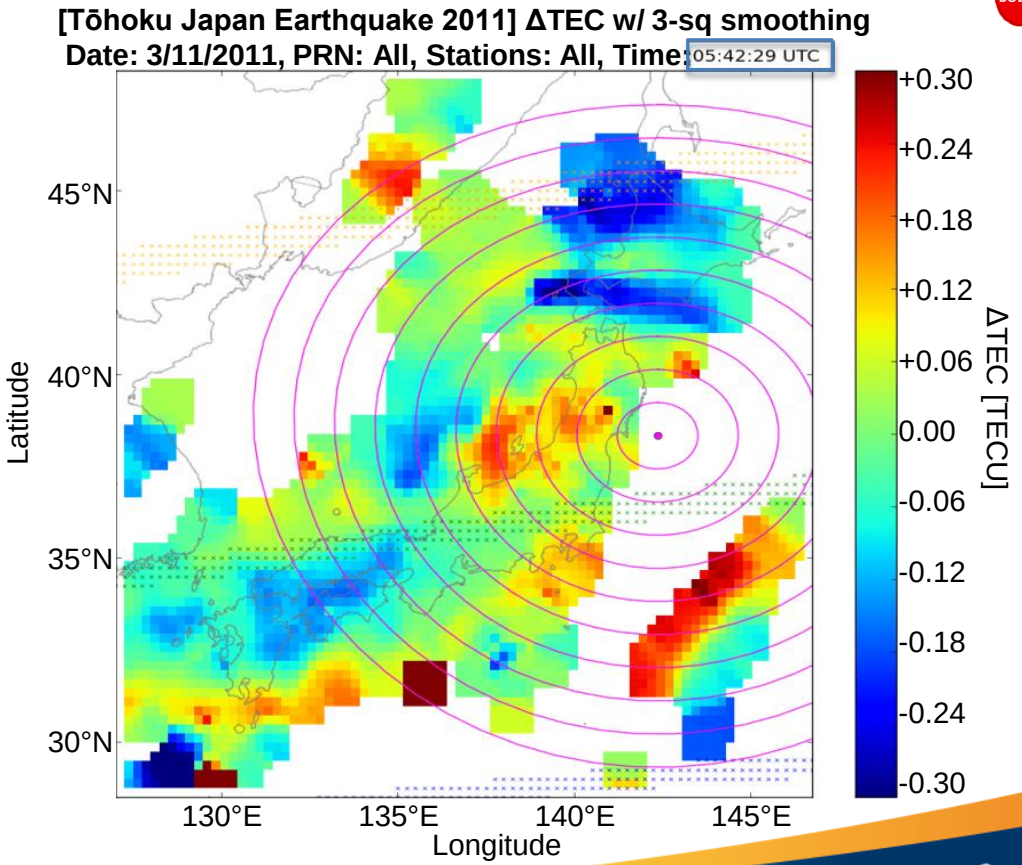


Validation: Tōhoku Earthquake 2011

Event Description:
- Name: 2011 Tōhoku Earthquake/ Tsunami
- Date: 03/11/2011
- Time: 5:46:24 UTC (14:46:24 JST)
- Loc: 38.322°N, 142.369°E (Japan)
- Type: Under-sea megathrust earthquake
- Duration: 6 min
- Depth: 31 km
- Mag: **9.0 M_w**
- Energy: **45 Mt** [Surface Seismic]

Advantages:
- large # ground stations
- small distances
- known / well-documented TEC observations

Difficulties:
- acquiring Data



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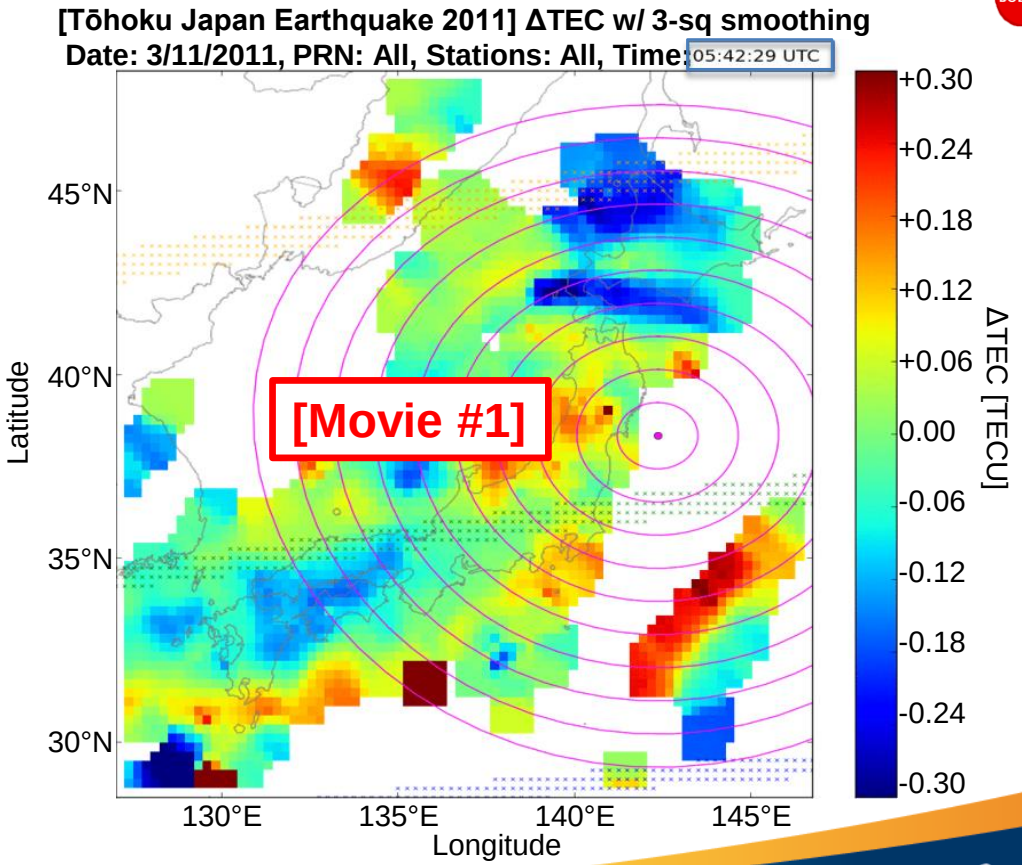

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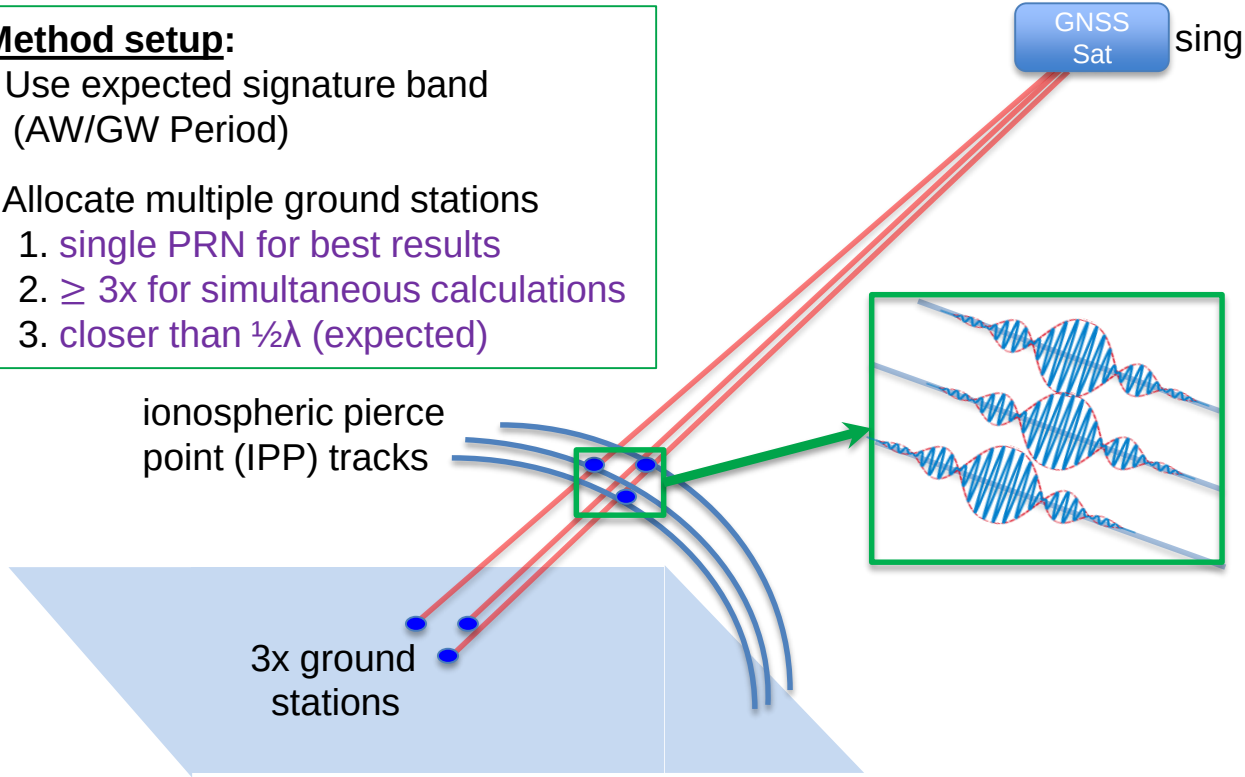
Determining Velocity and Direction from GPS-TEC

Method setup:
- Use expected signature band (AW/GW Period)

- Allocate multiple ground stations
  1. single PRN for best results
  2. ≥ 3x for simultaneous calculations
  3. closer than ½λ (expected)



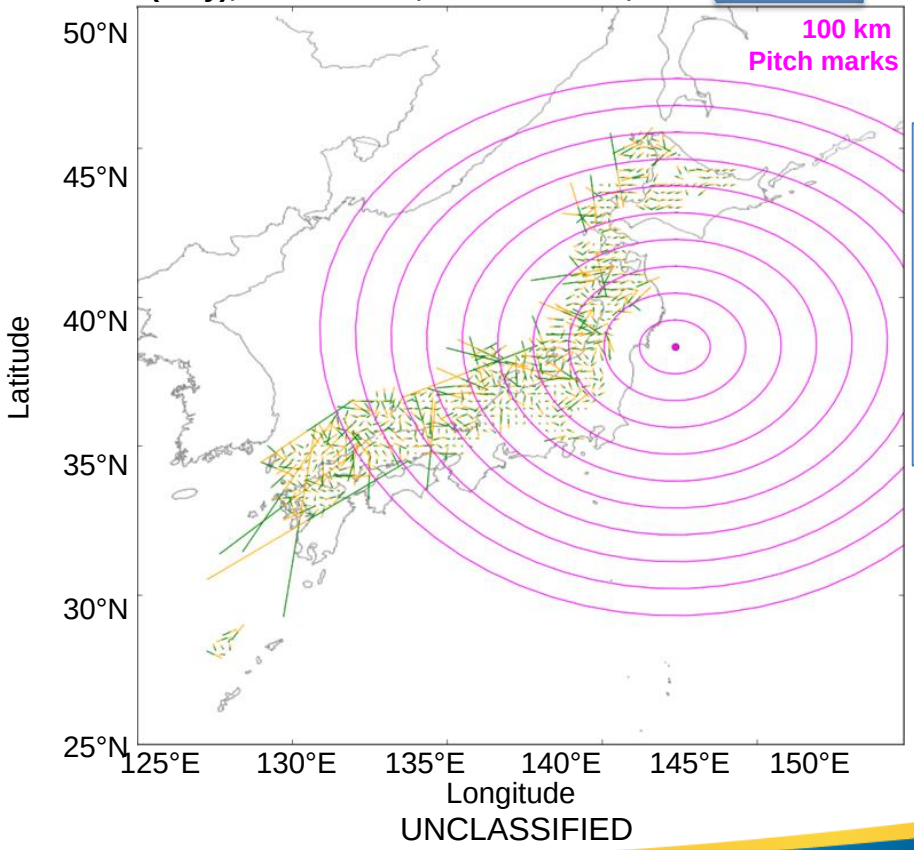
Method Execution:

Calculate first:
a. band-pass amplitudes
b. relative Morlet phases (C)
c. ellipsoidal distances (x, y)

Solve 1D wave equation:
i. wavelength
ii. speed
iii. direction

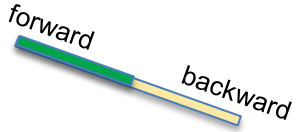
Validation: Tōhoku Earthquake/Tsunami 2011

[Tōhoku Japan Earthquake 2011] Dense Velocity Vectors, Date: 3/11/2011
PRN: 15 (only), Stations: All, Period: 4 min, Time: 05:30:59 UTC



Earthquake begins @ 5:46 UTC

Explanation:
Arrows indicate local propagation direction. Length indicates velocity:



Limit used: smallest band-passed amplitude >= .02 TECU.

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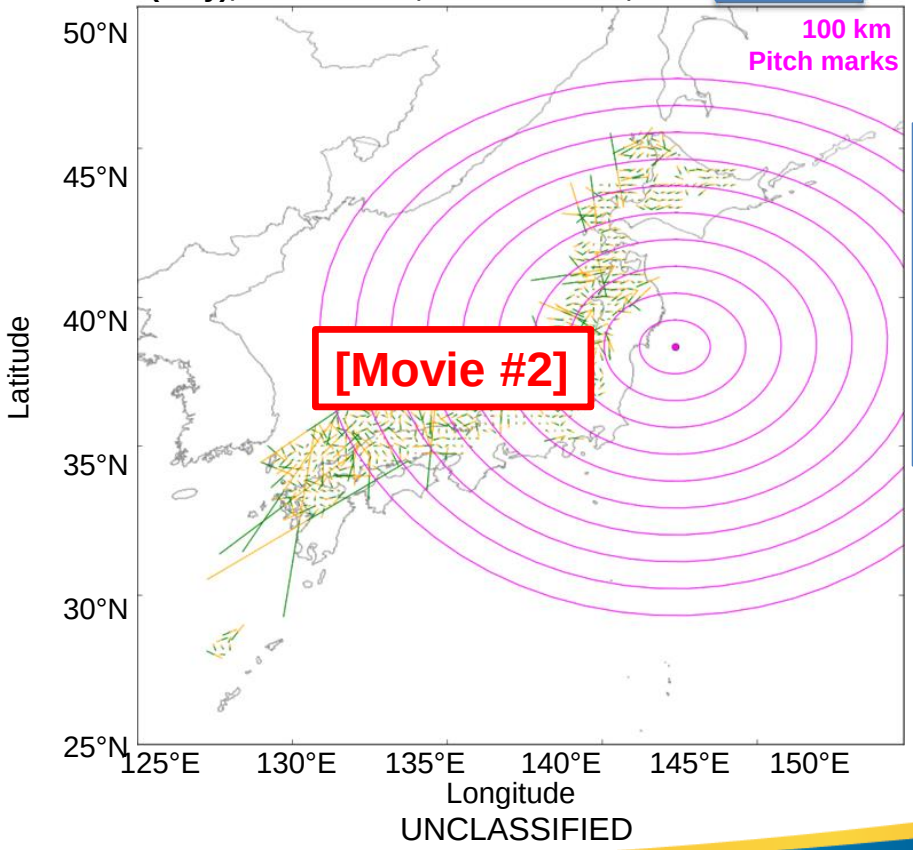

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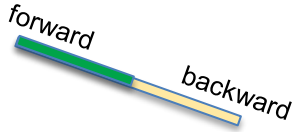

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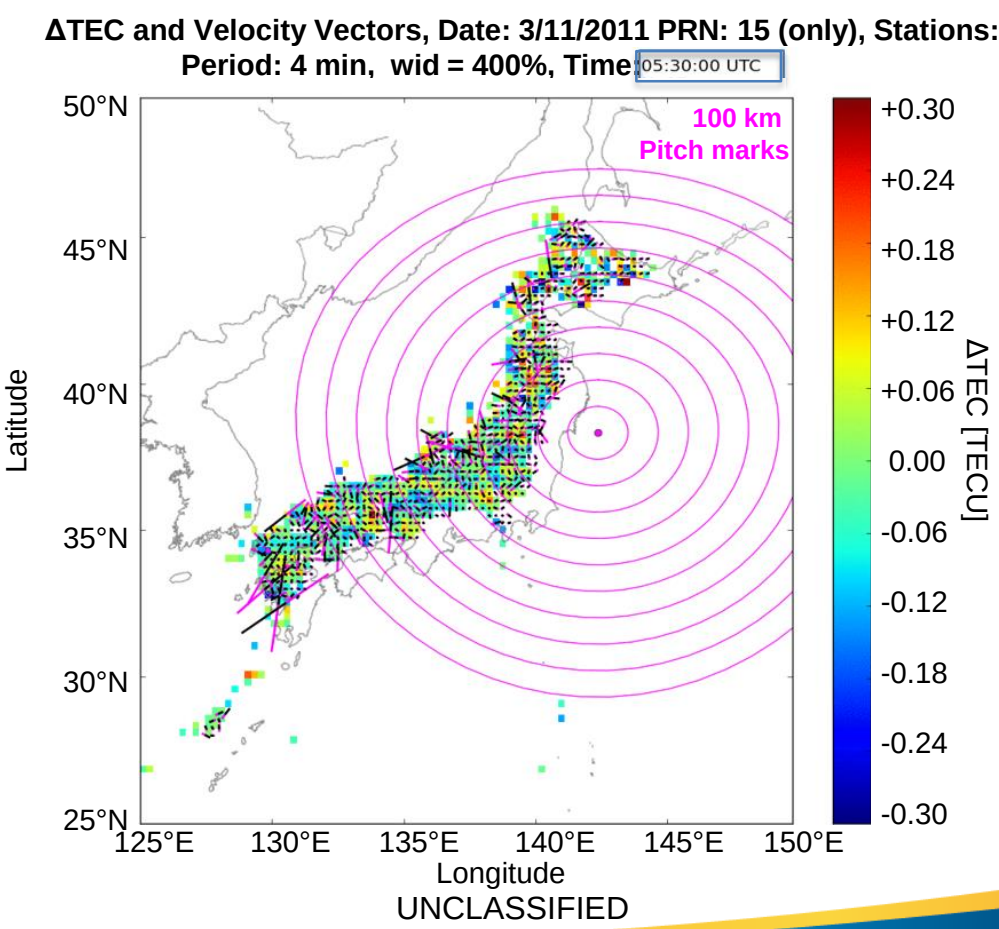

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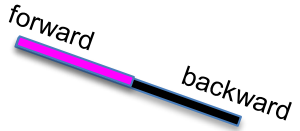

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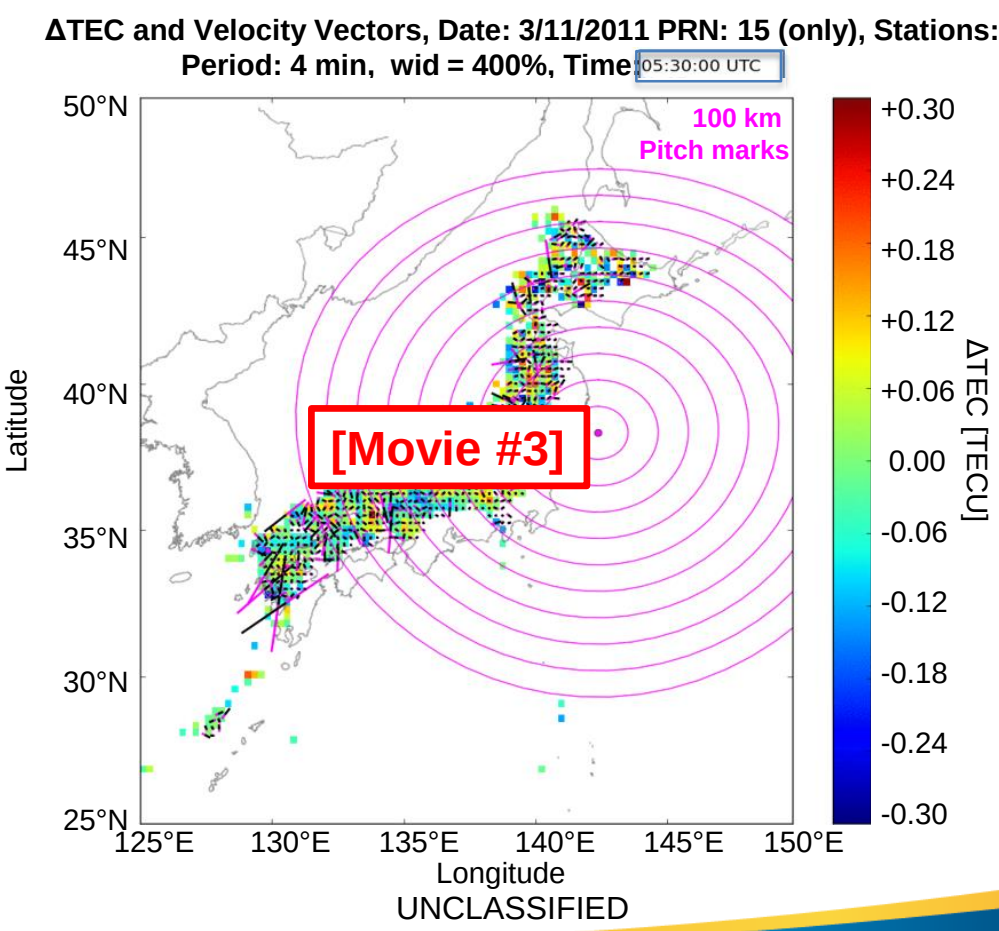

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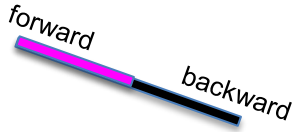

Limit used: smallest band-passed amplitude >= .02 TECU.

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Chelyabinsk Bolide 2013

Event Description:

Event Name:	Chelyabinsk Bolide (Superbolide)
Event Date:	02/15/2013
Event Time:	03:20 UTC (9:20 YEKT) - morning
Event Location:	55.15°N 61.41°E (near Chelyabinsk, RU)
Bolide travel:	Westward
Meteor Shower:	N/A. Not associated with but close to *2012 DA14*.
Abs Magnitude:	≈ -27
Diameter, Type:	≈ 20 m, Ordinary Chondrite
Mass, Speed:	≈ 1.2×10^{7}kg, 20 km/s
Energy*:	400 - 500 kt
Explosion Alt:	≈ 30 km

Notes:
- Best IPP-track: Station: ARTU, PRN: 18
- sparse ground stations

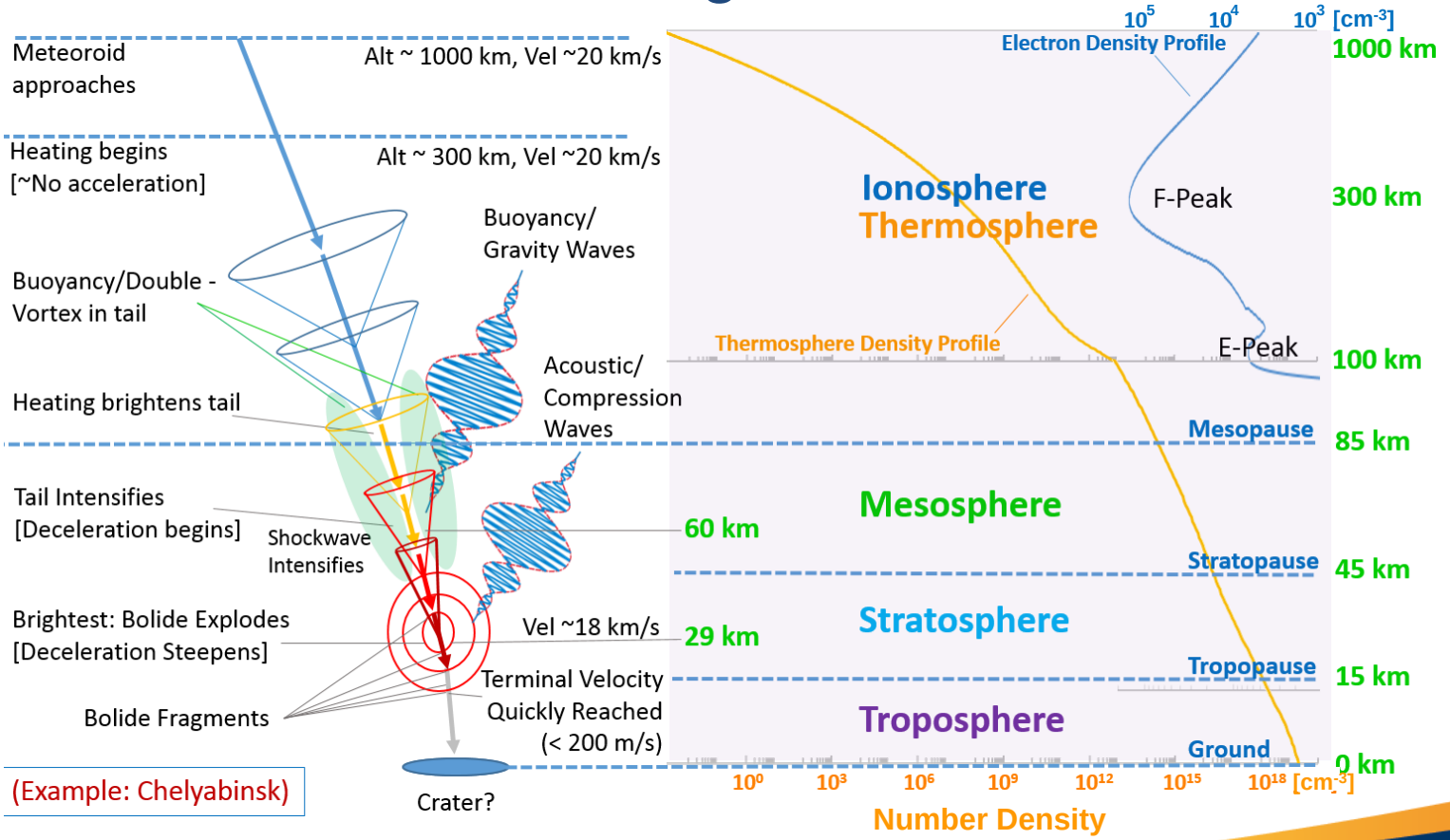
Expectations:
- Large, easily observable acoustic signature
- Observe acoustic signature at ~14-18 min (@350 km).
- Observe gravity waves at some time later.

TEC signature details:

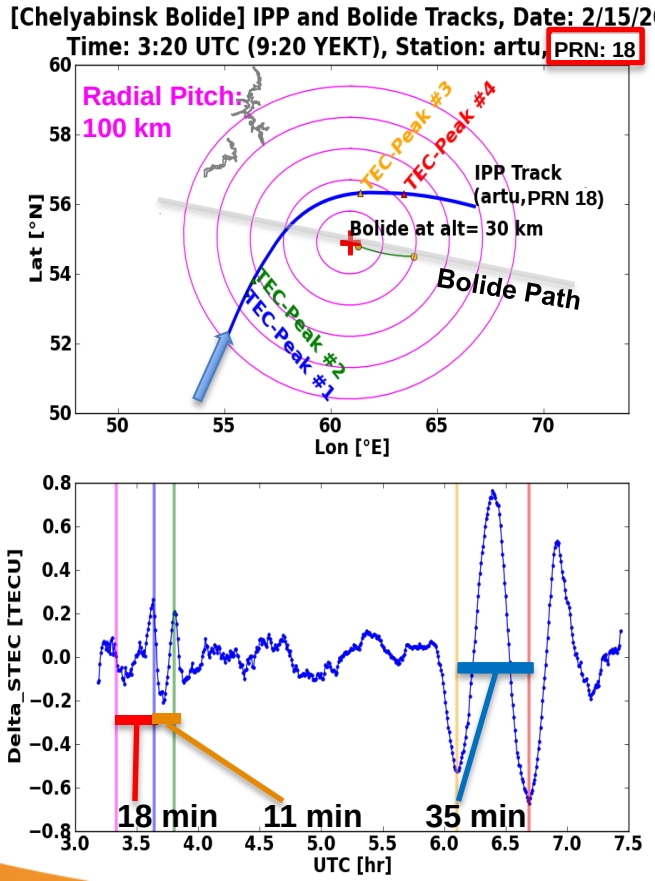
- modes:	2		
- periods:	11 min	/	35 min
- velocities:	≈ 800 m/s	/	< 50 m/s
- ΔTEC:	0.3 TECU	/	0.8 TECU

*Convert: 1 kt = 4.2×10^{12} J

Forming a Bolide



Local Signatures: Chelyabinsk Bolide 2013



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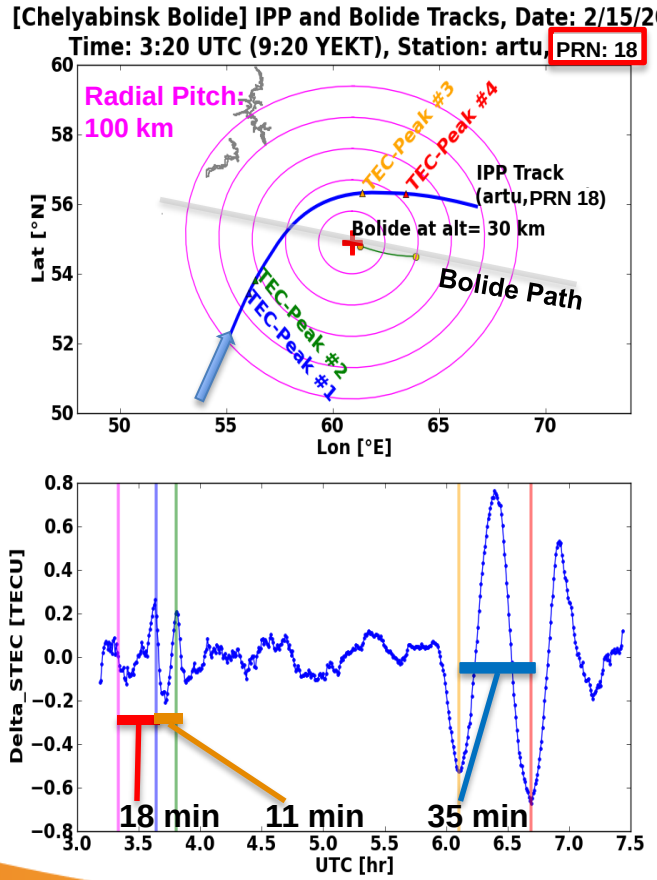

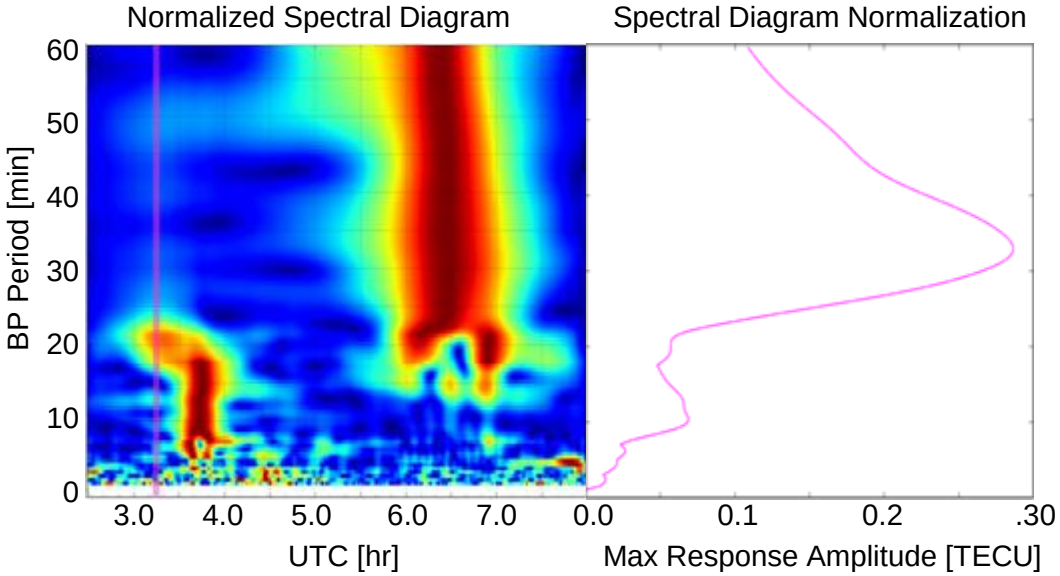

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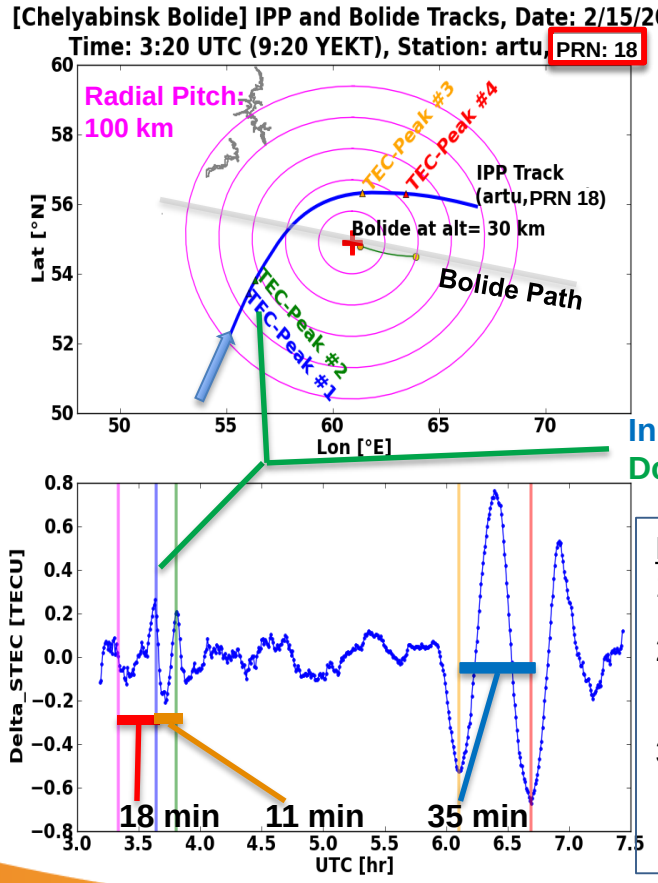

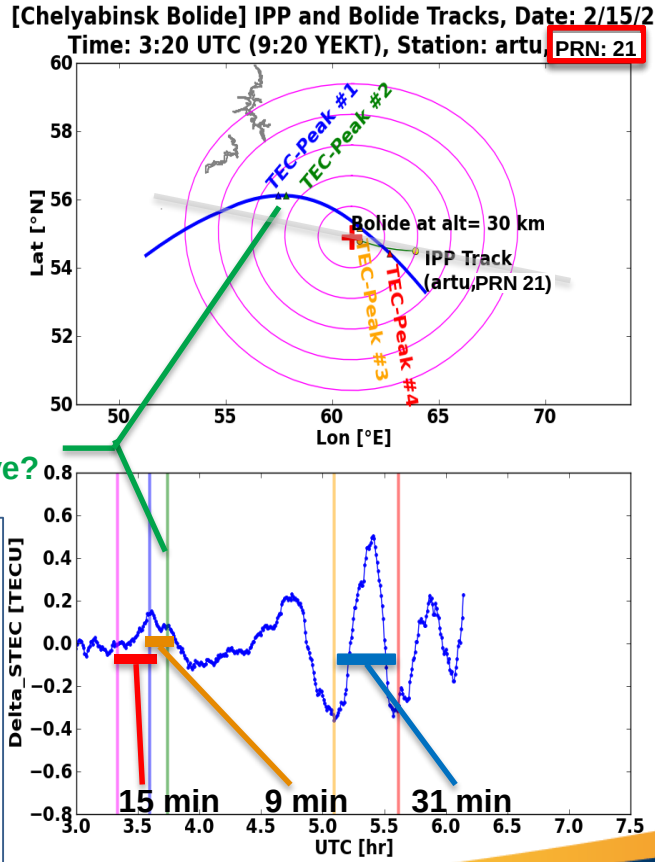

Initial Signature:
Double Acoustic Wave?

Possible Source(s):

1. Temporary mode
2. Acoustic pulses from two paths.
3. Multiple Explosions

Acoustic cut-off:

$\omega_a \approx \frac{\gamma g}{2c_s} \approx .08$ rad/s

$T_a \approx 13\ min$

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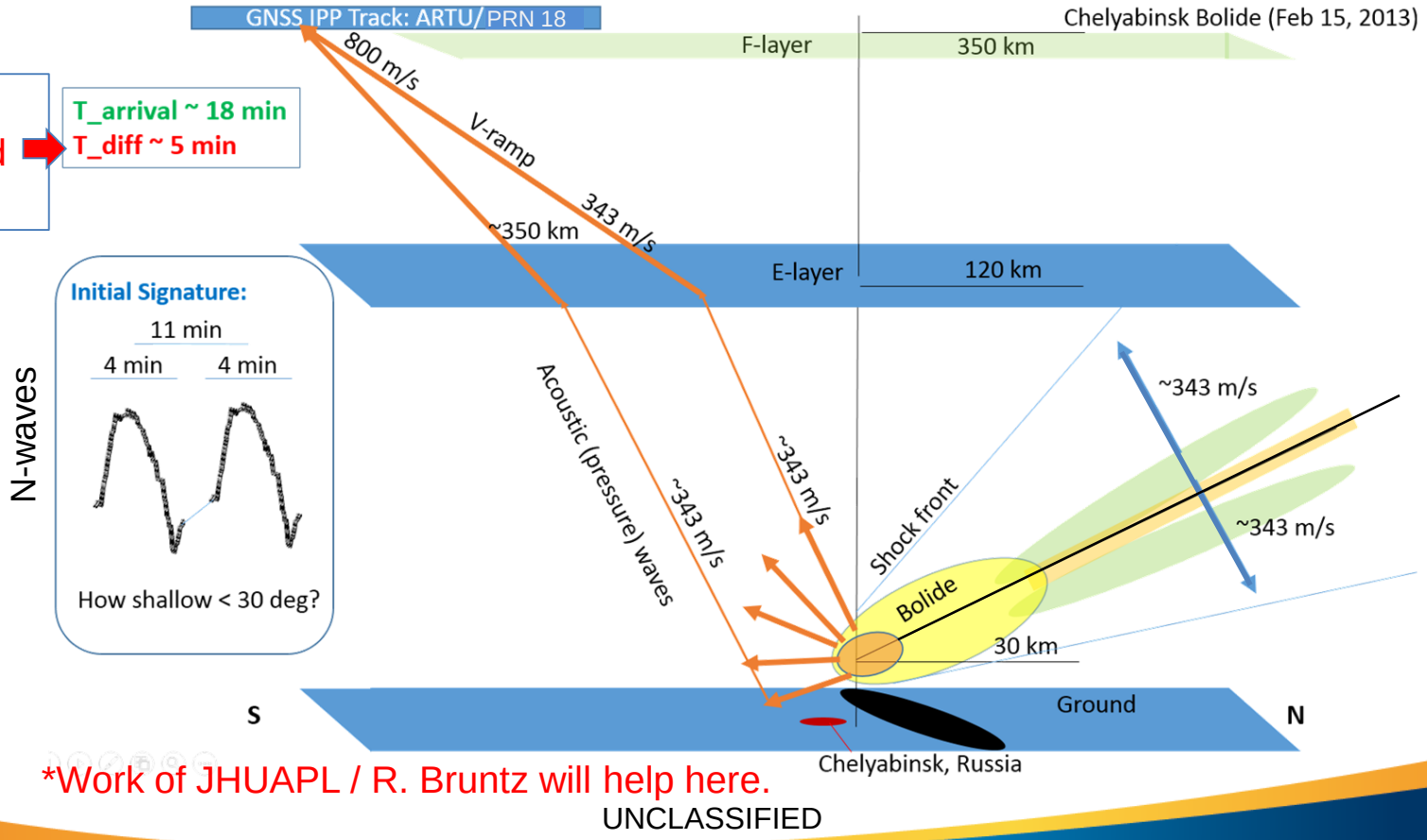
Sample TOA Estimation: Two Acoustic Waves

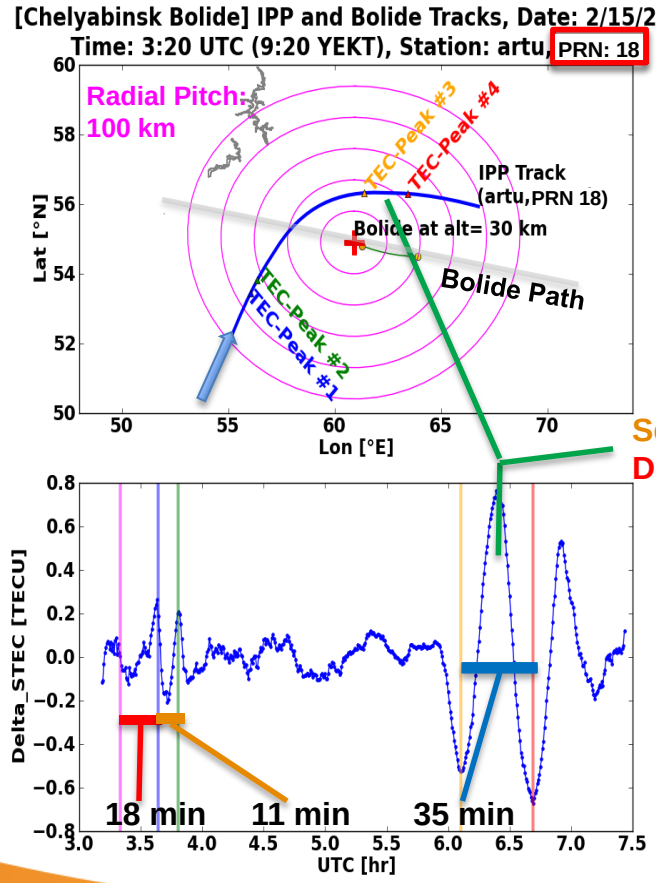
*Half of needed time

T_arrival ~ 18 min
T_diff ~ 5 min

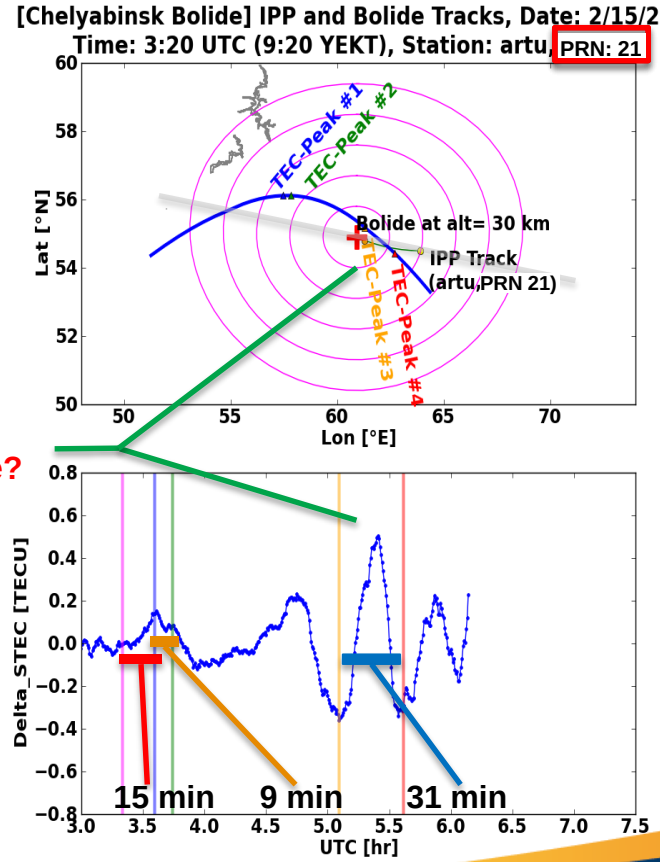


*Work of JHUAPL / R. Bruntz will help here.

Local Signatures: Chelyabinsk Bolide 2013



Second Signature:
Double Gravity Wave?



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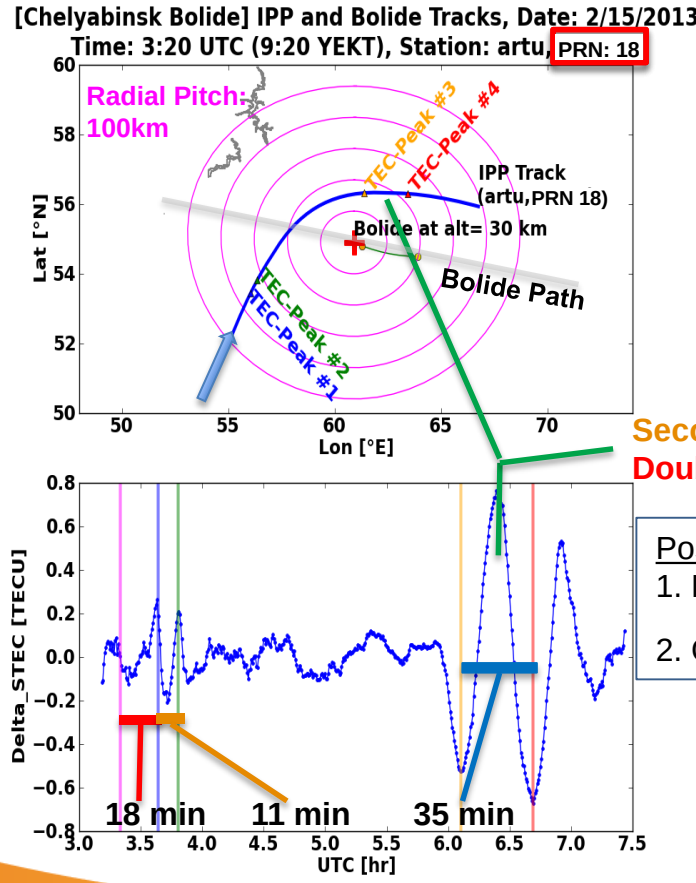

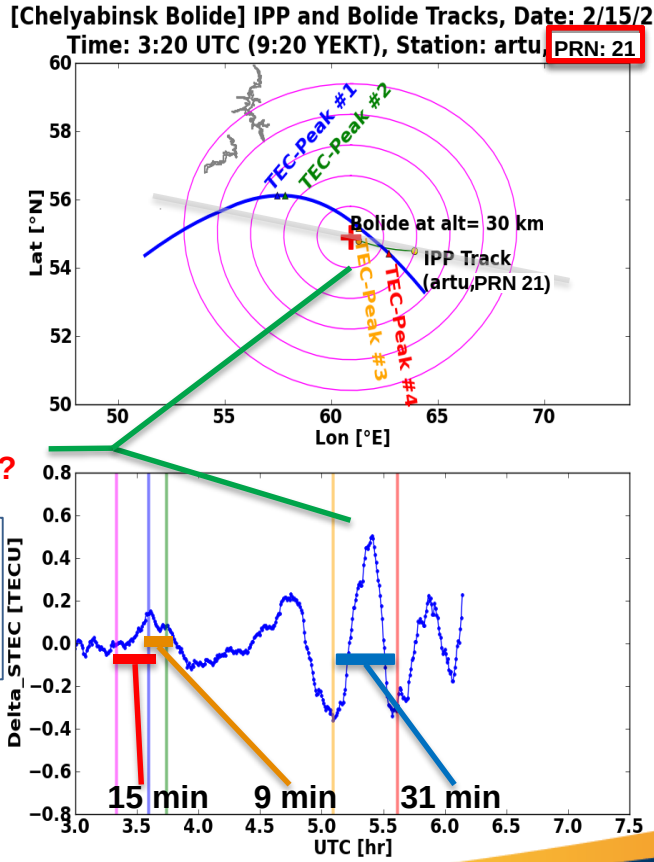

Second Signature: Double Gravity Wave?

Possible Source(s):
1. Double-vortex
2. Gravity waves

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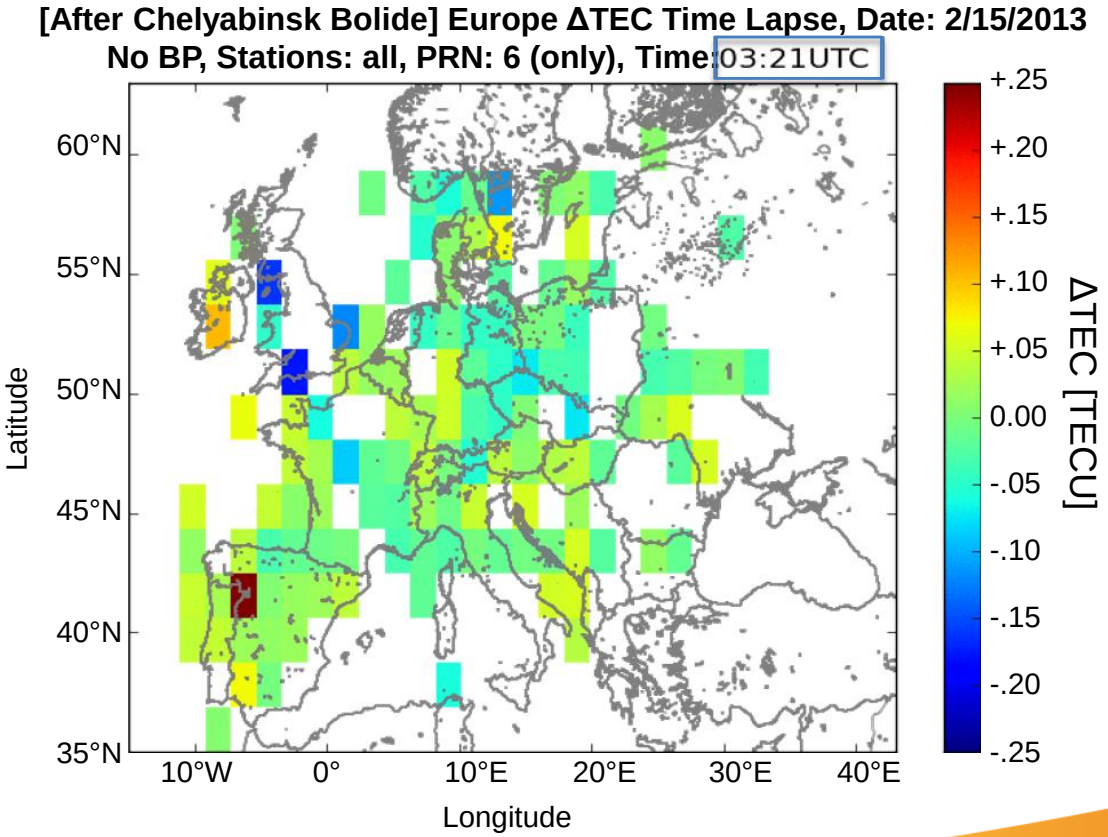
Global Signatures after Chelyabinsk Bolide: Europe

Observation:
Large scale waves over Europe

TEC wave details:
Period: 30 - 35 min
Speed: 500 - 600 m/s
Direction: -80° (azn)
Wavelength: >1200 km
ΔTEC: 0.25 TECU

Likely source(s):
- Chelyabinsk (+2:10, 4500 km)
- sunrise (> 5:40 UTC)

Notes:
- Best observed with PRN 6
- Similar signature over US



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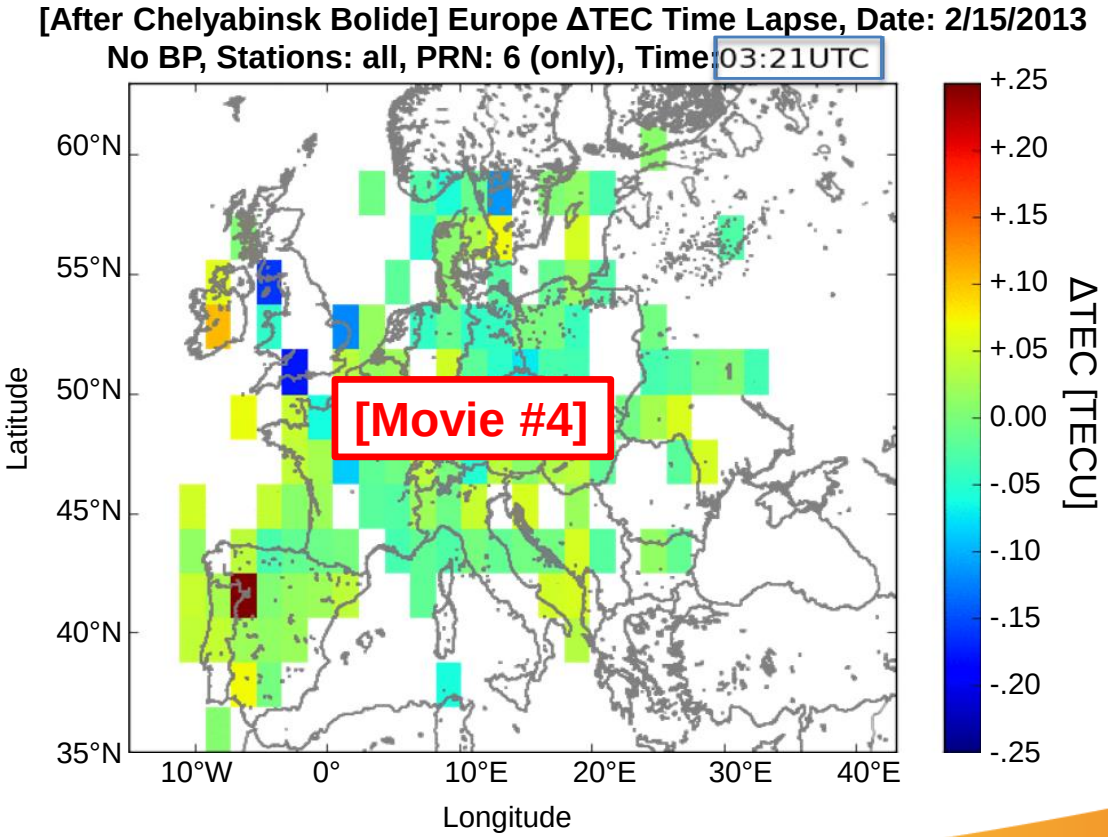

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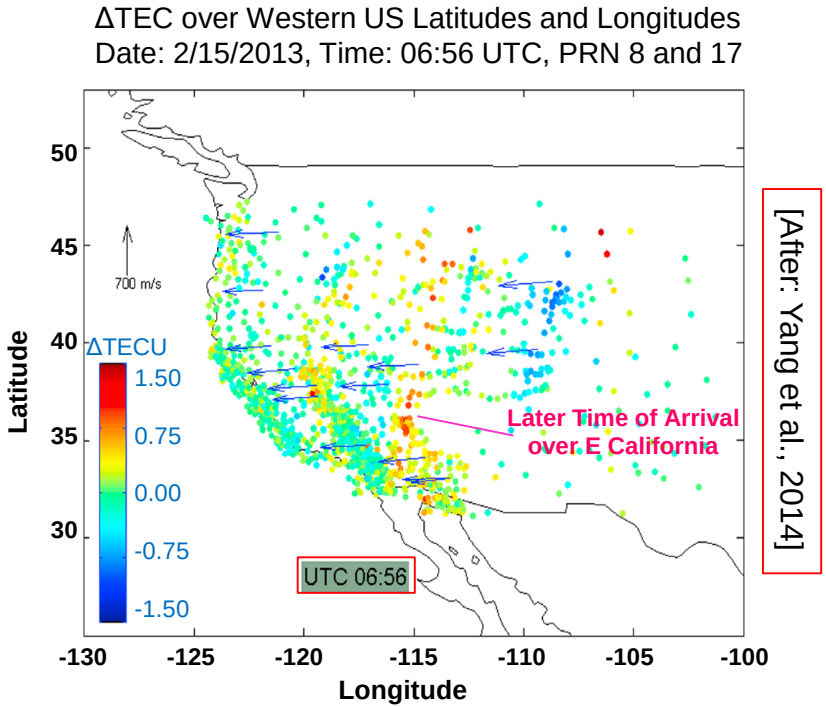
Global Signatures after Chelyabinsk Bolide: US



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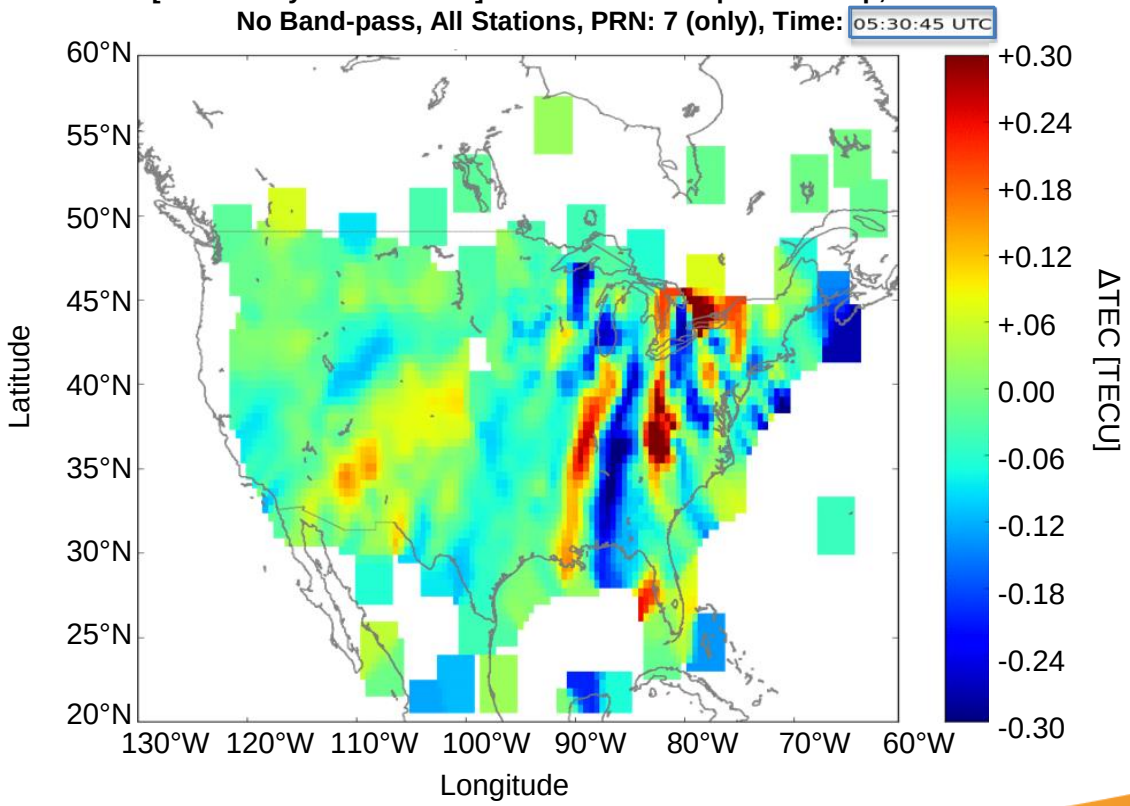
Global Signatures after Chelyabinsk Bolide: US

Observations:
- Raw GPS-ΔTEC signature is same as the 2013 JPL paper.
- Large scale waves travel < 500 m/s near eastern US and speed up as they cross the continent.

TEC signature details:
Period: 35 min
Speed: 500 - 600 m/s
Direction: -80° (azn)
Wavelength: 1200 km
ΔTEC: 0.5 TECU

Likely sources:
- Tropospheric storms over the Great Lakes and Atlantic Ocean
- Probably not from Chelyabinsk.



Global Signatures after Chelyabinsk Bolide: US

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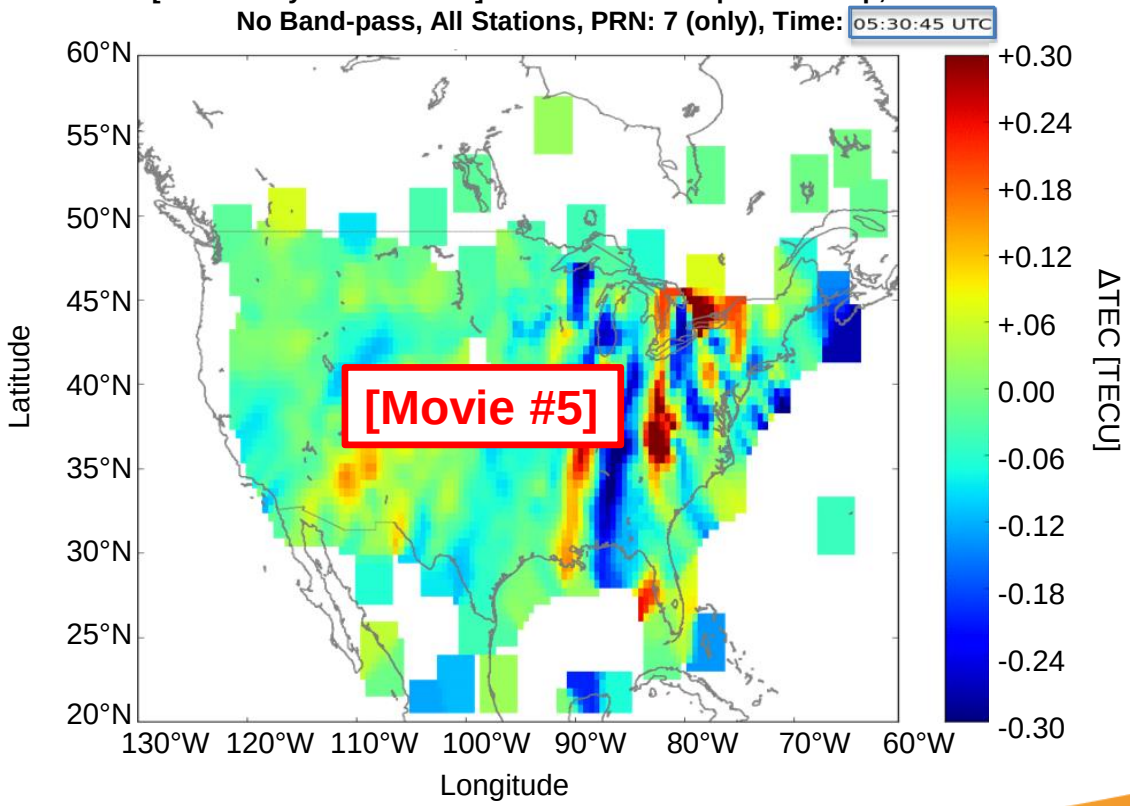


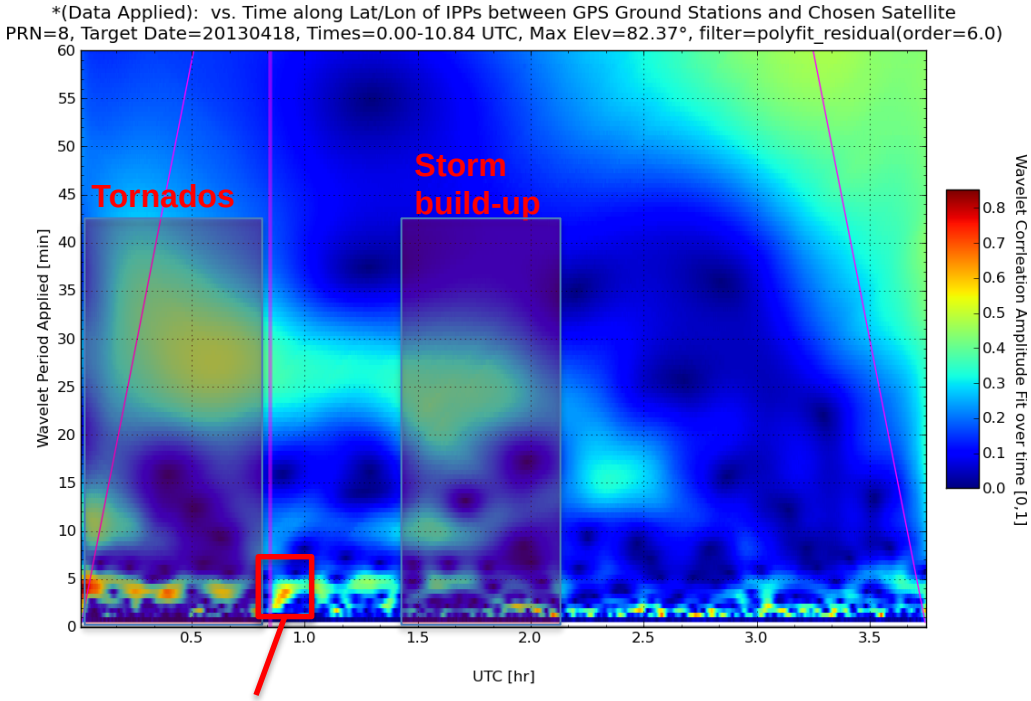
West TX Fertilizer Plant Explosion

Event Description:

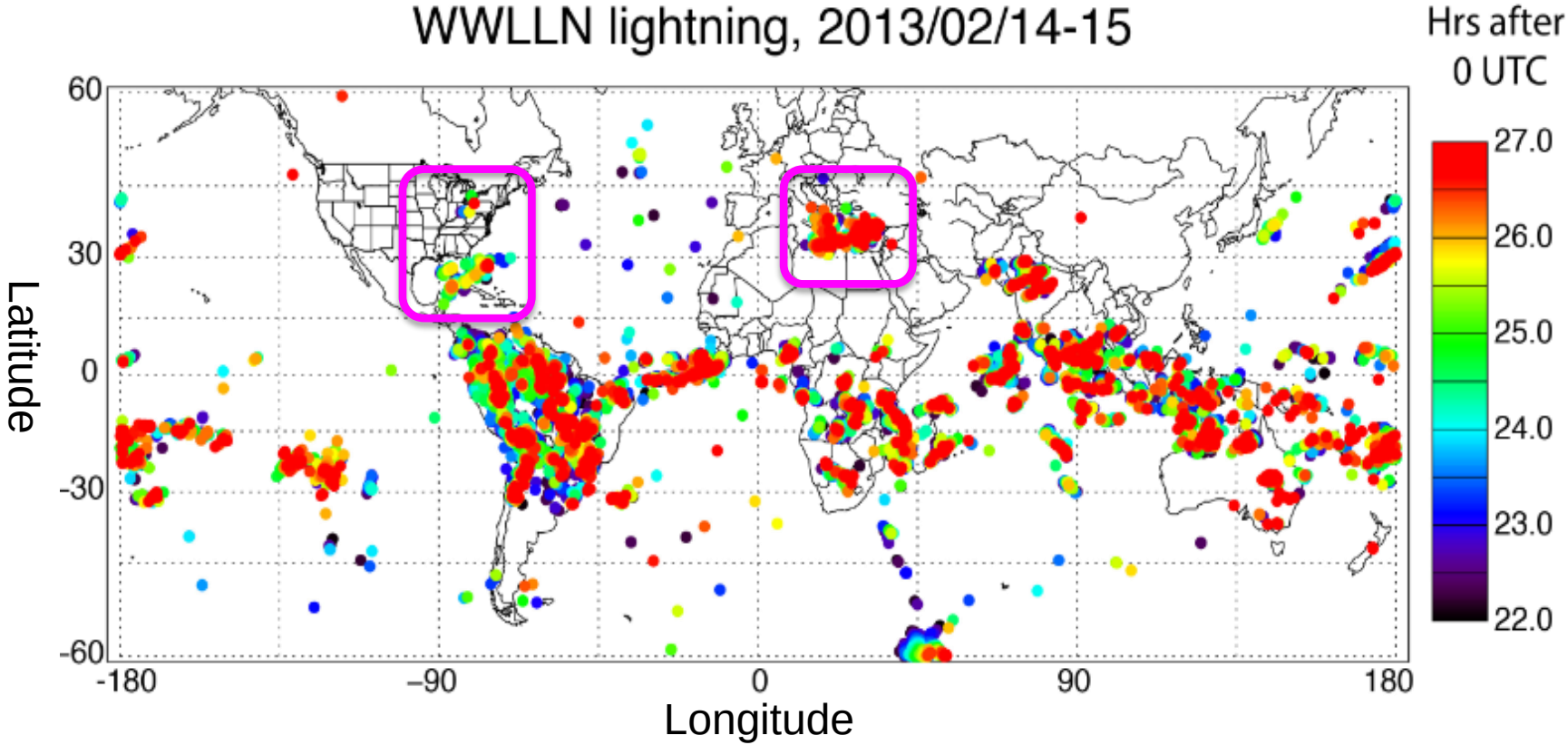
Event Name:	West TX Fertilizer Plant Explosion
Event Date:	4/17/2013 (local)
Event Time:	00:50:38 UTC (19:50:38 CDT)
Event Loc:	31.82°N 97.09°W (West, TX)
Type:	Ground Explosion
Seismic Mag:	2.1
Energy:	~10 tons of TNT

TEC signature details:
- Best IPP-track: Texas Stations/PRN 8 (+PRN 28)
- 9-10 minute delay to ionosphere
- Acoustic-range signature (4 min)

Difficulties:
- Background TEC wave producers:
  1. Tornados over Oklahoma (3 modes)
  2. Storm build-up over south Texas (3 modes)



Possible Explosive Acoustic Signature (4 min)


WWLLN lightning, 2013/02/14-15
Hrs after
0 UTC
27.0
26.0
25.0
24.0
23.0
22.0
60
30
0
-30
-60
-180
-90
0
90
180
Latitude
Longitude

Global Signatures after Chelyabinsk Bolide: US

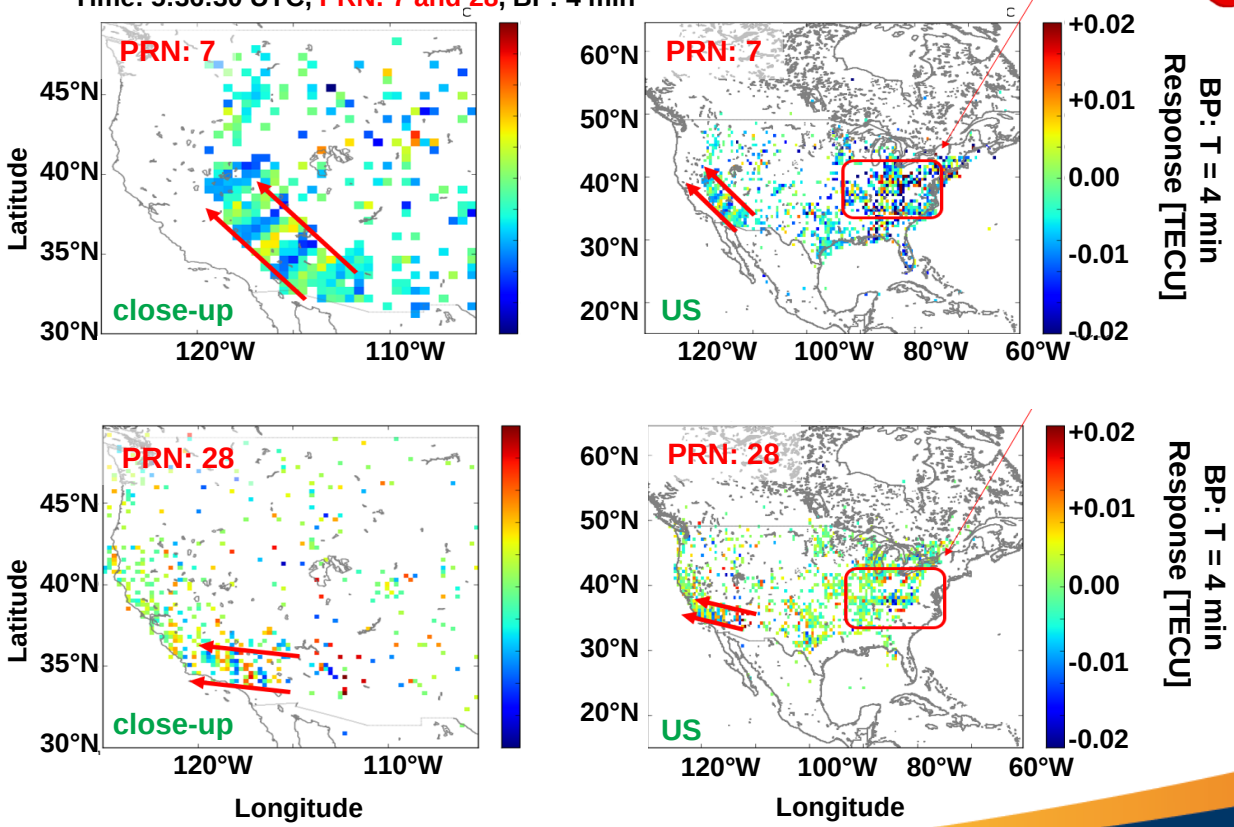
Wave Signatures over US, Date 2/15/2013
Time: 5:36:30 UTC, PRN: 7 and 28, BP: 4 min

Snow Storms over US [NEMO]

Observation:
Acoustic modes over California

TEC signature details:
- Period: 4 min (25% width)
- Speed: 1100 m/s
- Direction: -55 / -80° (azn)
- Wavelength: 264 km
- ΔTEC: 0.02 TECU

Comments:
- Fast moving waves moving to the NW.
- Investigating 25° calculated wave direction difference between PRN 7 and 28.



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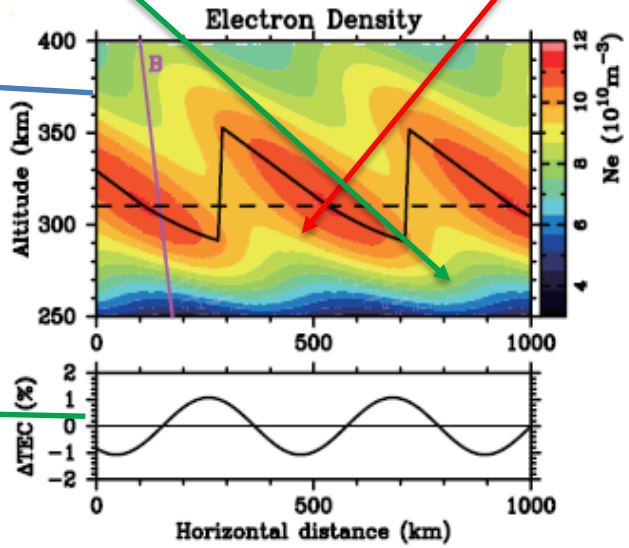
Look Angle: Slanted Vertical Profiles

GPS TEC Calculation

GPS TEC Calculation

Sample Model:
Altitude profile of TIDs



Projected: TEC signal through profile (upward)

[Otsuka et al., 2013]

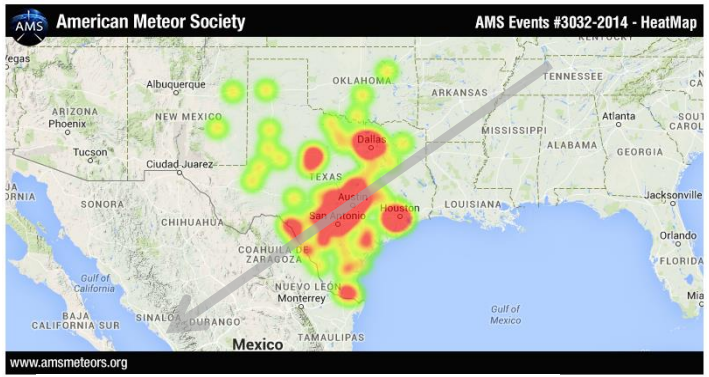
San Antonio Bolide 2014

Event Description: [AMS Event #: 3032-2014]
- Event Date: 11/09/2014
- Event Time: 02:43 UTC (20:45 CST) - evening
- Event Location: 29.3°N, 99.3°W [~San Antonio, TX]
- Bolide travel: West-Southwest
- Meteor shower: 2014 Leonids (early)
- Abs. magnitude: > -14
- Diameter, type: ≈ 1 m, [not recovered]
- Mass, speed: ≈ 1800 kg, > 16 km/s
- Energy: ≈ 55 tons TNT (est.)
- Explosion alt: ≈ 20 km

TEC signature details:
- best IPP-track: PRN 31 (All Stations)
- periods: 12 min / 4 min
- velocity: ? m/s (at ??° azn), 800 m/s expected
- wavelength: 400 km
- ΔTEC: 0.04 TECU / 0.03 TECU

Notes:
- audible from ground (very loud near TX/MX border)
- evening background fluctuations
- possibly 2 events: ~15 min apart

Round Rock, TX
(Photo: John Gutierrez]



[AMS Sighting Map]

Ground Sighting Map

UNCLASSIFIED

San Antonio Bolide 2014

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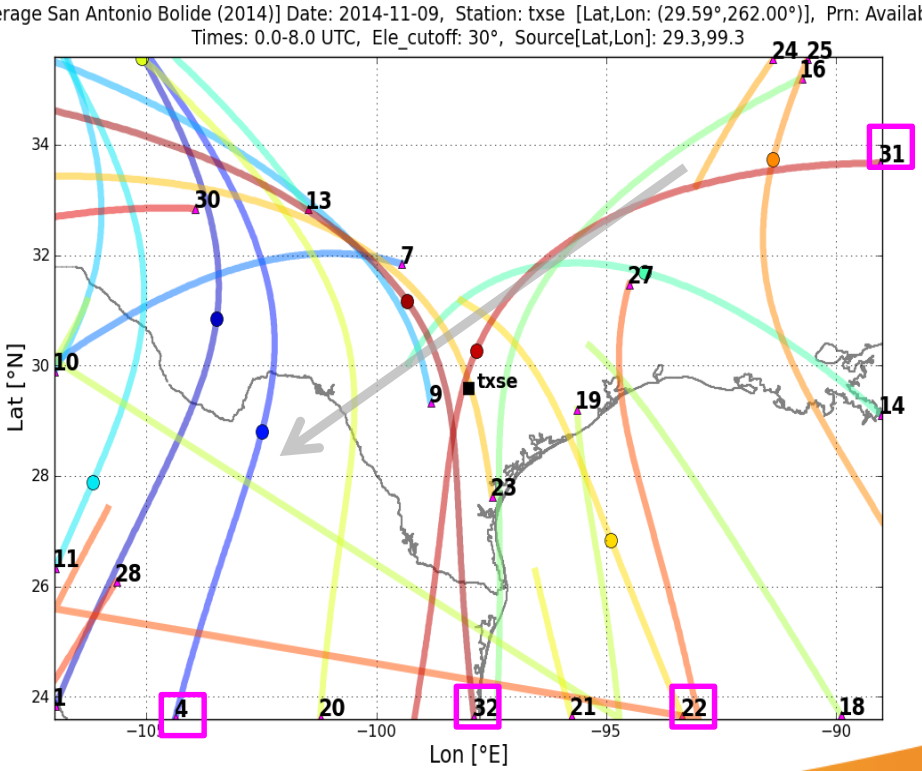
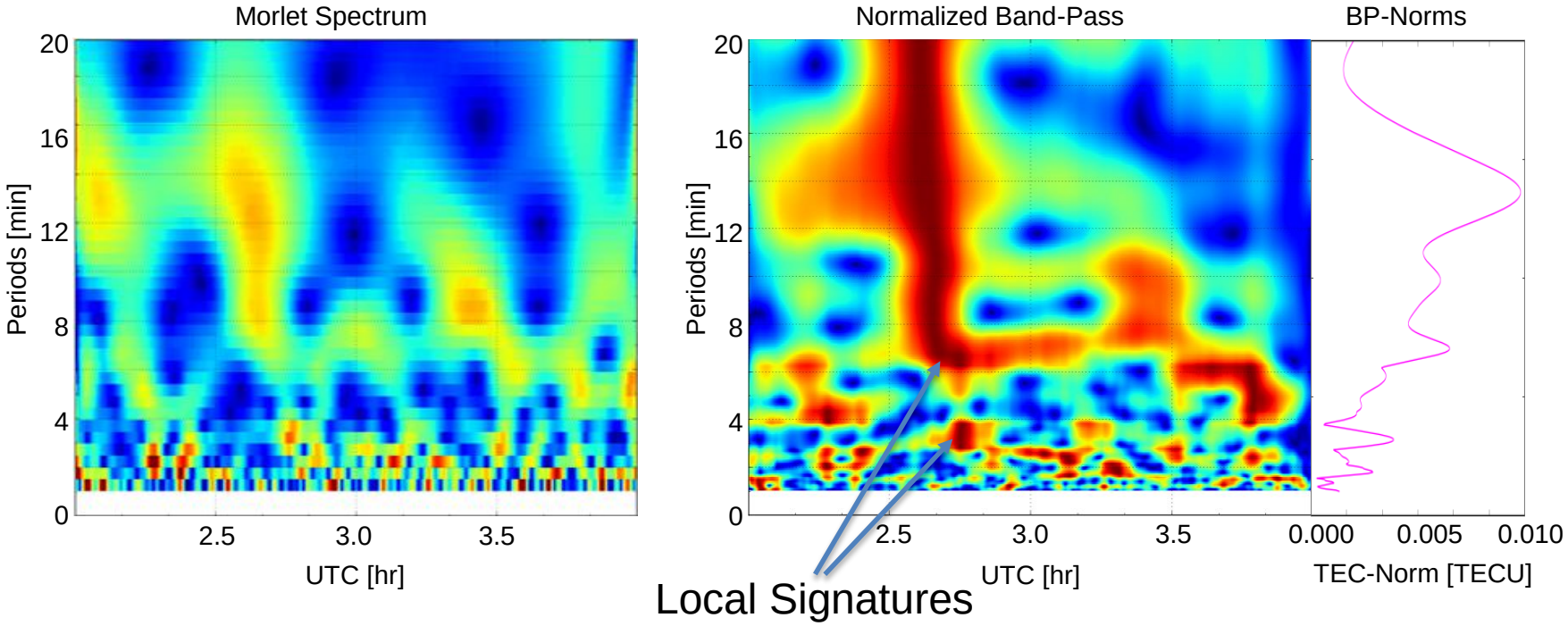


UNCLASSIFIED

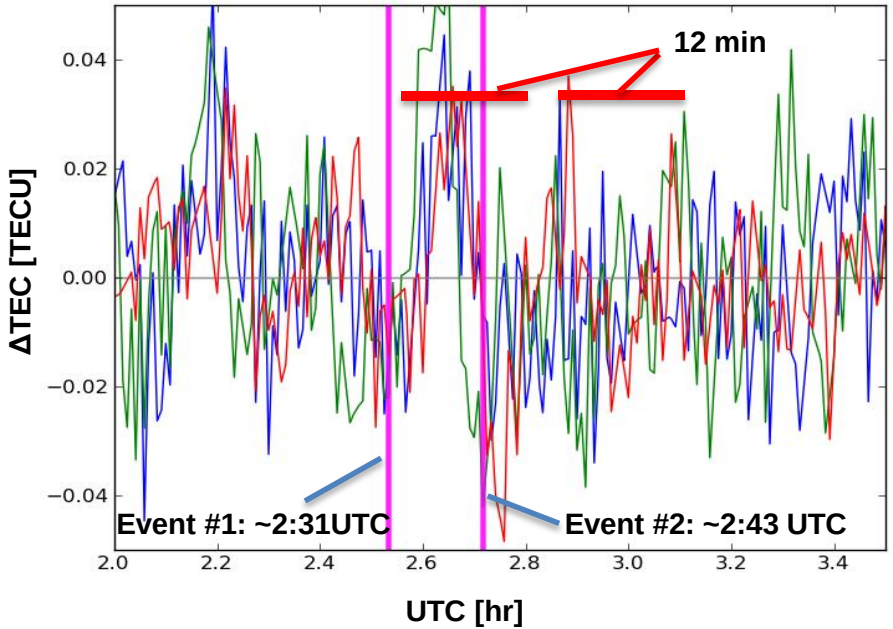
Local Signature: San Antonio Bolide 2014

11/09/2014, station: TXSM/PRN: 31



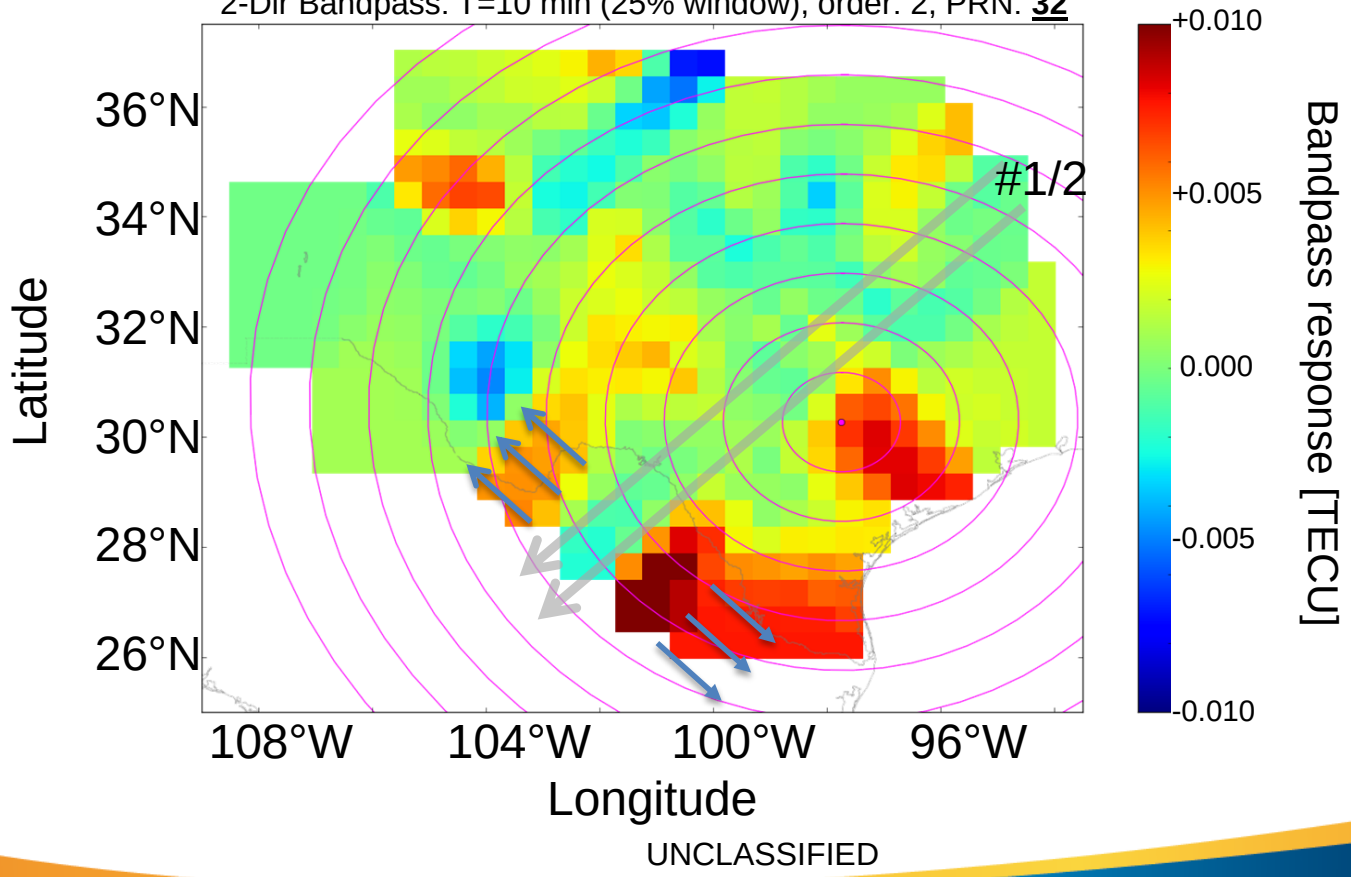
Local Signature: San Antonio Bolide 2014

Event: San Antonio Bolide, ΔTEC w/ HP-Filter(@30 min),
Date: 11/09/2014, Stations: txse, txsm, txgz, PRN: 31



Local Signature: San Antonio Bolide 2014

Loc: Texas San Antonio Bolide, Date: 11/09/2014, Time: 02:40:00 UTC
2-Dir Bandpass: T=10 min (25% window), order: 2, PRN: **32**



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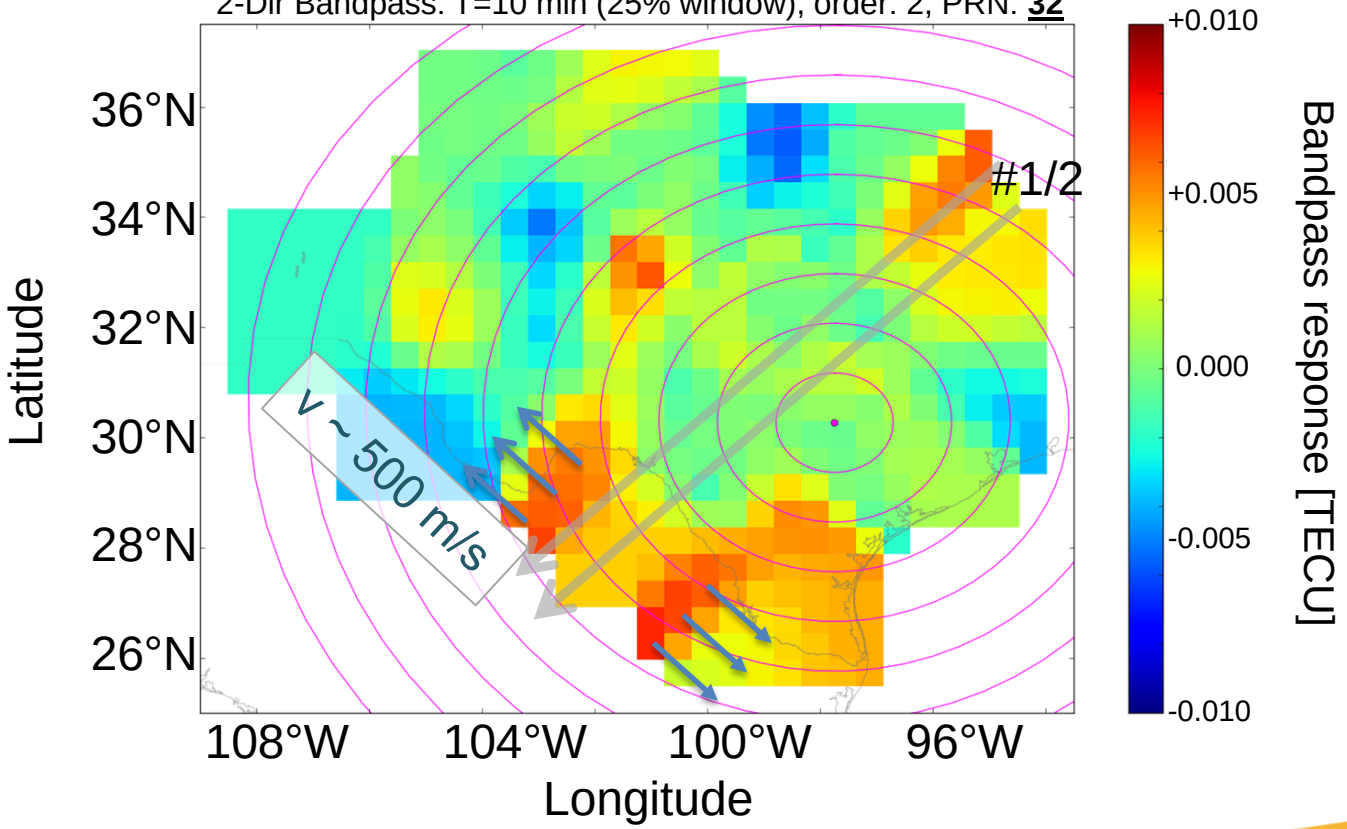
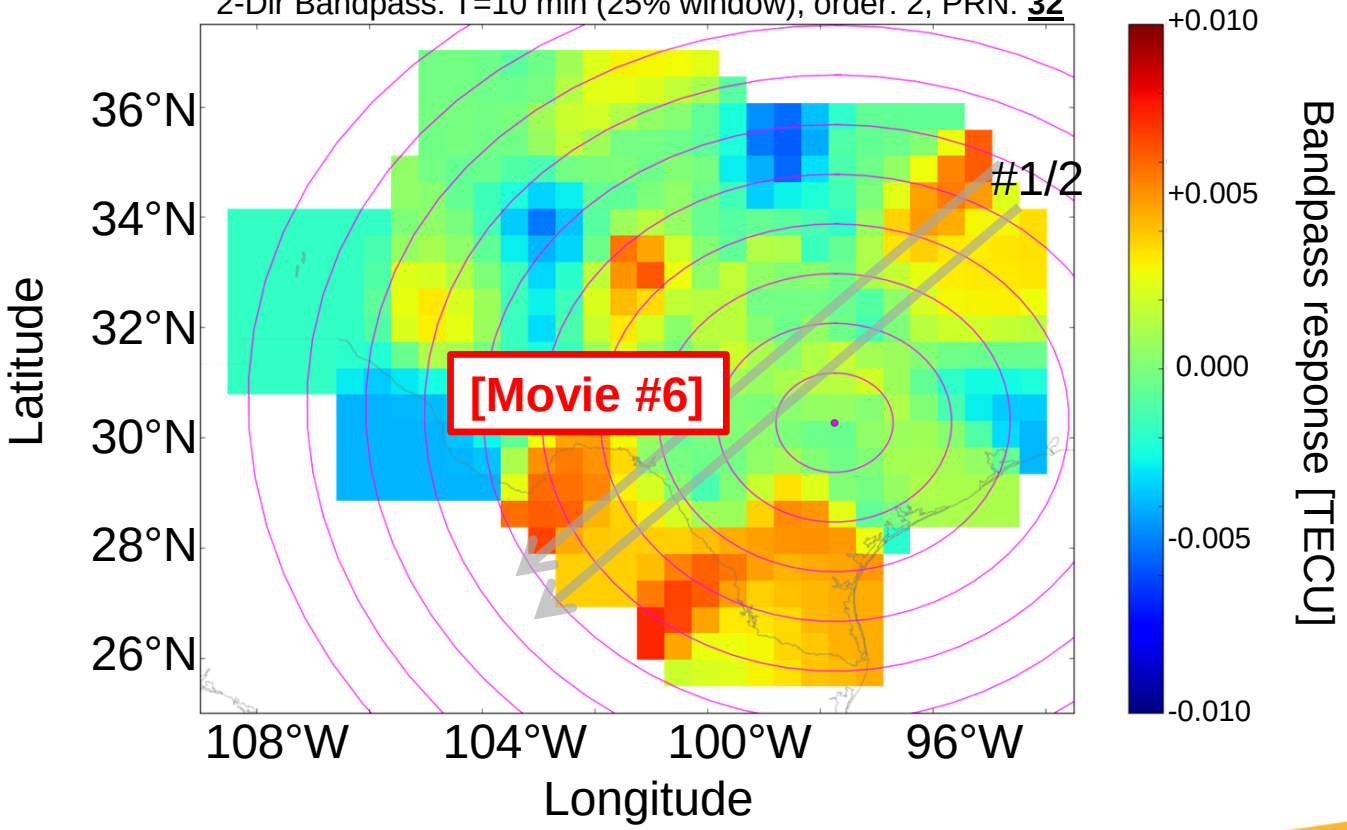
Local Signature: San Antonio Bolide 2014

Loc: Texas San Antonio Bolide, Date: 11/09/2014, Time: 03:01:00 UTC
2-Dir Bandpass: T=10 min (25% window), order: 2, PRN: **32**



Local Signature: San Antonio Bolide 2014

Loc: Texas San Antonio Bolide, Date: 11/09/2014, Time: 03:01:00 UTC
2-Dir Bandpass: T=10 min (25% window), order: 2, PRN: **32**



Sutter's Mill Bolide 2012

Event Description: AMS Event #: 588-2012

Event date:	4/22/2012
Event time:	14:51 UTC (7:51PDT) - morning
Event location:	37.6°N 120.5°W, *Marshall Gold Discovery State Historical Park* [Sutter's Mill]
Bolide travel:	Westward
Meteor shower:	2012 Lyrids
Abs magnitude:	≈ -26 (reported)
Diameter, type:	≈ 2.5 m, CM Chondrite
Mass, speed:	≈ 4×10^4kg, 28.6 km/s
Energy:	≈ 4 kt
Explosion Alt:	≈ 48 km

TEC signature details:

best PRN:	14 (All Stations)
periods:	4 min
velocity:	1600 m/s, at 100° (azn)
wavelength:	400 km
ΔTEC:	0.25 TECU

Major Difficulty:

Morning background acoustic (4-min) signature
(south-easterly propagating waves from the ocean)

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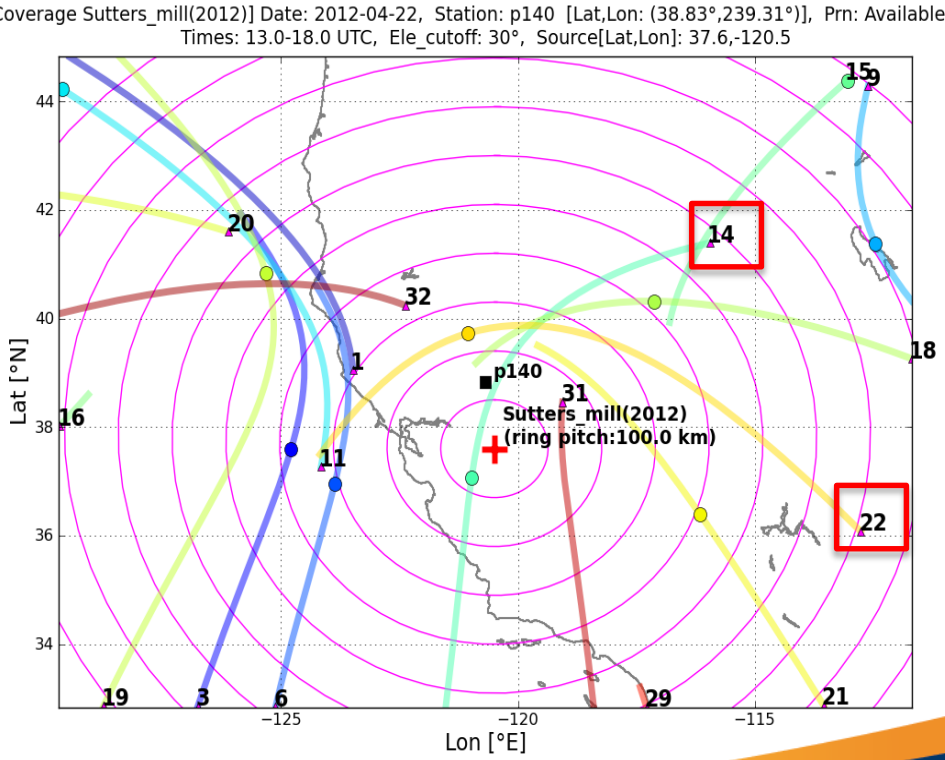

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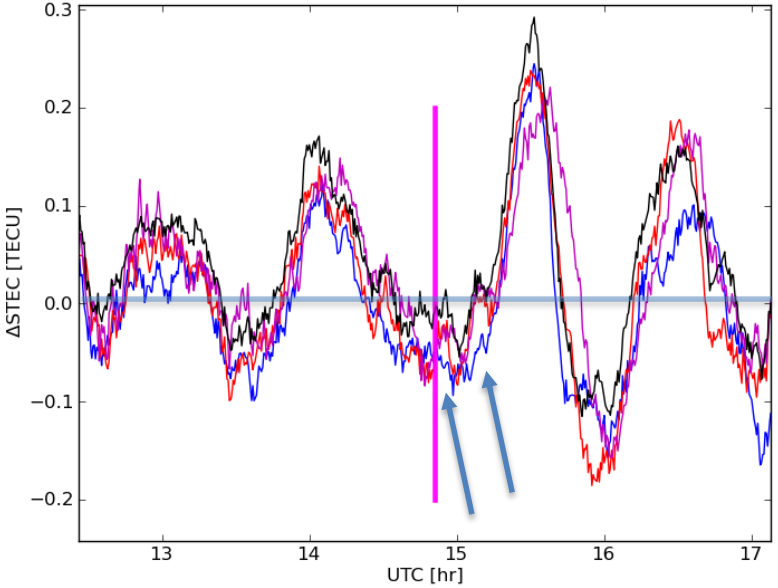
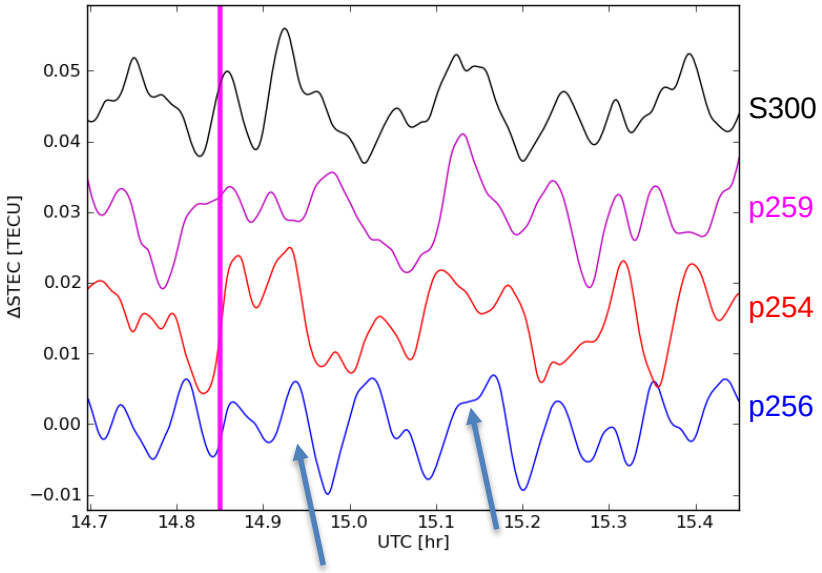
Sutter's Mill Bolide 2012

Bandpass: N/A

[Sutter's Mill] ΔSTEC, Date: 4/22/2012, Time: 14:51 UTC
Stations: p256, p254,p259,s300, PRN:22



Bandpass Amplitudes: T = 4.0 min (25%)



Offset NW ~ 55 km (per line)

index offset +

Sutter's Mill Bolide 2012

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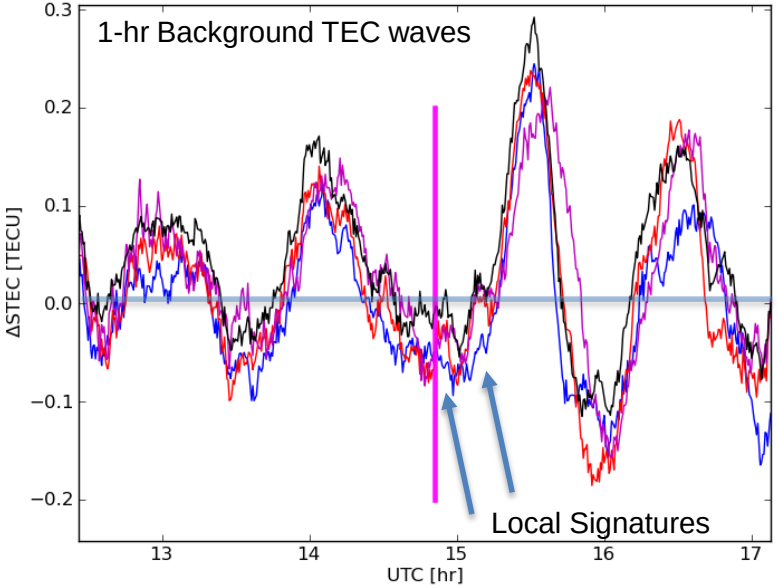
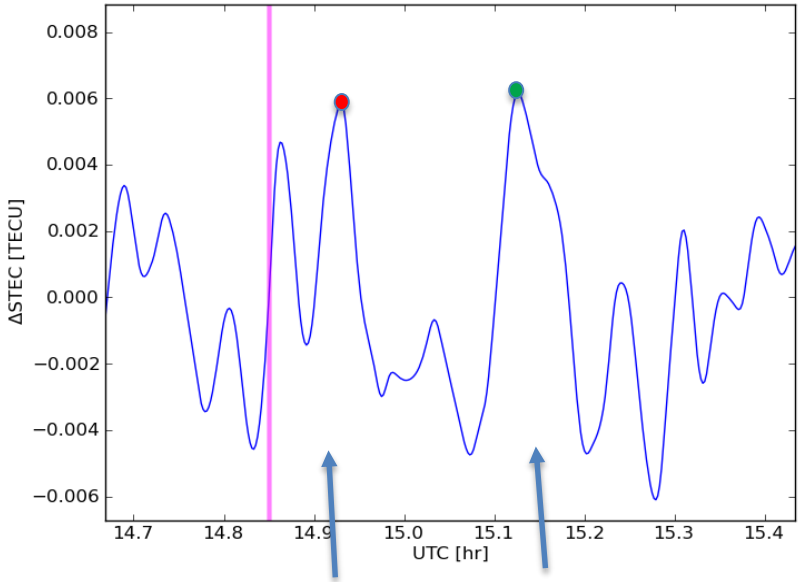


Summed Bandpass Amplitudes/num: T = 4.0 min (25%)

[Sutter's Mill] ΔSTEC, Date: 4/22/2012, Time: 14:51 UTC
Stations: p256, p254,p259,s300, PRN:22



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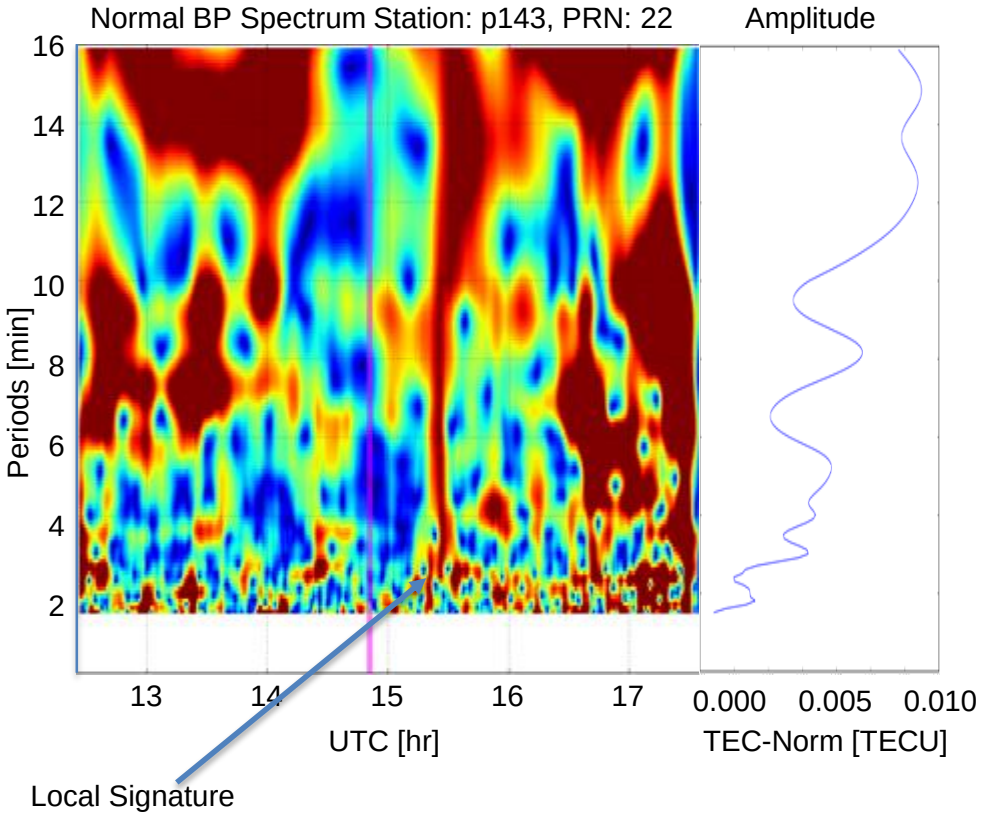
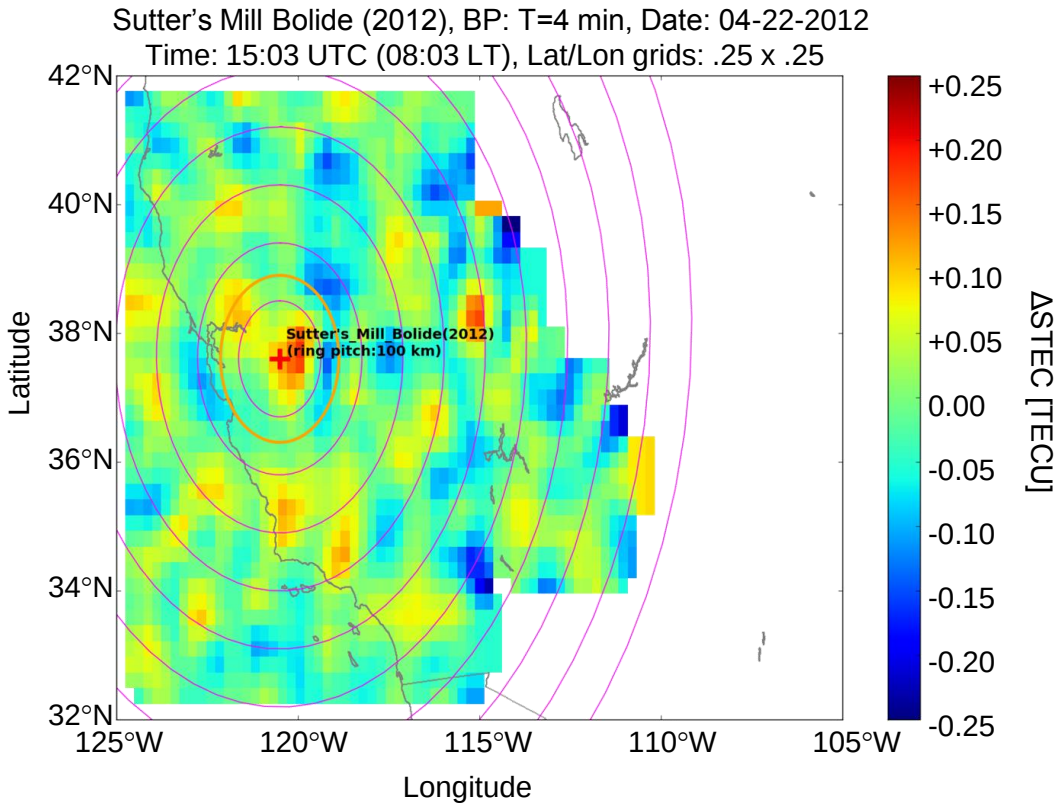
Sutter's Mill Bolide 2012



Sutter's Mill Bolide 2012



Initial Science Results

Chelyabinsk Bolide (2/15/2013):

- Confirmed Local Chelyabinsk Signature in acoustic range.
- Still need to completely understand the double-acoustic/9-12 min signature.
- Large period gravity waves (30-35 min) observed globally are most likely associated with storms and not Chelyabinsk.
- Signature ΔTEC ~ .3 TECU at a distance of 350 km (for 400 kt input)

Sutter's Mull Bolide (4/22/2012):

- 4-minute acoustic signature observed directly over event despite background noise.
- Signature: Amp ~ 0.25 TECU (BP Period: 4 min) at distance of 50 km (for 4.0 kt input).

San Antonio Bolide (11/09/2014):

- Observed cylindrical wave propagating outward from trail.
- Shock fronts appear to produce periods in the range of 9-12 minutes in the ionosphere.
- Signature ΔTEC ~ .01 TECU (BP Period: 10 min) at distance of 100 km (for .050 kt input).

Forward

Progress:

- Generated analysis tools to improve ability to identify events in TEC data.
- Validated analysis tools on Japan earthquake event (2011).
- Began cataloguing example bolide and comparison signatures.
- Developed and improved models/explanations of observations.

Currently working on:

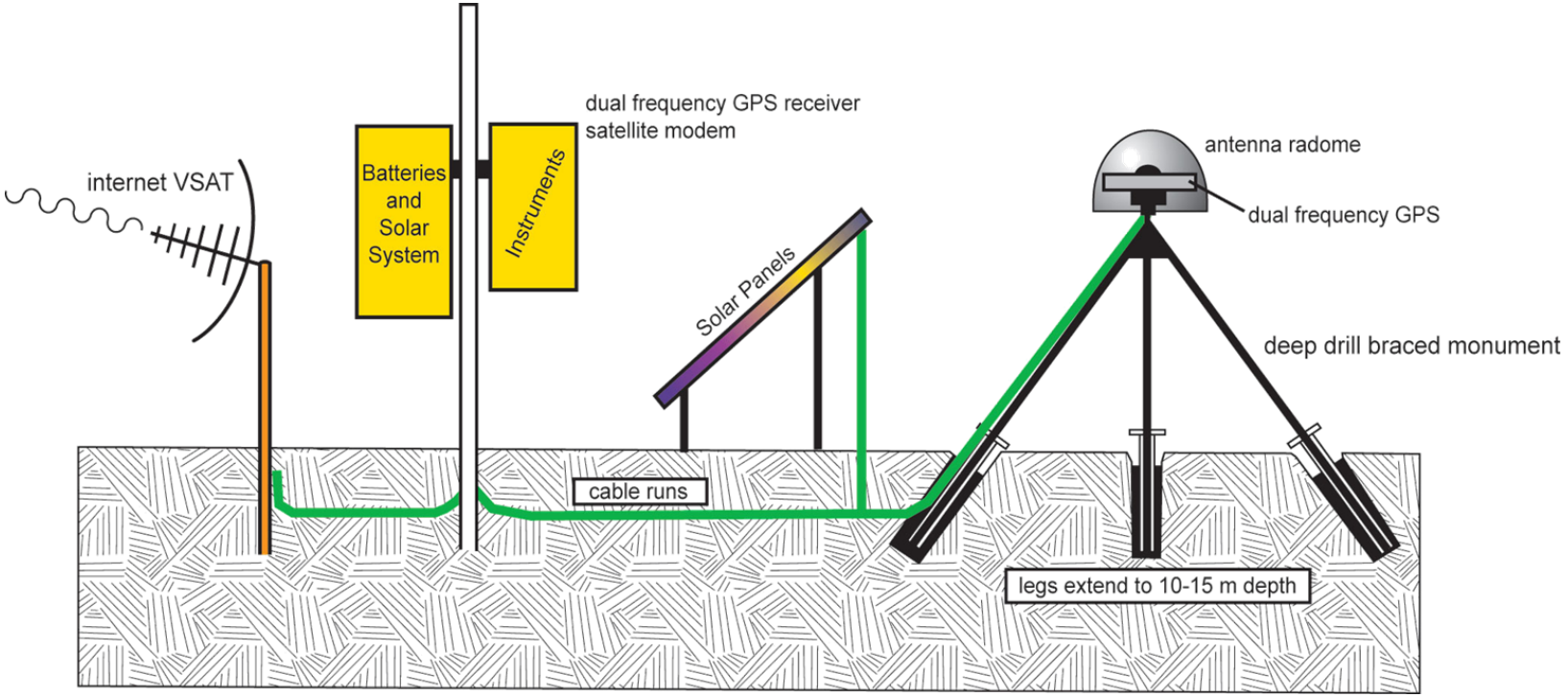
- Further improving SNR in TEC signals from bolide events.
- Examining more bolide cases.
- Examining published physics models for measurement limits with GPS-TEC.
- Paper #1: “Systematic Analysis Techniques for Studying Ionospheric Responses”

Future:

- Determine limits of sensitivity of detecting bolides using GPS-TEC.
- Paper #2: “Global Ionospheric Response to the Chelyabinsk Bolide (2013)”
- Paper #3: “Signature Comparison for Multiple Bolides”

Questions?

GPS Ground Station Diagram



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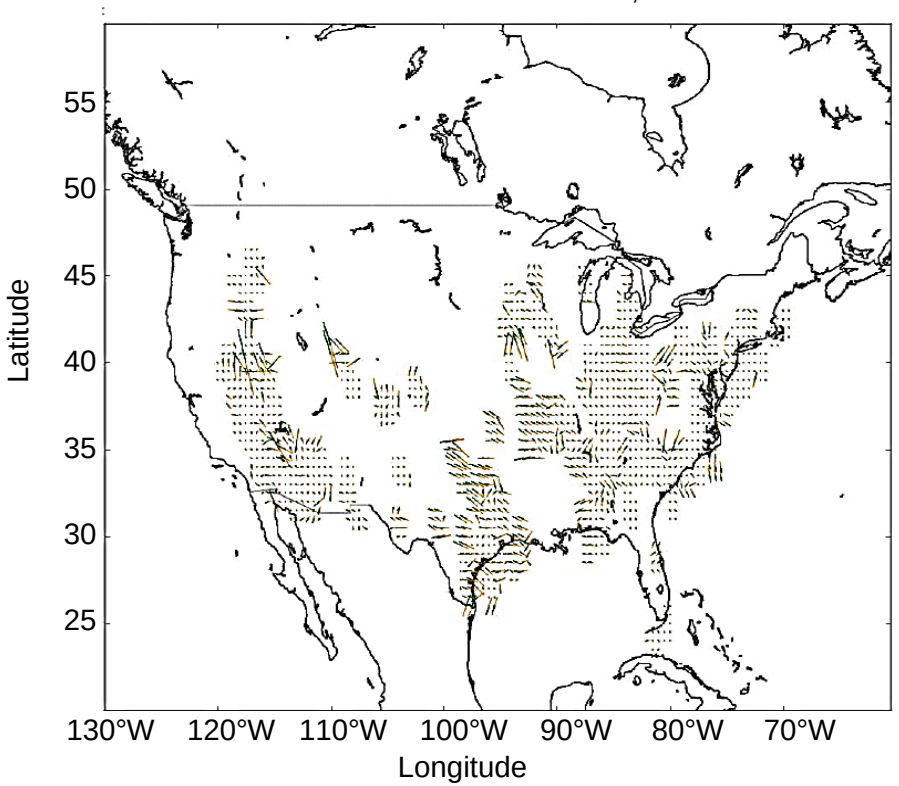
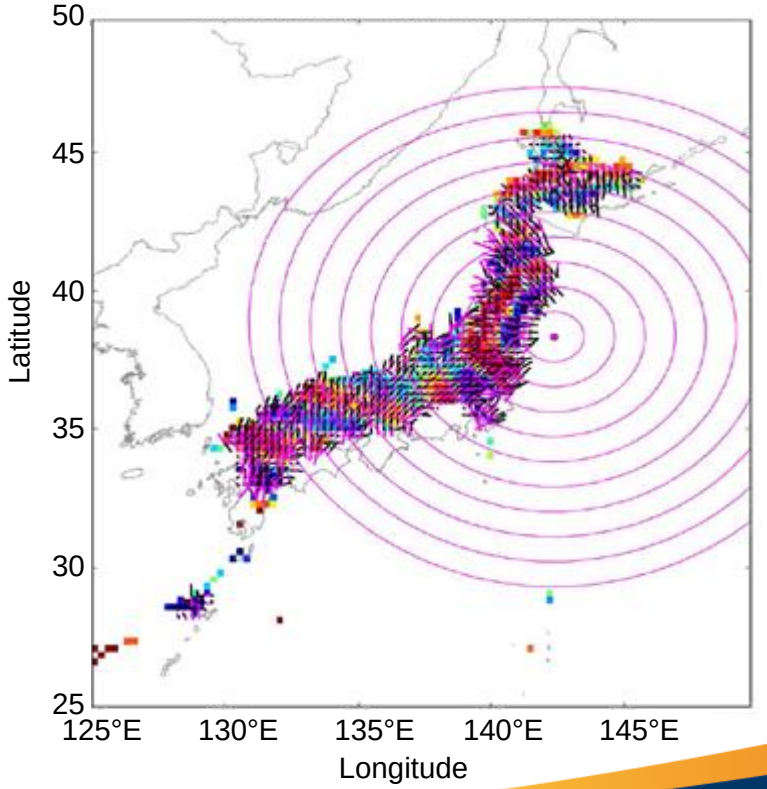
Global Propagation: Station Coverage Comparison

GPS-TEC Velocity Calculation Coverage
Date: 2/15/2013 Time: 05:47:30 UTC, BP: T = 4 min



GPS-TEC Velocity Calculation Coverage,
Date: 03/11/2011 Time: 06:08:30 UTC, BP: T = 4 min



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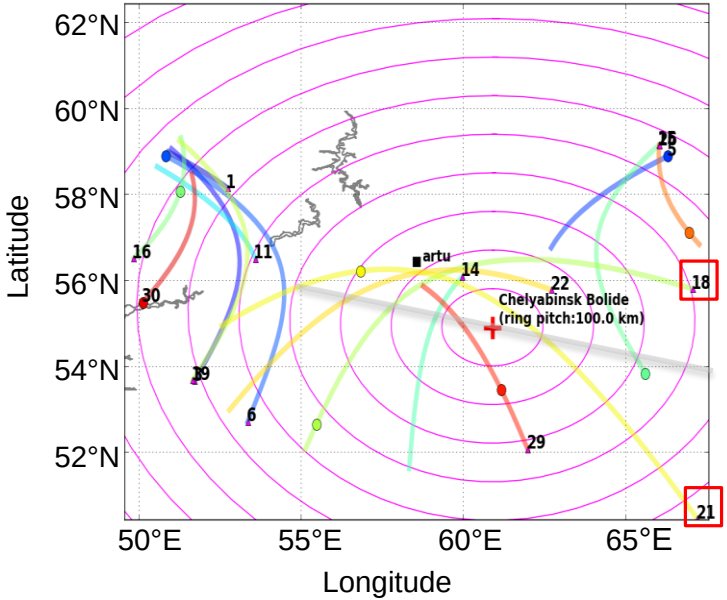
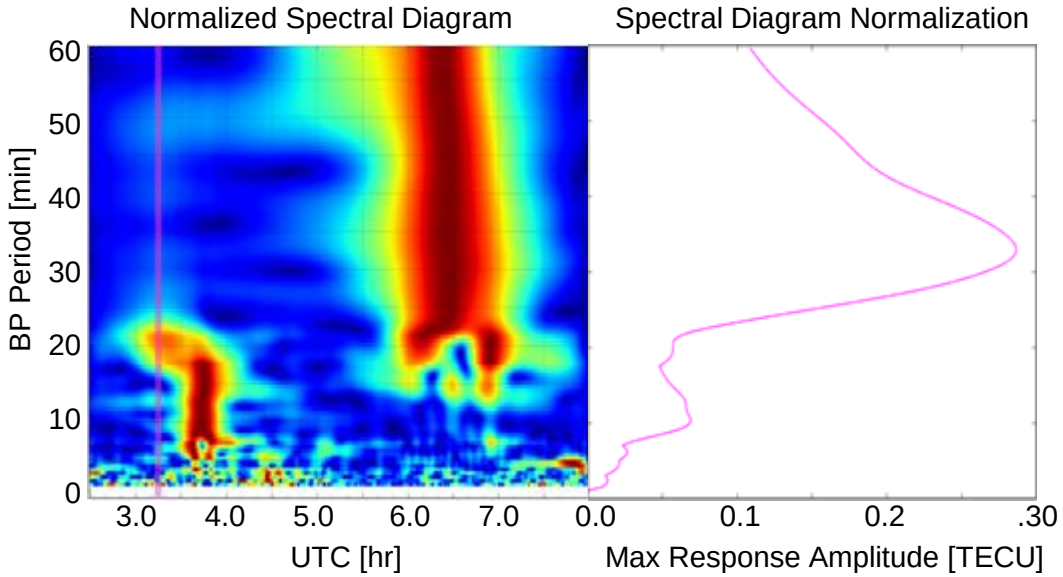
Local Signatures: Chelyabinsk Bolide 2013

[Coverage Chelyabinsk Bolide, Date: 2/15/2013, Station: ARTU]



Description:
Shows GPS coverage over Chelyabinsk Bolide Area. Best PRNs are 18 and 21.

[Chelyabinsk Bolide, Date: 2/15/2013, Station: ARTU, PRN: 18]



Description:
Shows ranges of band dominance and Pulse-like behavior in Spectrum.
Red/Blue: 1/0 (highest/lowest values)

Description:
Highest values for each BP, used to normalize spectral diagram.

Theoretical Considerations

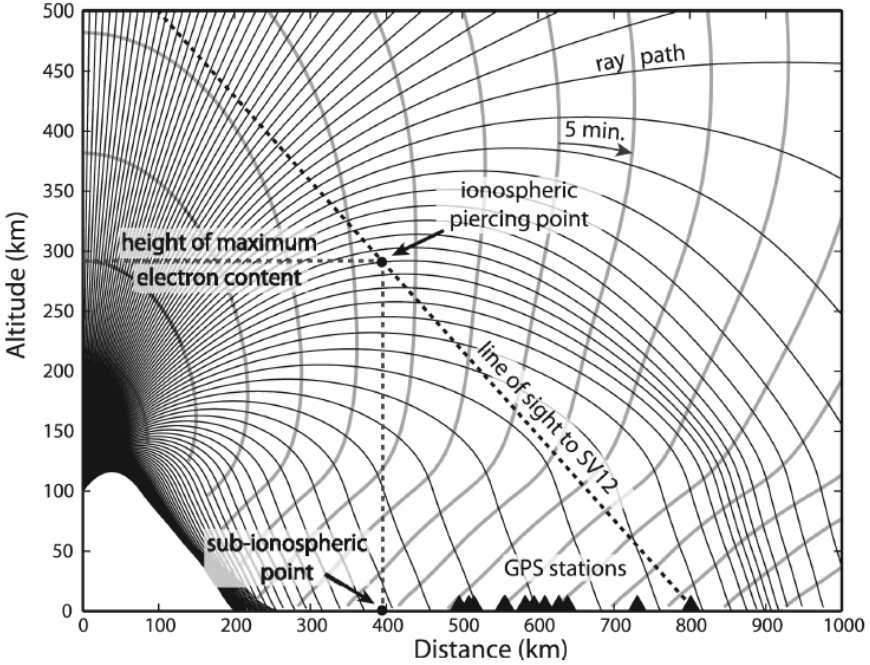


Figure 6. Ray tracing geometry for a single point source, in plane perpendicular to the shuttle trajectory. Black triangles show the projection of GPS stations onto this plane. The black dashed line shows the projection of the line of sight between a GPS station and satellite 12 onto this plane. The IPP and its projection onto the Earth's surface, or SIP, are indicated. Only the southern half of the modelled domain is shown. Solid black lines show rays produced by a source at 100 km altitude with takeoff angles above 31°. Rays with lower takeoff angles are trapped in the low-velocity channel between the mesopause and thermocline, or are reflected between the Earth's surface and the mesopause and are not shown here. Assuming a cylindrically spreading source, only ~23 per cent of the source energy reaches the altitude of maximum electron content (281 km here). Grey lines locate the acoustic wavefront at 5 min intervals.

[From Bowling, 2013: Sensing STS-125 Launch]

Theoretical Considerations

[After Bowling, 2013: Sensing STS-125 Launch]

Table 1. Comparison of different studies of acoustic waves produced by shuttle ascents.

Study	Amplitude [TECU]	Velocity [m s^{-1}]	Mission	Technique
Noble (1990)	N/A	628–735	STS-4	Incoherent Scatter Radar
Li *et al.* (1994)	0.0093–0.0703	600–700	STS-58, STS-60	VLBI
Calais and Minster. (1996)	0.039–0.25	862–894	STS-60	GPS
Afraimovich *et al.* (2002)	0.27–0.57	1529	STS-90, STS-95	GPS
This study	0.16–0.65	516–716	STS-125	GPS
Model	0.23–0.71	757	STS-125	GPS

TABLE 1B. Seismic Detections of Man-Made Atmospheric Events

Date	Detected Object	Latitude	Longitude	Country	Observations	Seismic Interpretation	References
1963	supersonic aircraft			California/Arizona/Utah, USA		acoustic: shock wave	*McDonald and Goforth* [1969]
19 Sep 1980 and 12 Oct 1982	missile silo explosion and supersonic aircraft			Kentucky/Tennessee, USA		acoustic: point	*Johnston* [1987]
1989/1991	space shuttle reentries			Southern California, USA	39	acoustic: shock wave	*Kanamori et al.* [1991, 1992]
8 Dec 1993 and 30 Jan 1992	supersonic aircraft and space shuttle *Discovery*			Southern California, USA	64+	acoustic: shock wave	*Cates and Sturtevant* [2002]
15 Jan 2006	NASA Stardust reentry	40.41°N	113.87°W	USA	2	acoustic: shock wave	*ReVelle and Edwards* [2007] and *Edwards et al.* [2007]

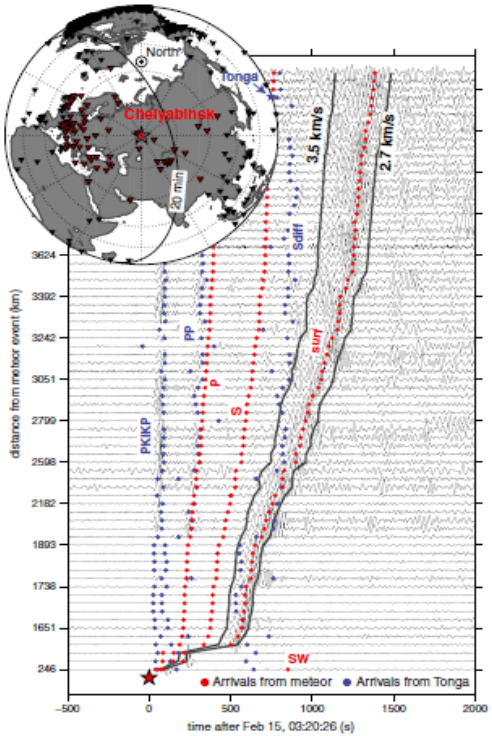
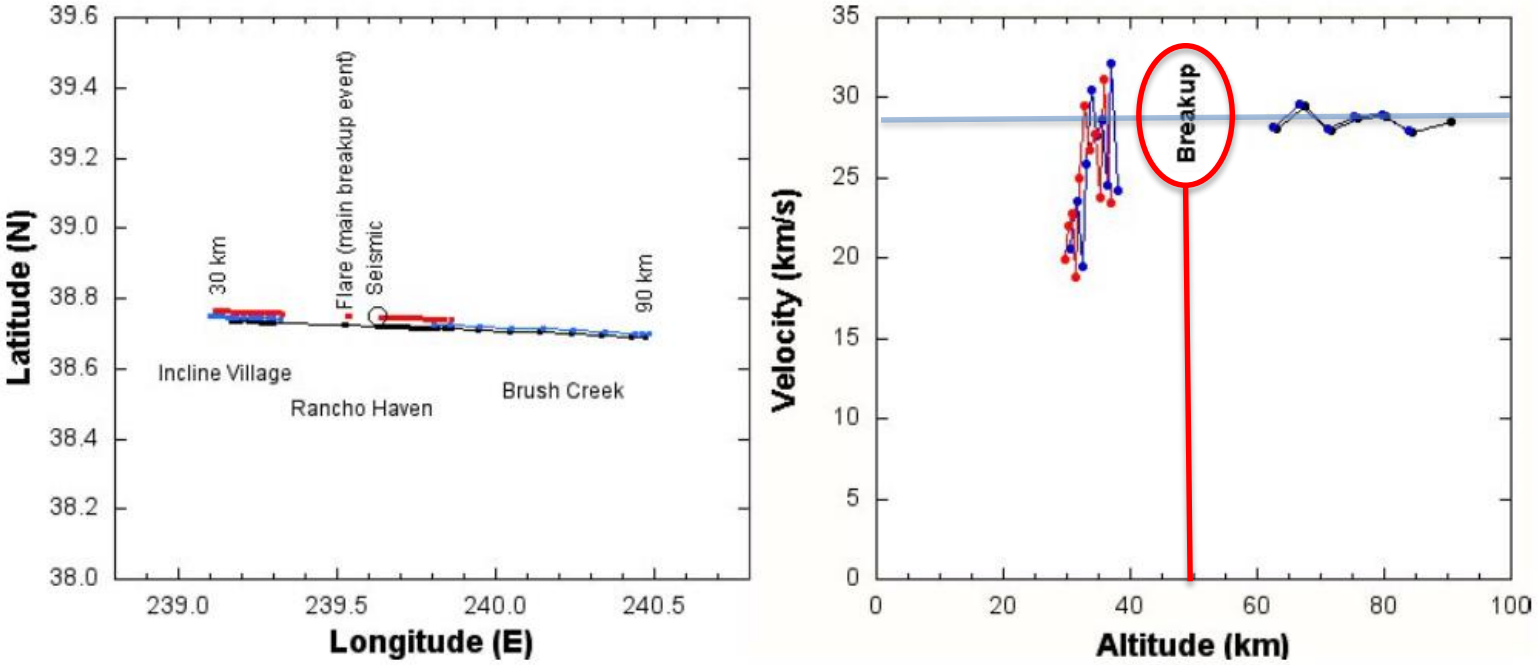


Figure 1. Vertical component seismograms for stations located within ±4000 km from the city of Chelyabinsk. The seismograms are band-pass filtered between 20 and 60 s. The origin time is the time proposed for the main meteor blast (i.e. t_0 = 03:20:36 UTC). Along the *Y* axis, the data are sorted by increasing distance from the reported burst point in this study (54.82°N, 61.24°E). Note that distance is not increasing linearly along this axis. Body waves (PKIKP, PP, and Sdiff) from the Tonga earthquake are indicated with blue dots. The gray curves delineate inferred Rayleigh waves associated with the Chelyabinsk meteor. They correspond to curves $t = t_0 + d/v$ with v = 3.5 and 2.7 km/s, respectively. Predicted travel times for *P*, *S*, surface waves, and shock waves (SW) induced by the meteor event are indicated with red dots. The map at the top left shows the location of the city of Chelyabinsk (red star) with all broadband seismological stations within 4000 km (red triangles) and away (black triangles). The North Pole is indicated with a double black circle. A 20 min travel time isocontour for *P* waves emitted by the Tonga earthquake is indicated as a black small circle on the sphere.

Sutter's Mill Bolide 2012



[Figure. Bolide trajectory from Peter Jenniskens' final report]

Explosion Comparisons: West and Tianjin

Event: 2015 Explosion Tianjin, China

Time: ~23:30 CST (~15:30 UTC) onwards (fire < 14:50 UTC)
Date: 12 August 2015 – present
Venue: Port of Tianjin
Location: Binhai, Tianjin, China
Coordinates: 39.0389°N 117.7371°E
Type: Ground Explosion
Cause: Under investigation
Deaths 114 (including 12+ firemen)
Non-fatal injuries 722 (including 58 severe injuries)
Missing: 70 (mostly firefighters)

1. ΔTEC: 0.3 TECU [PP], T~ 3 - 6 min @1330 UTC – coh >.6
2. ΔTEC: 0.6 TECU [PP], T~11 - 30 min @1530 UTC – coh ~.5
3. ['1st'] ΔTEC: 1.2 TECU [PP], T~16 - 30 min @1530 UTC – coh > .6

ΔTEC [meas]: Station=BJNM/PRN=15, at ~< 300 km
Seizmic (est): 2.3; ??
Energy (est): 3; 20 tonnes (22.4 tons) TNT
Cause: Fire + water + Sodium Cyanide, calcium carbide, 800 tonnes ammonium nitrate and 500 tonnes of potassium nitrate

Event: West Texas Fertilizer Explosion

Time: 7:50:38 p.m. CDT (UTC−05:00)
Date: April 17, 2013
Location: West Fertilizer Co., 1471 Jerry Mashek Drive, West, Texas, United States
Coordinates: 31.816°N 97.088°W
Deaths 15 confirmed
Non-fatal injuries: More than 160
Property damage: West Fertilizer Company building obliterated, 60–80 homes destroyed, 50–75 homes damaged, 50-unit apartment building destroyed
West Middle School damaged

ΔTEC amplitude: 0.? TECU (Station=?/PRN=?)
Seismic (est): 2.1
Energy (est): 7-10 tons TNT

Cause: Fire + 240 tons of ammonium nitrate
+ 50 t of anhydrous ammonia

*Note: Chelyabinsk Bolide (500 kt) demonstrated ΔTEC [PP] = 0.3 TECU [PP] @ 11 min, .8 TECU @ 35 min
Measurement taken from Station=ARTU / PRN=18, at ~< 400 km.

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West TX Fertilizer Plant Explosion

Event Description:

Event Name:	West TX Fertilizer Plant Explosion
Event Date:	4/17/2013 (local)
Event Time:	00:50:38 UTC (19:50:38 CDT)
Event Loc:	31.82°N 97.09°W (West, TX)
Type:	Ground Explosion
Seismic Mag:	2.1
Energy:	~10 tons of TNT

TEC signature details:
- Best IPP-track: Texas Stations/PRN 8 (+PRN 28)
- ? 9-10 minute delay to ionosphere
- ? Acoustic-range signature

Difficulties:
- Background TEC wave producers:
  1. Tornados over Oklahoma (3 modes)
  2. Storm build-up over south Texas (3 modes)

[Photo posted online by MSNBC News]

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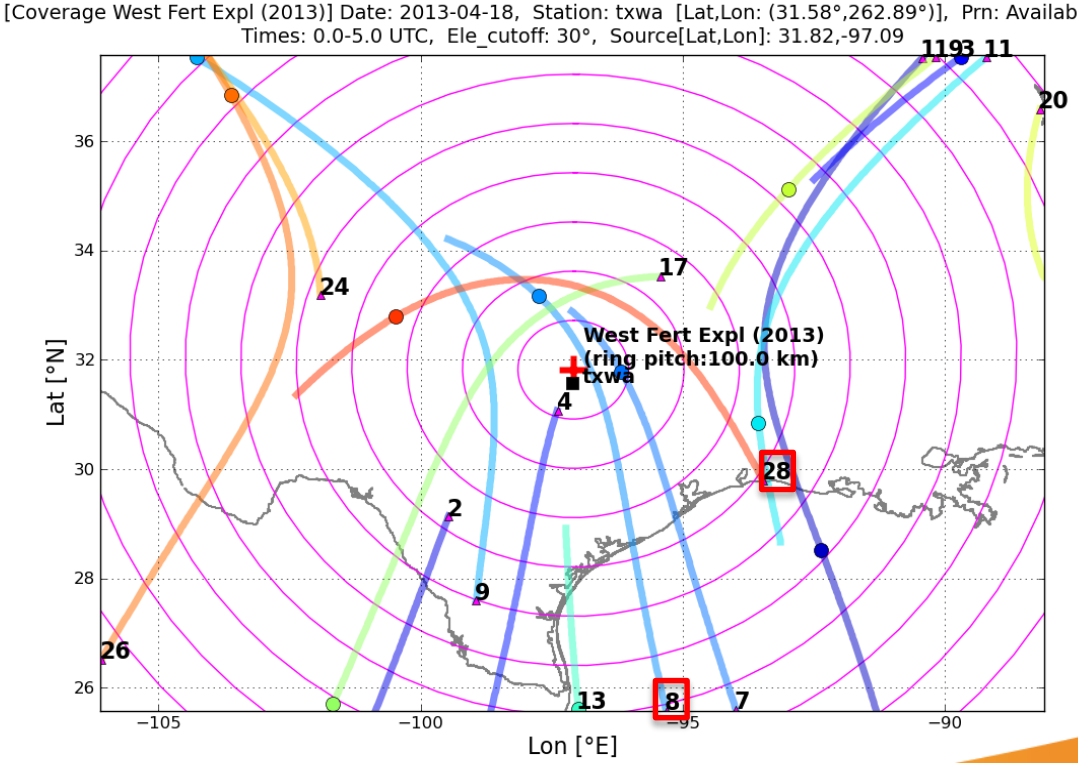

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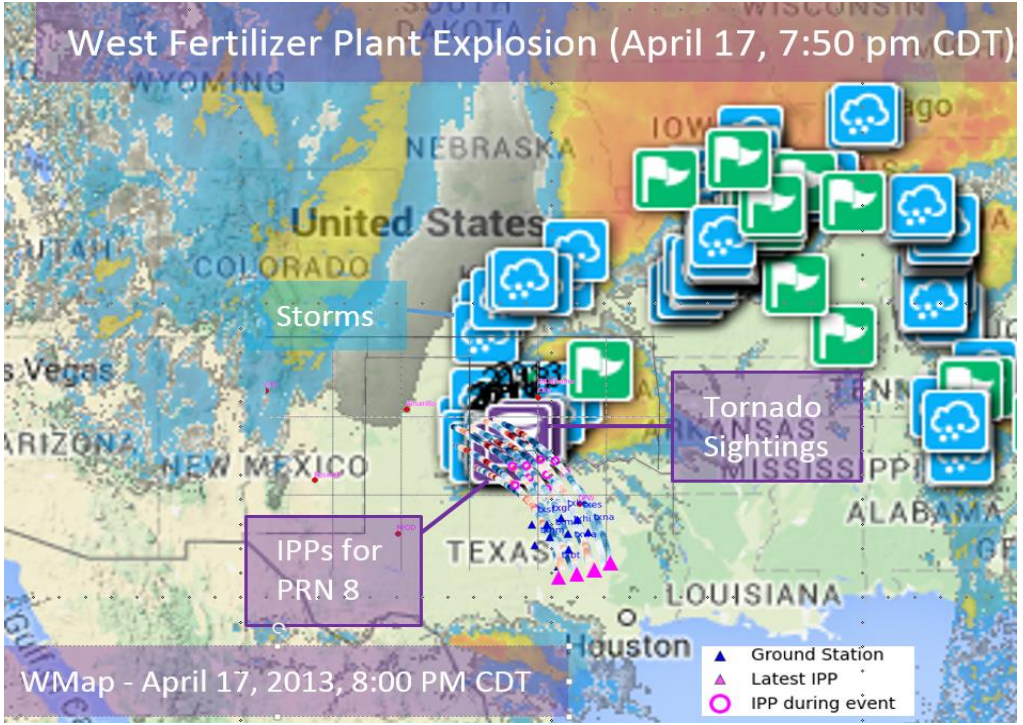

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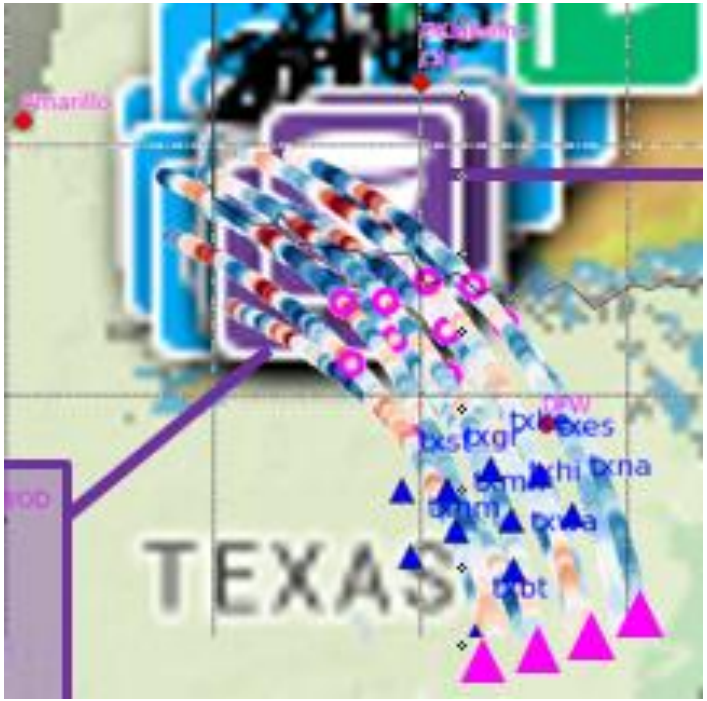

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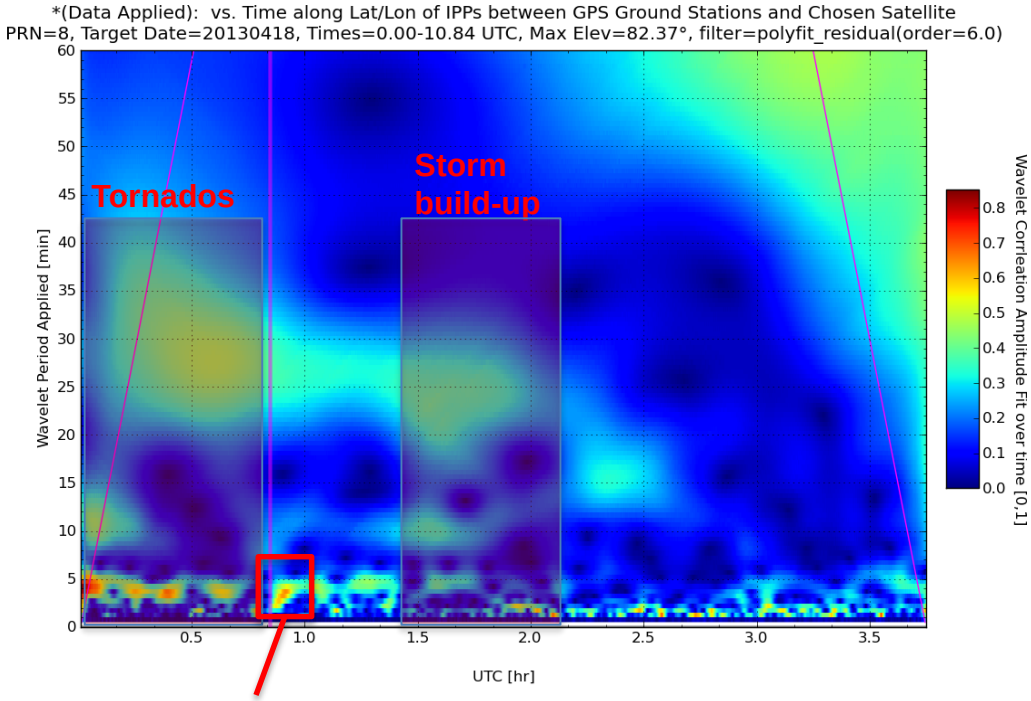

Possible Explosive Acoustic Signature (4 min)

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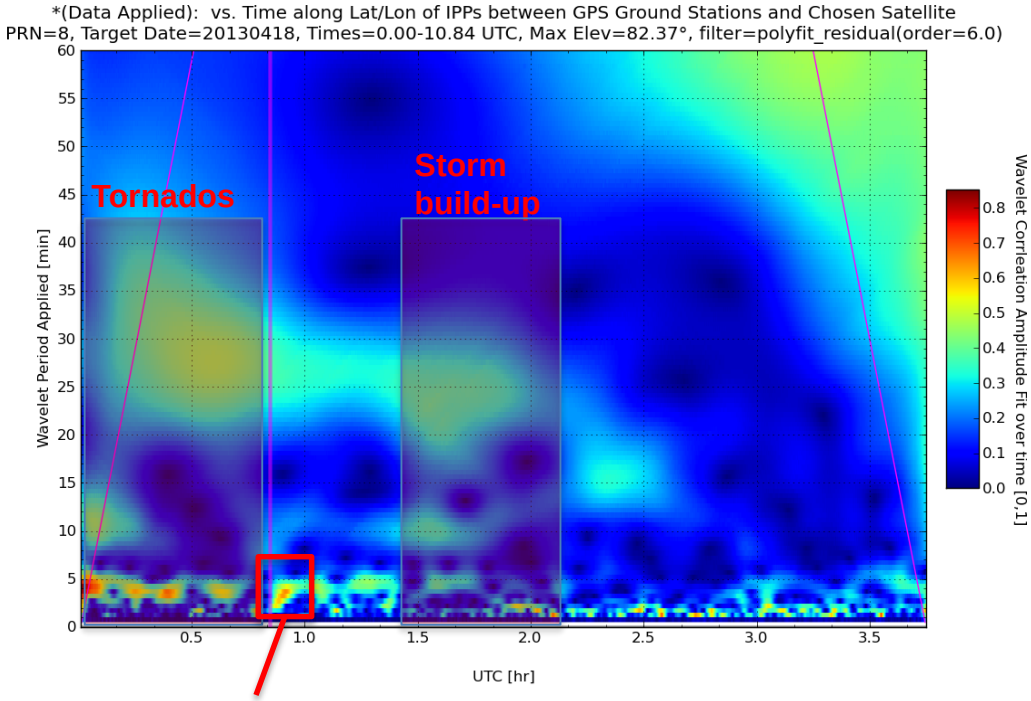

Possible Explosive Acoustic Signature (4 min)

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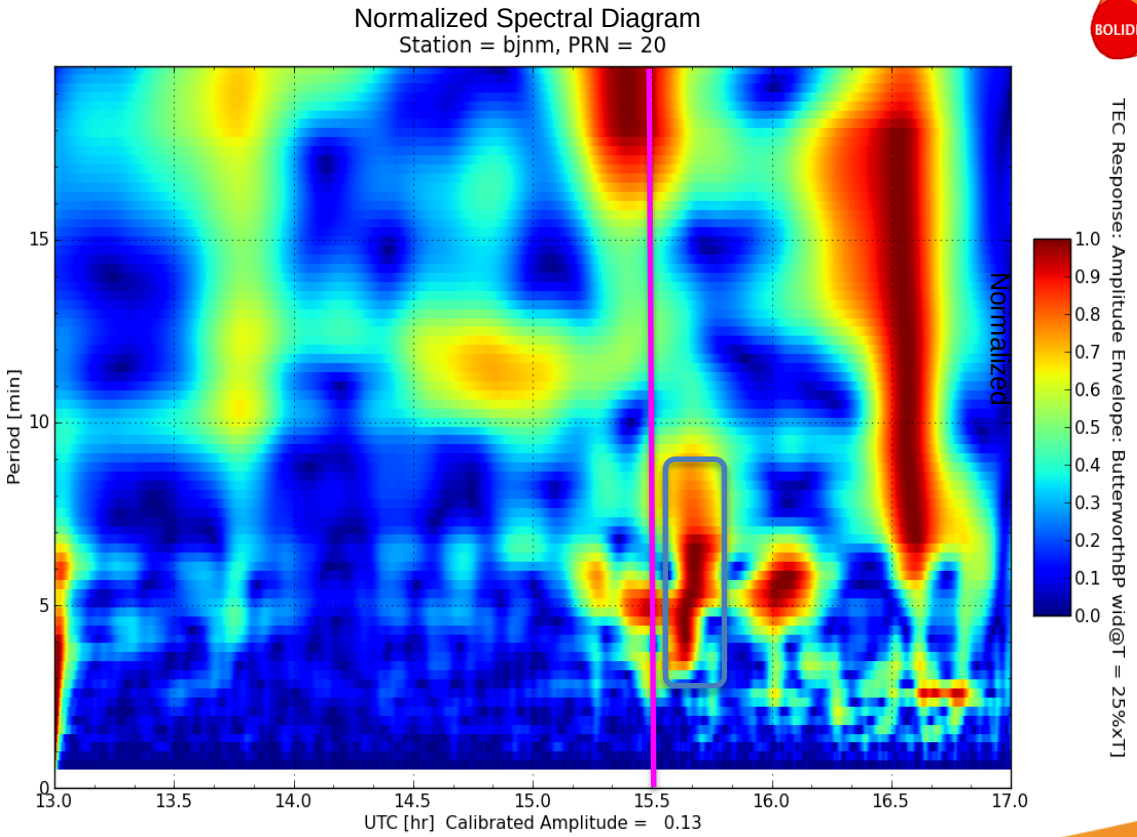
Tianjin Explosion

Event Description:

Event Name:	Tianjin Explosion
Event Date:	8/12/2015
Event Time:	15:30 UTC (23:30 CST)
Event Loc:	39.04°N 117.74°E (near Binhai, Tianjin, China)
Type:	Ground Explosion
Seismic Mag:	2.3
Energy:	~23 tons of TNT

TEC signature details:
- Best IPP-track: bjnm/PRN 20
- 9-10 minute delay to ionosphere
- Acoustic-range signature

Major Difficulty:
- Only 7 applicable ground stations submitted to IGS
- Not enough ground stations to make good direction calculation.



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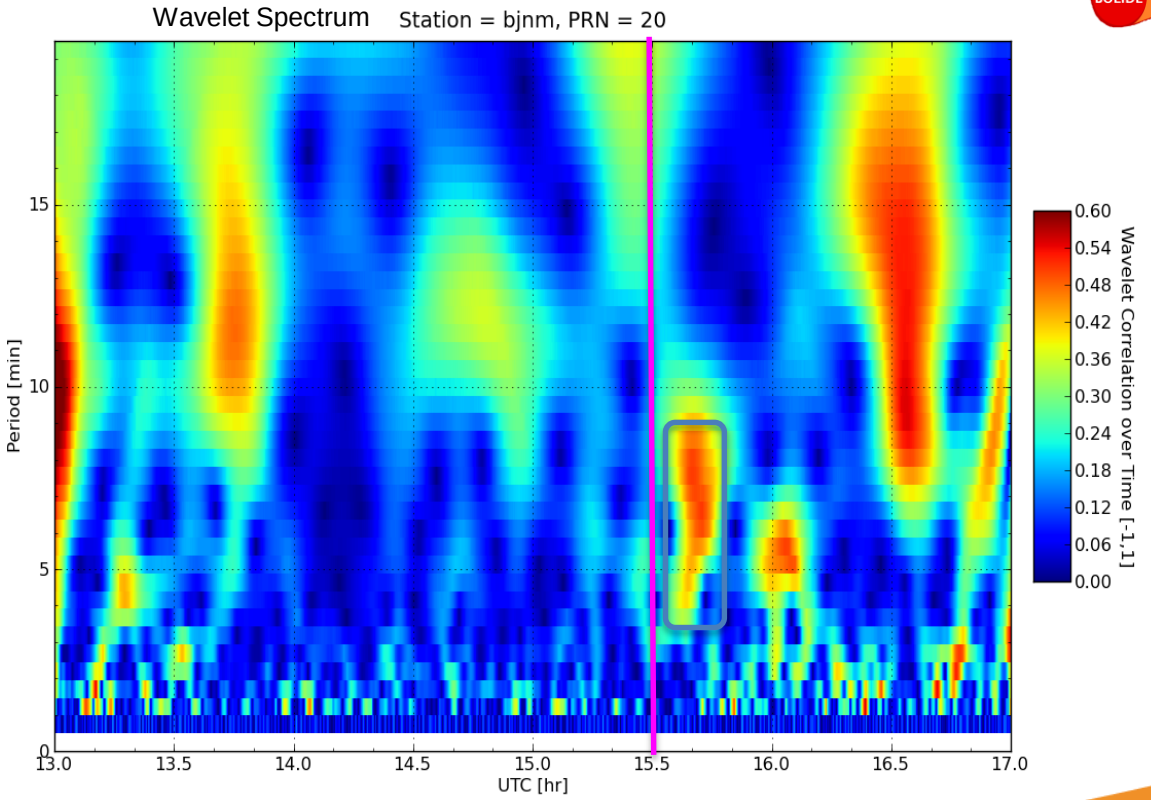
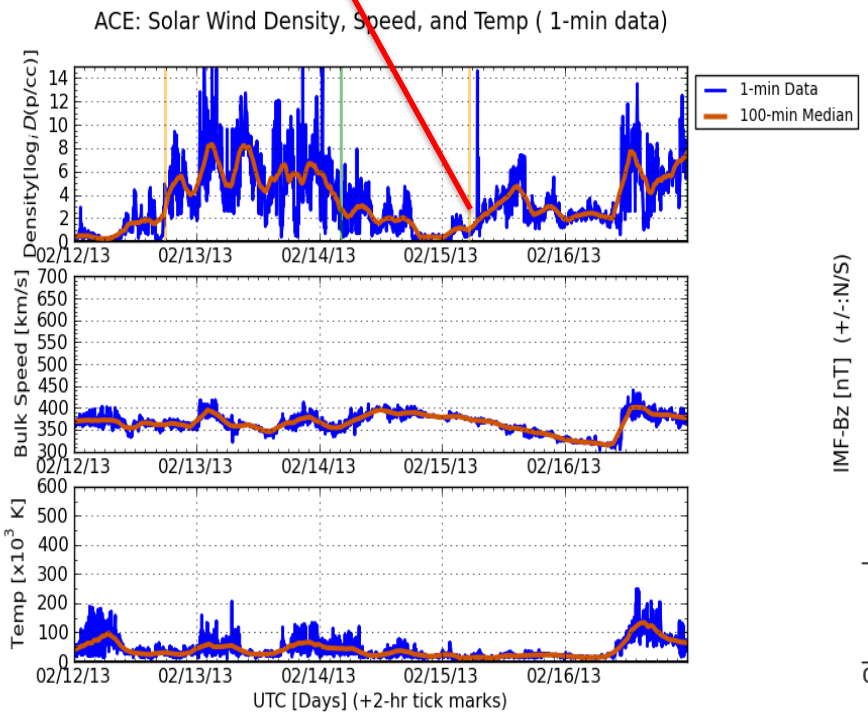
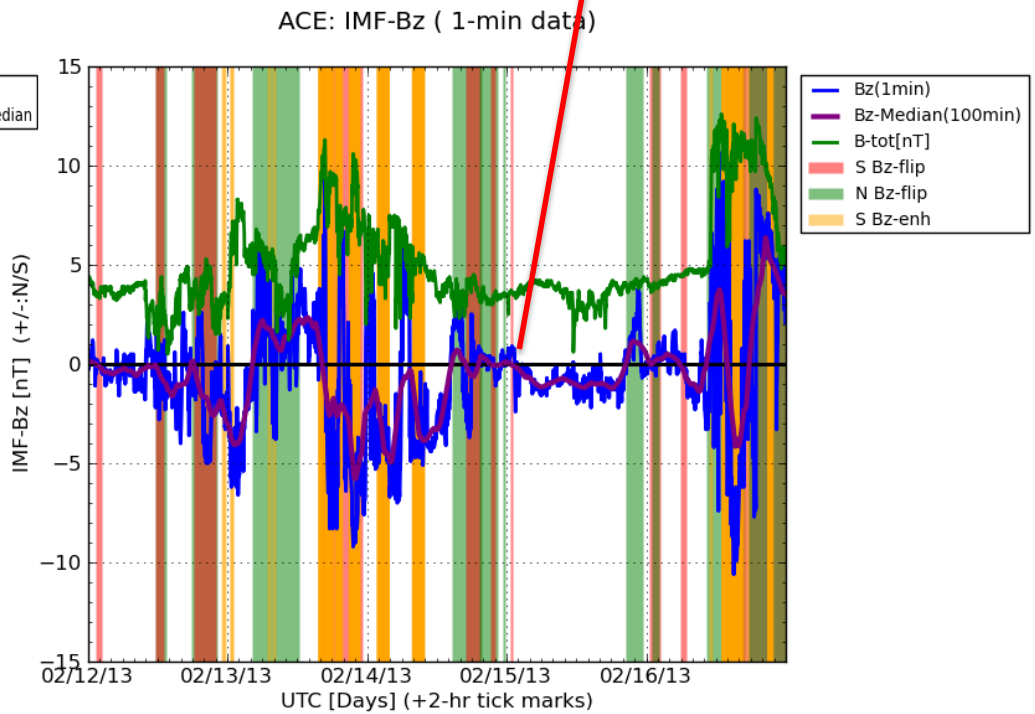


Space Weather

SW Density Spike (>~ 0600 UTC)

IMF-Bz: Very Brief Southward Turn At ~0200 UTC





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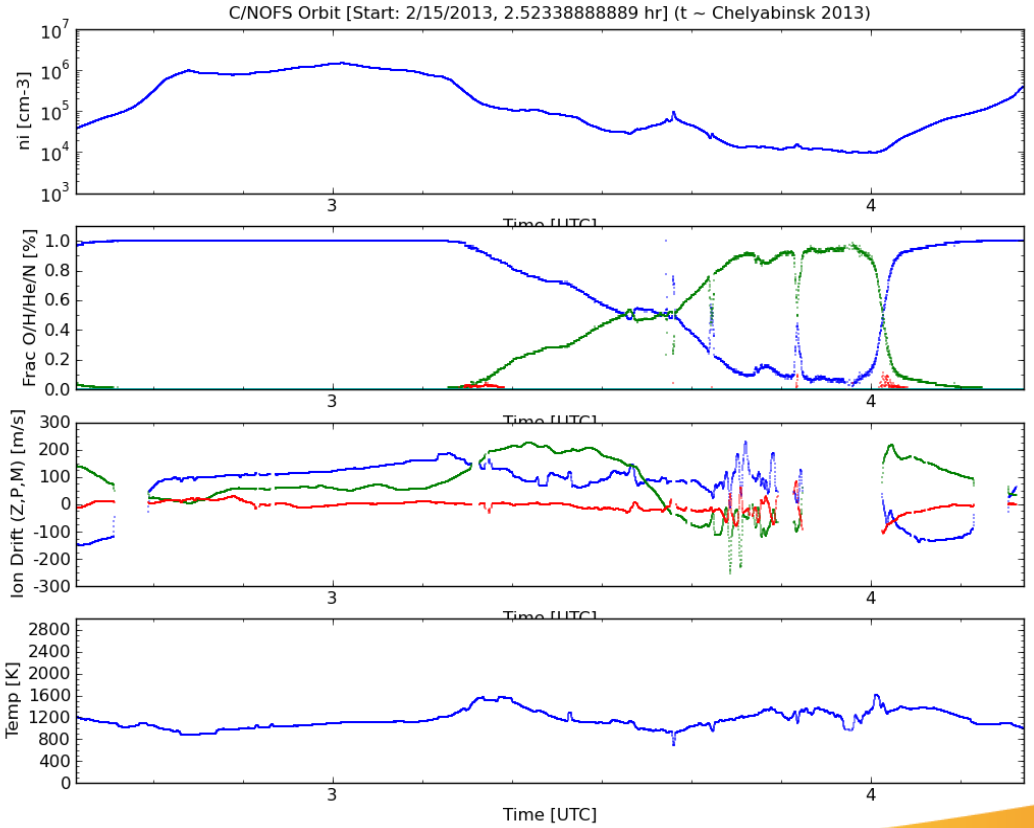
Equatorial Satellite Observations In-situ (C/NOFS)

Event Description:
Event Name: Chelyabinsk



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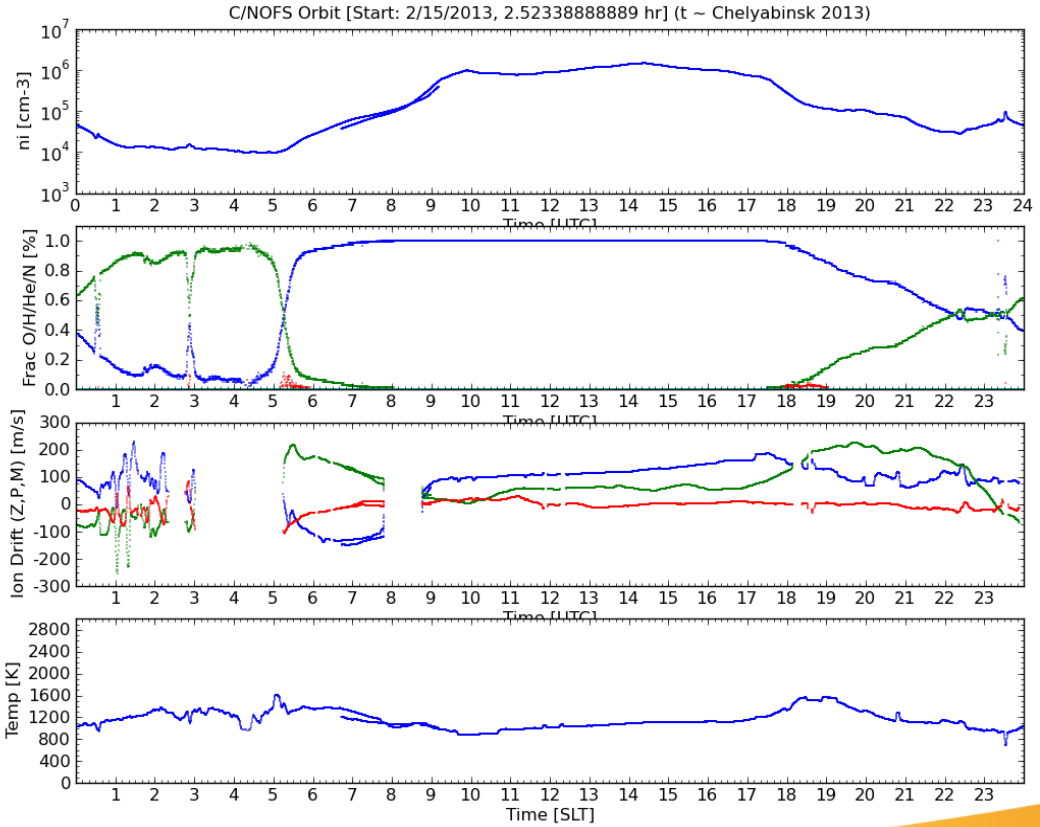

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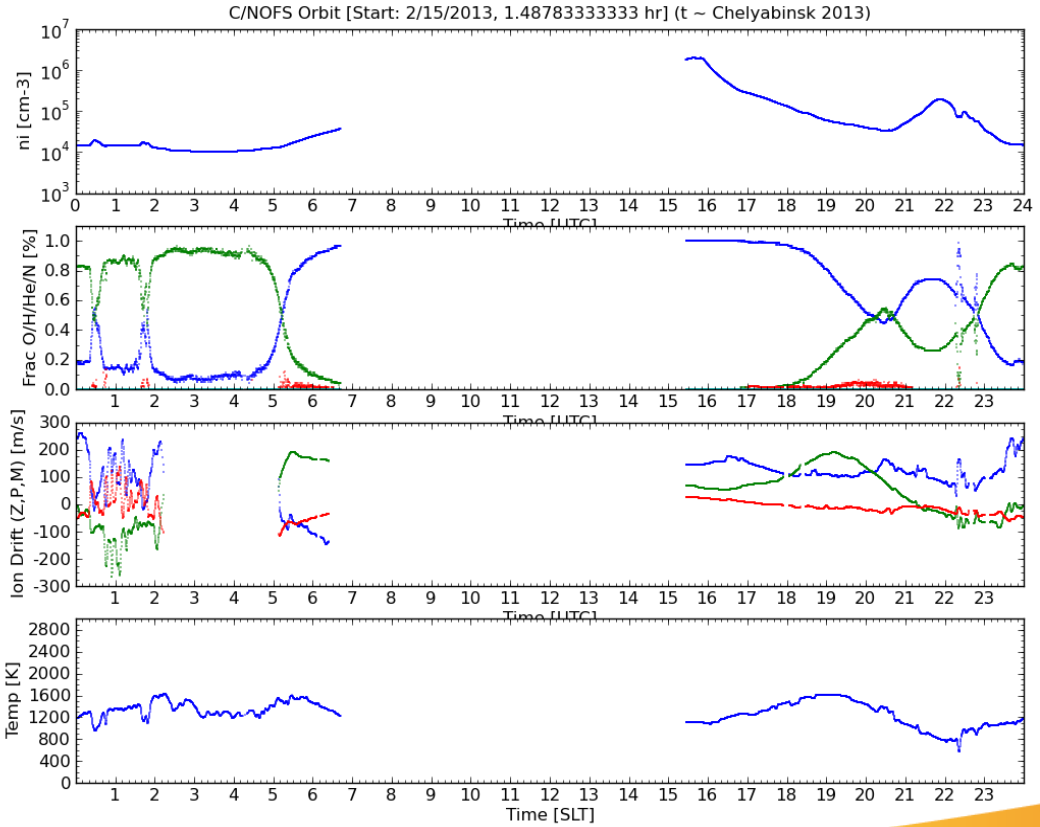

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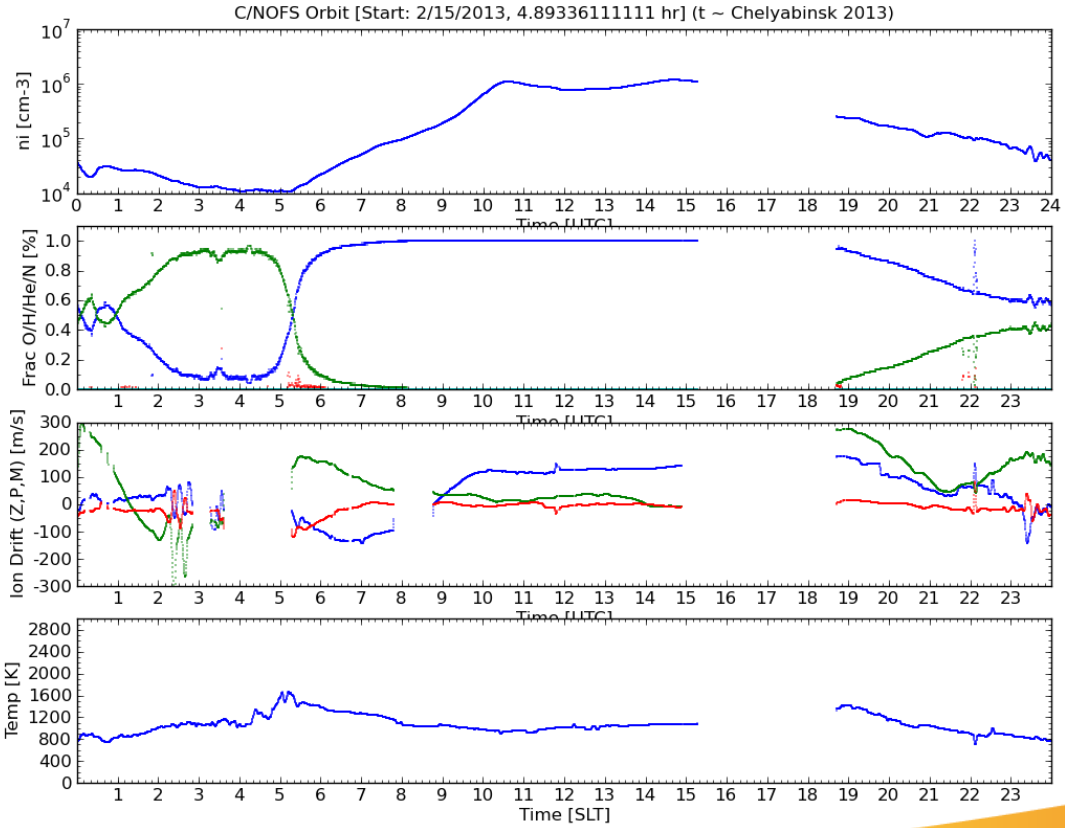

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