

Analysis of Regional Seismic and Infrasound Data

Five North Korean Nuclear Explosions

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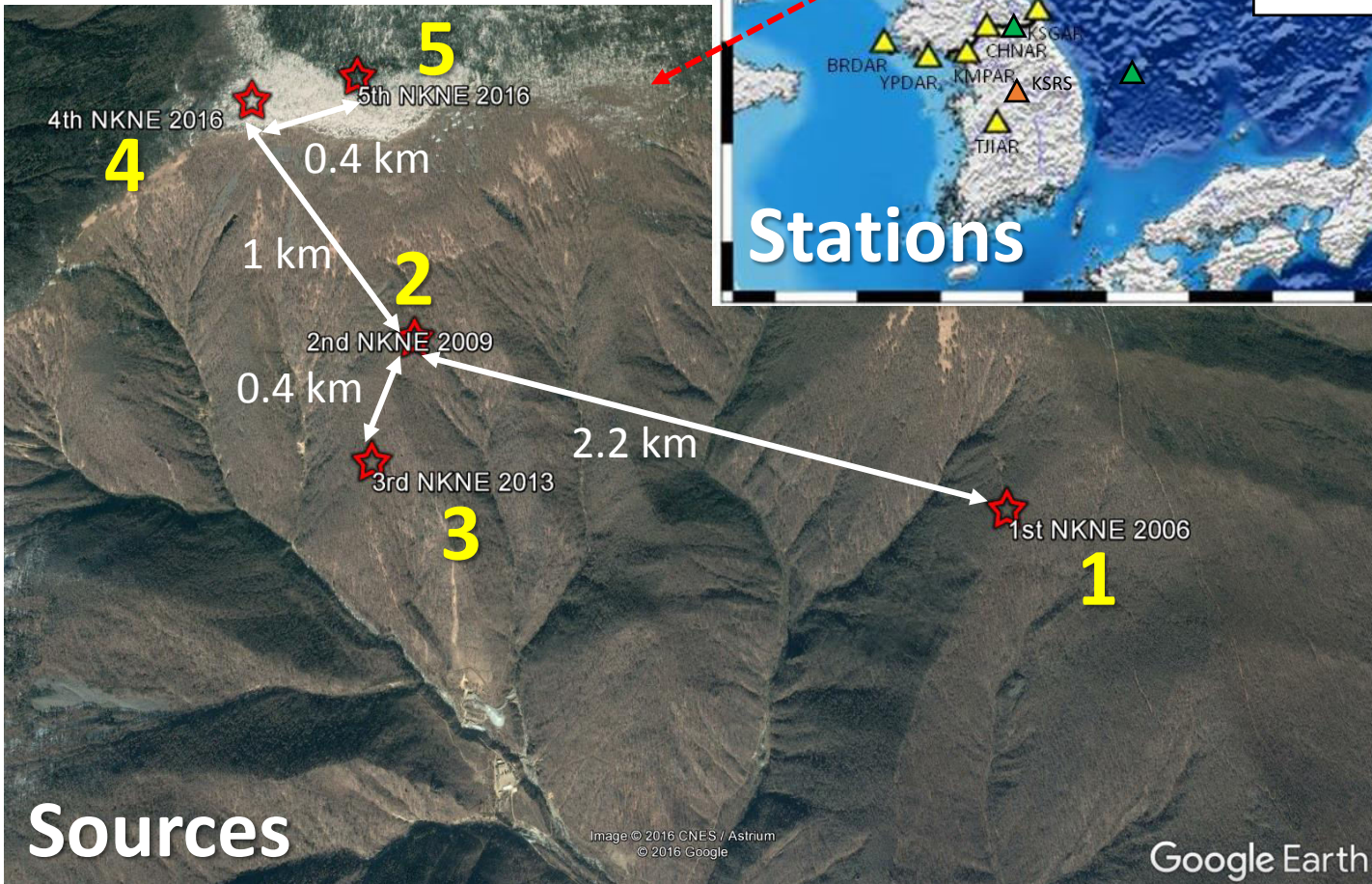
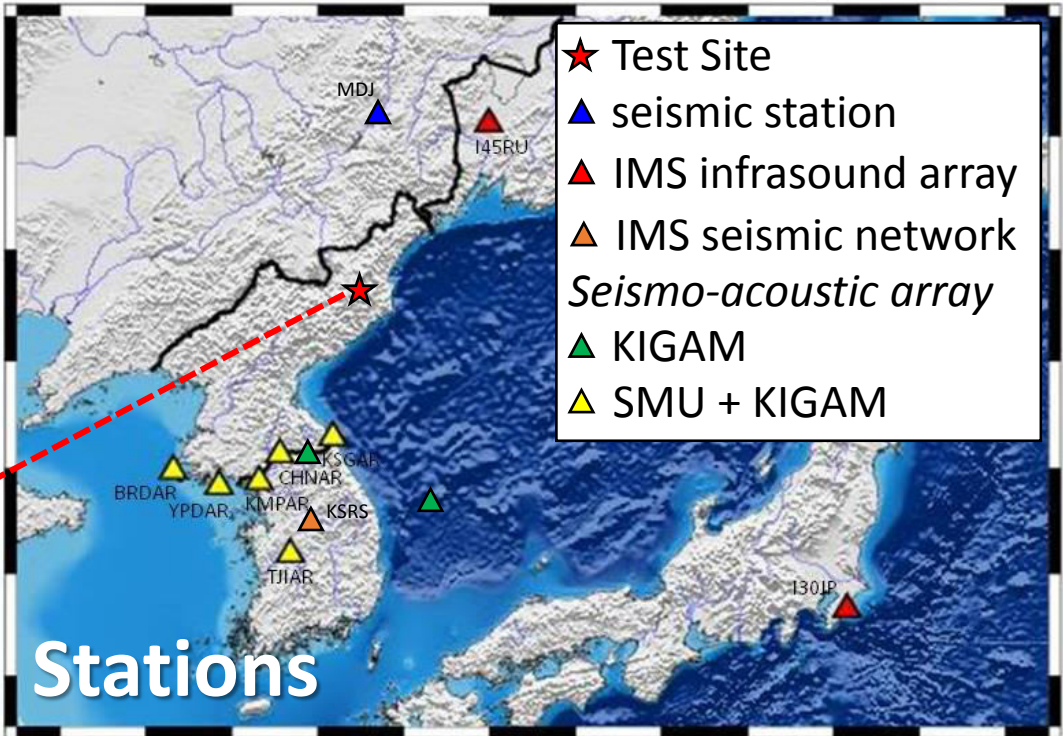
Outline

- **Relative Seismic Source Scaling** of 5 North Korean Nuclear Explosions (NKNEs) - regional data (constraining *depth of burial and yield*).
- **Detection and Interpretation of Infrasound Signals** from NKNEs (*realistic atmosphere model predictions and estimates of source energy*).

NKNE	mb	Date
1 st	3.9	10/09/06
2 nd	4.5	05/25/09
3 rd	4.9	02/12/13
4 th	4.8	01/06/16
5 th	5.0	09/09/16

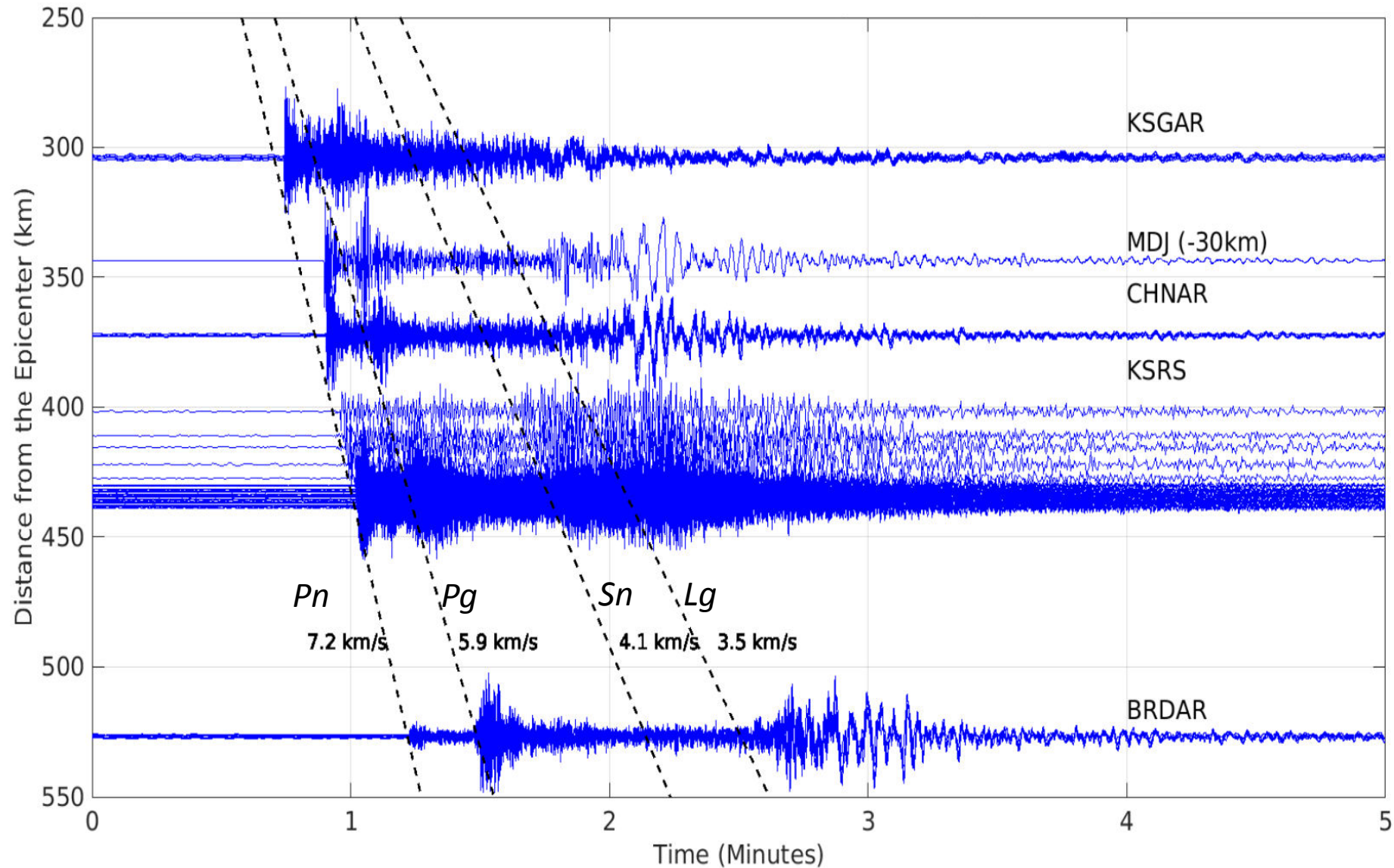
m_b estimates by KIGAM

Regional Observations



Source location estimates by KIGAM

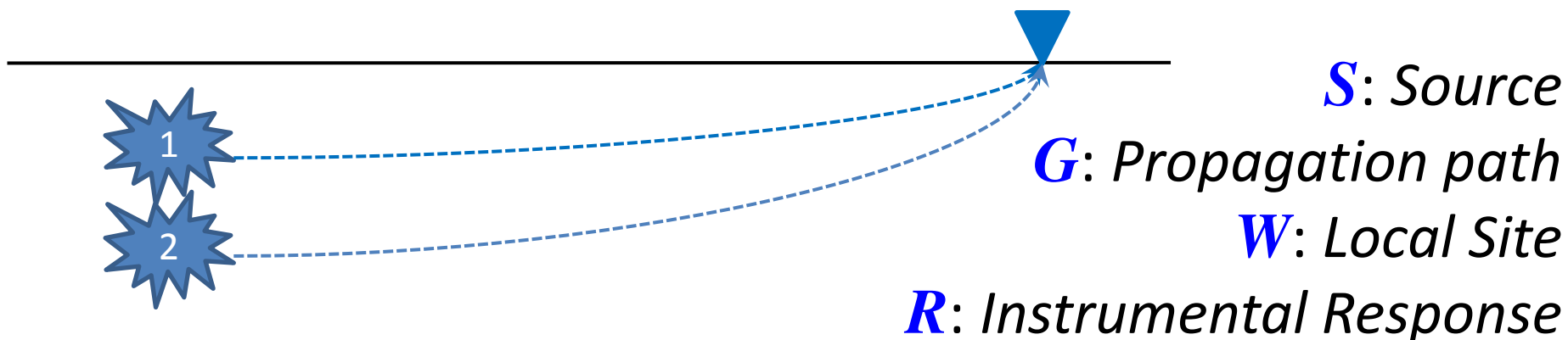
Seismic Data - Sept 2016 Explosion



Seismic Phase ID Based on the IASPEI model

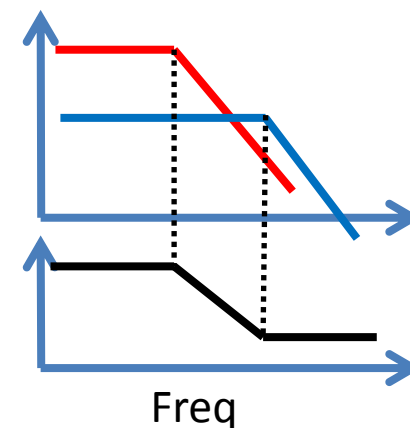
Seismic Source Model

$$u = S \otimes G \otimes W \otimes R$$

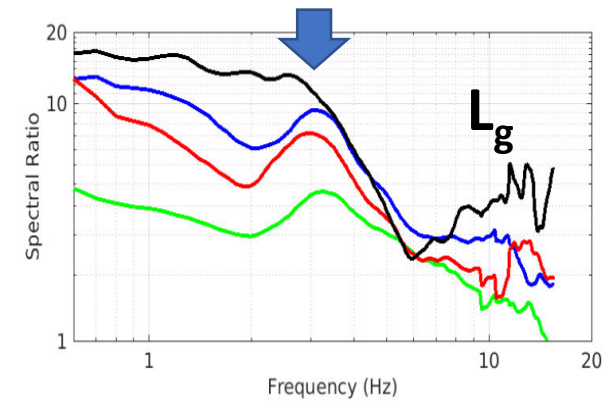
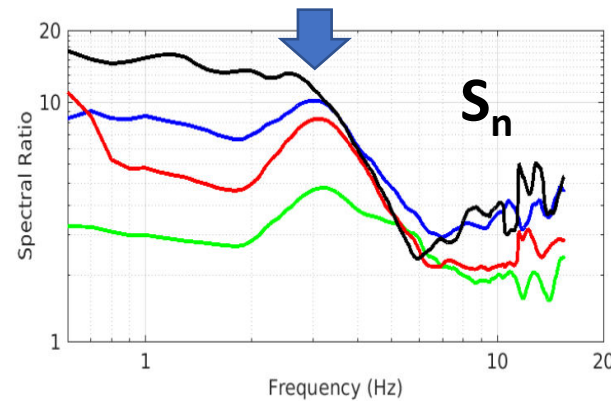
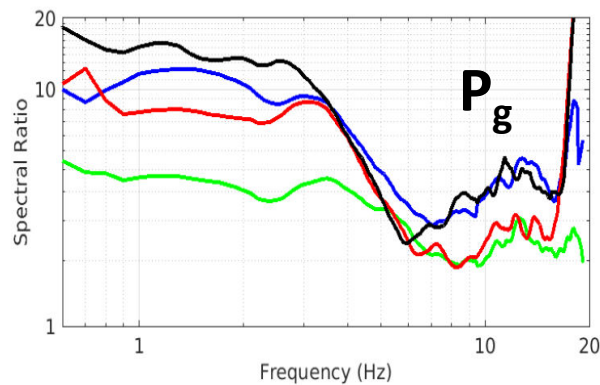
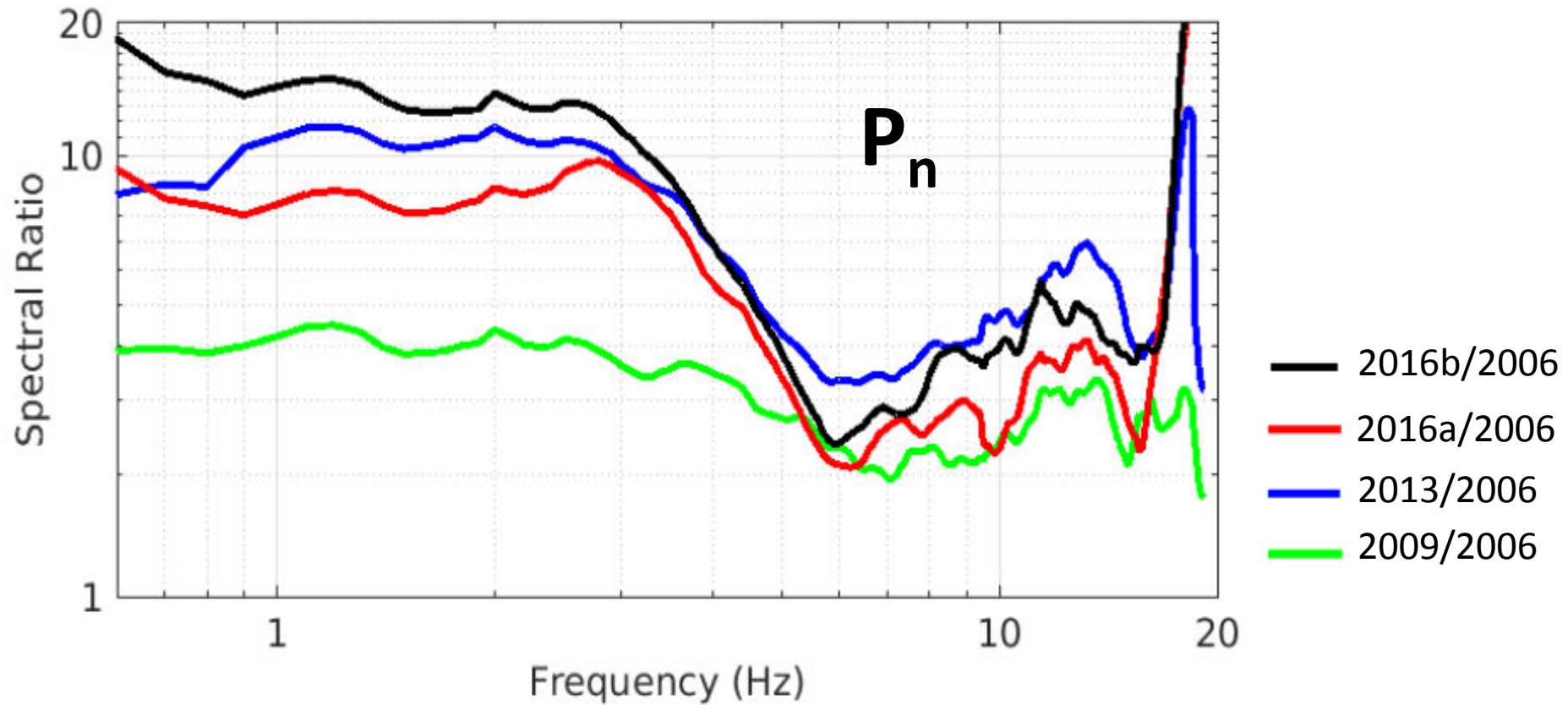


Same Path and Receiver

$$\frac{U_{ki1}(f)}{U_{ki2}(f)} = \frac{S_1(f) \cdot G_{ki1}(f) \cdot W_i(f) \cdot R_{ki}(f)}{S_2(f) \cdot G_{ki2}(f) \cdot W_i(f) \cdot R_{ki}(f)} = \frac{S_1(f)}{S_2(f)}$$

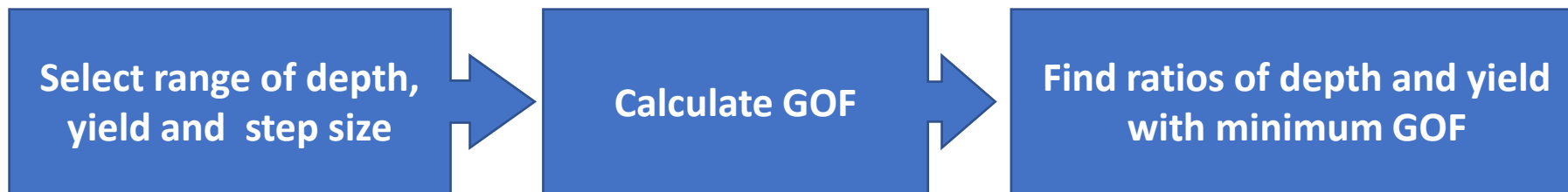


Seismic Spectral Ratios



Grid Search Method

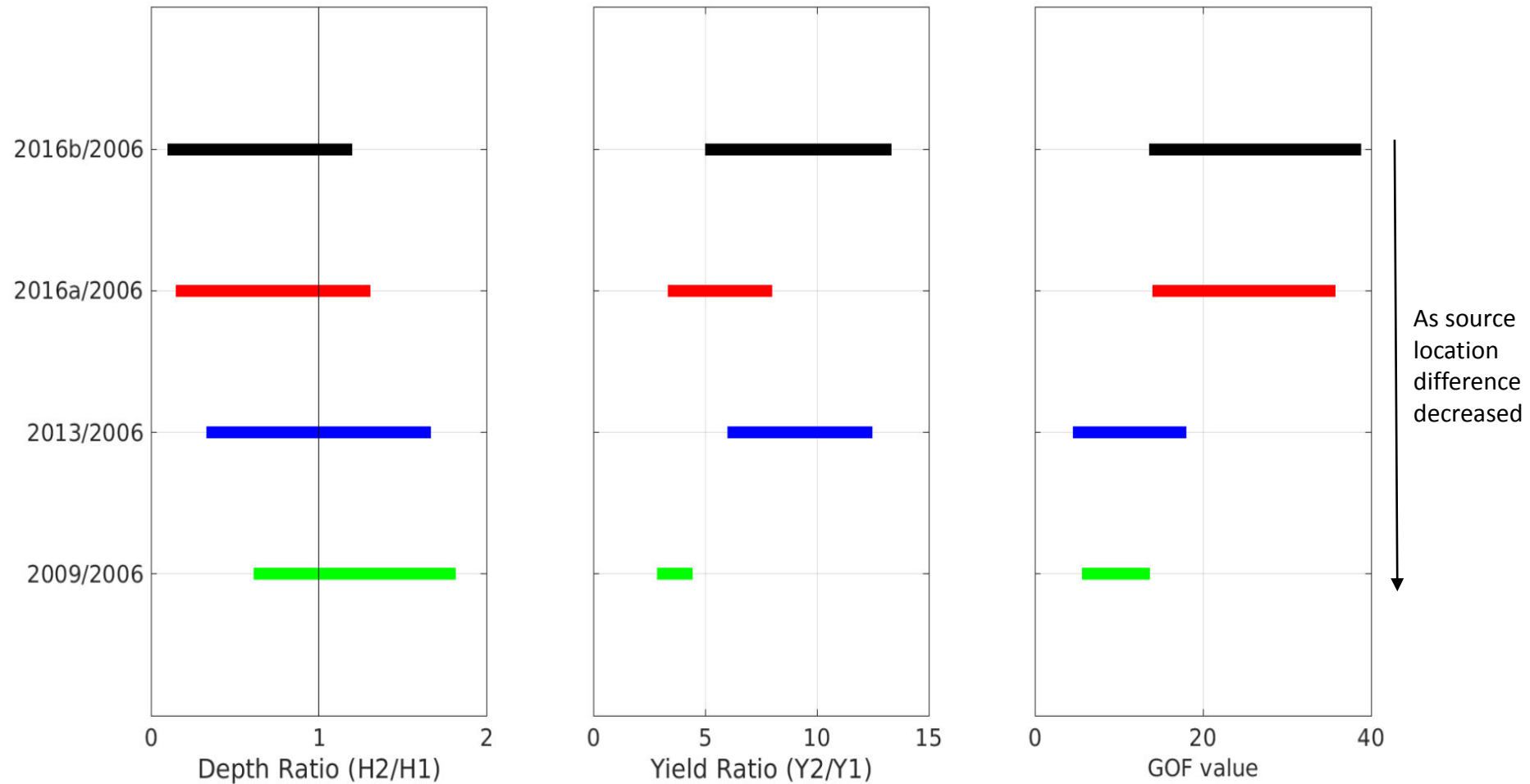
Yield and Source Depth



- Frequency range, 1-8 (15) Hz
- Search range
 - Depth : 100-1000m
 - Yield : 1-10kt (0.1-5kt for 2006)
- Spectral ratios using all five explosions

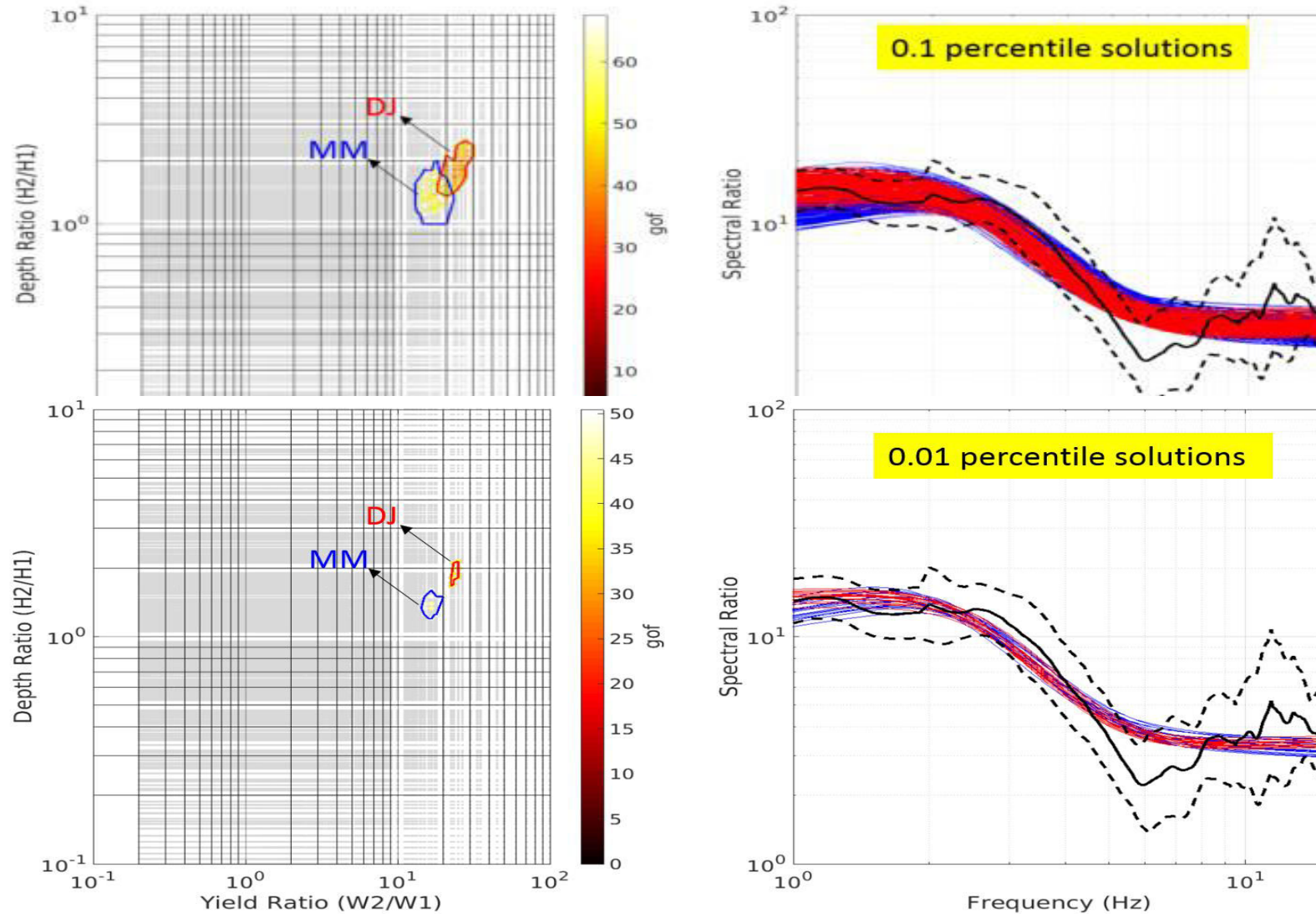
Depth and Yield Ratios - 5 NKNEs

GOF values



Models with 1% lowest GOF

Solution is Model Dependent (2016b/2016)



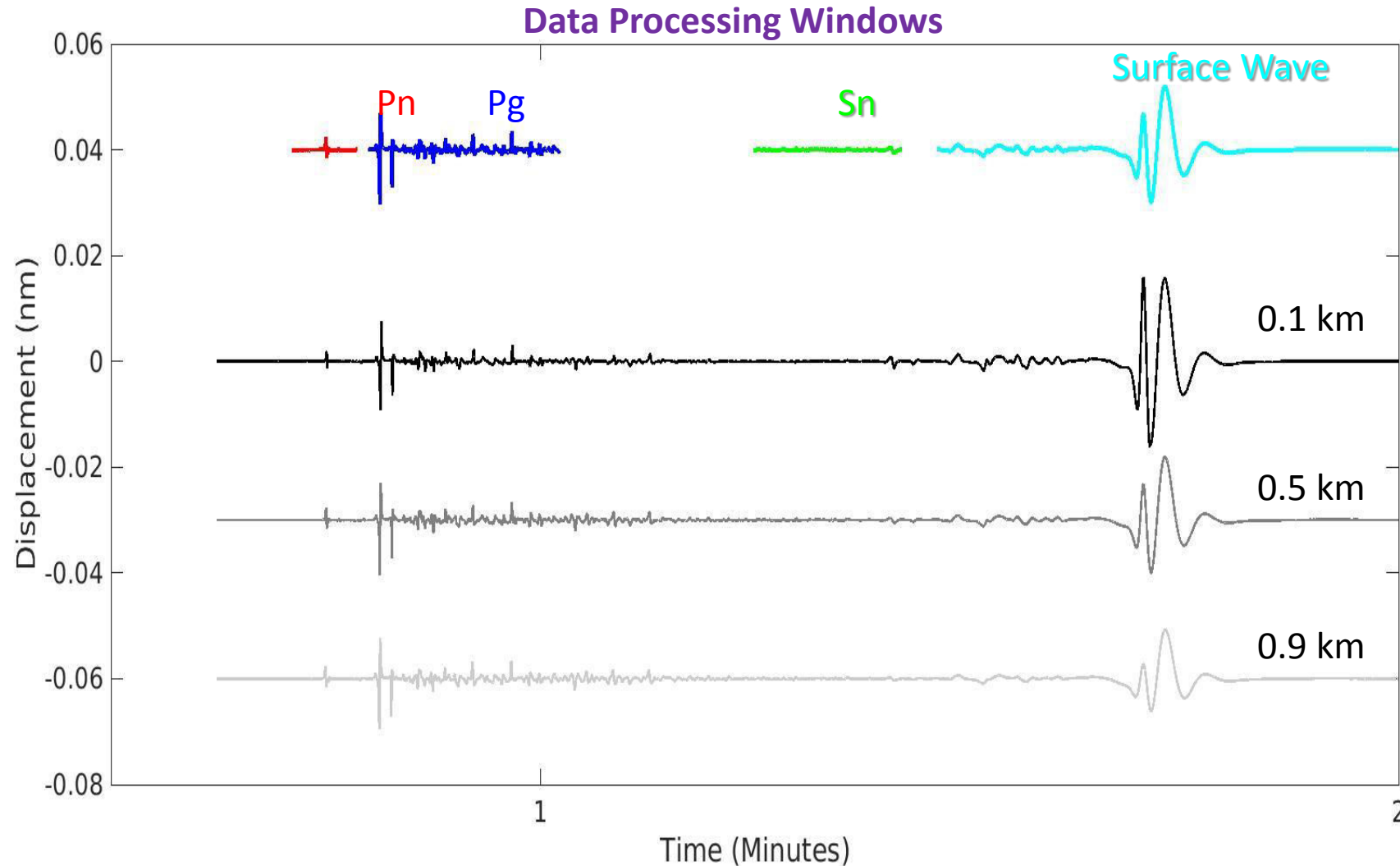
MM: Revised Mueller-Murphy (1971)

DJ: Denny-Johnson (1991)

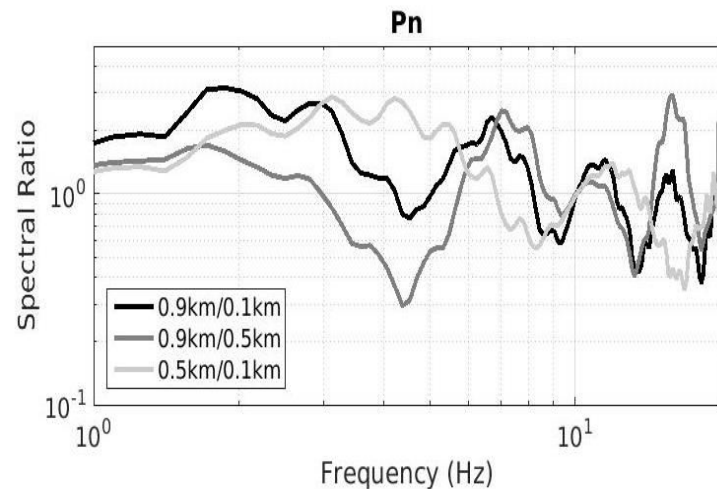
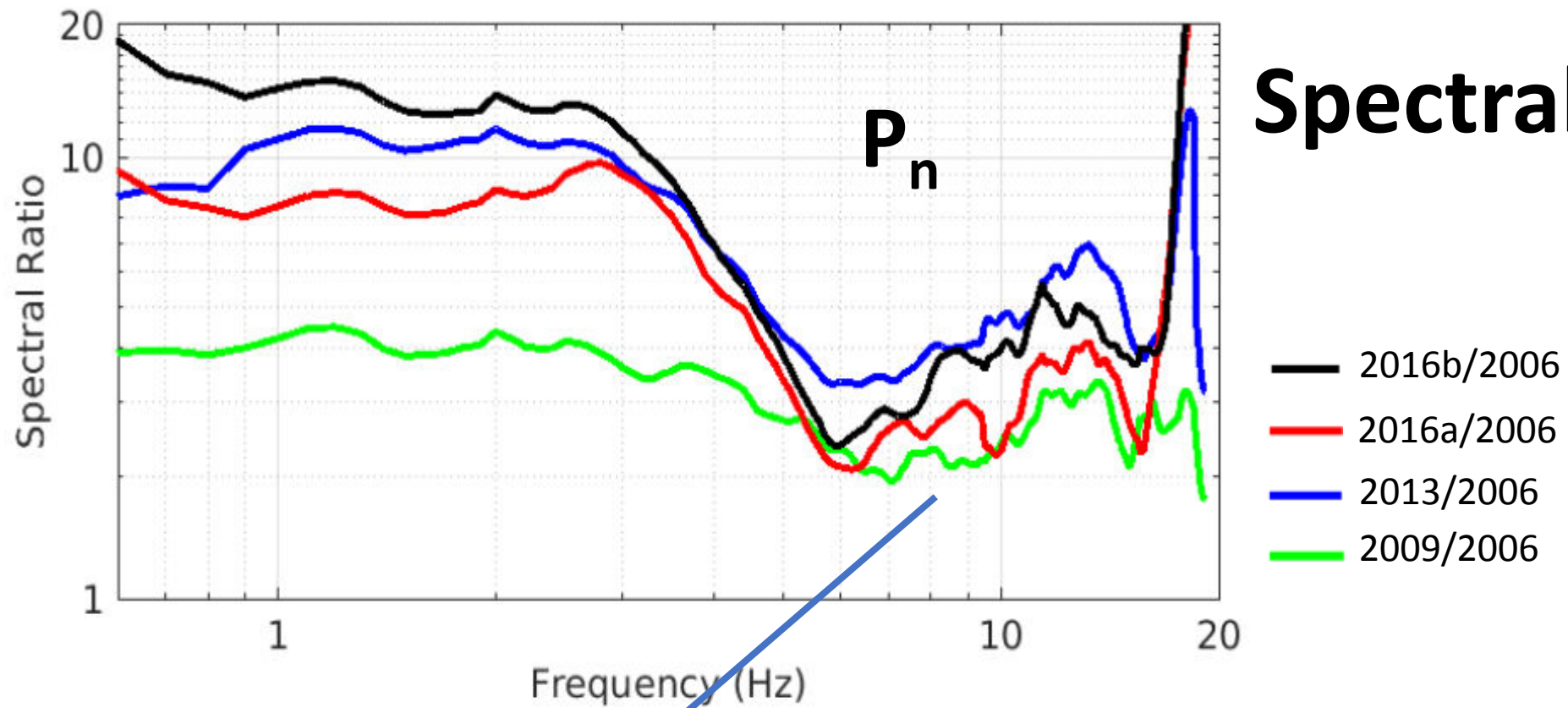
Synthetic Seismograms - Reflectivity Method

M_0 1.0E+23 (2016 September Explosion), **Different Depths**

Azimuth and Range KSGAR and 1D Velocity Model Chang & Baag (2006)



Spectral Ratios



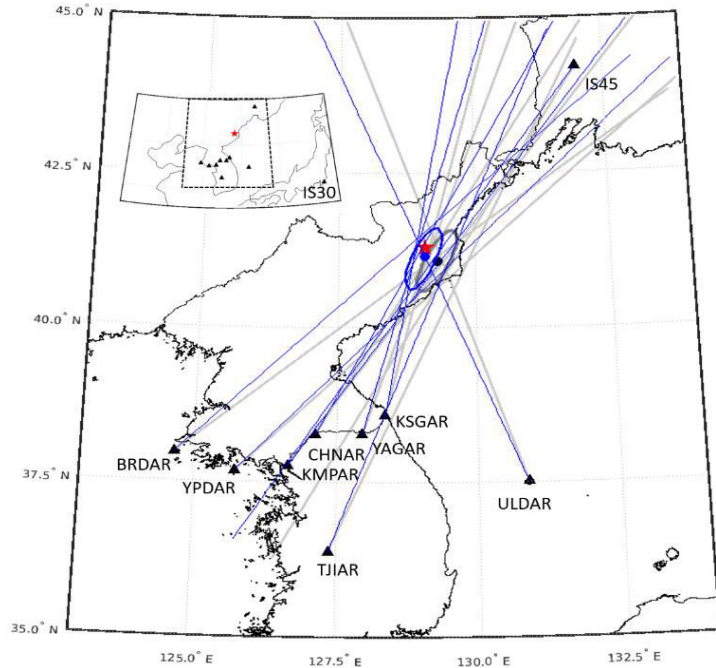
Effect of surface pP phases should be included following Murphy et al. (2013)

Seismic Summary

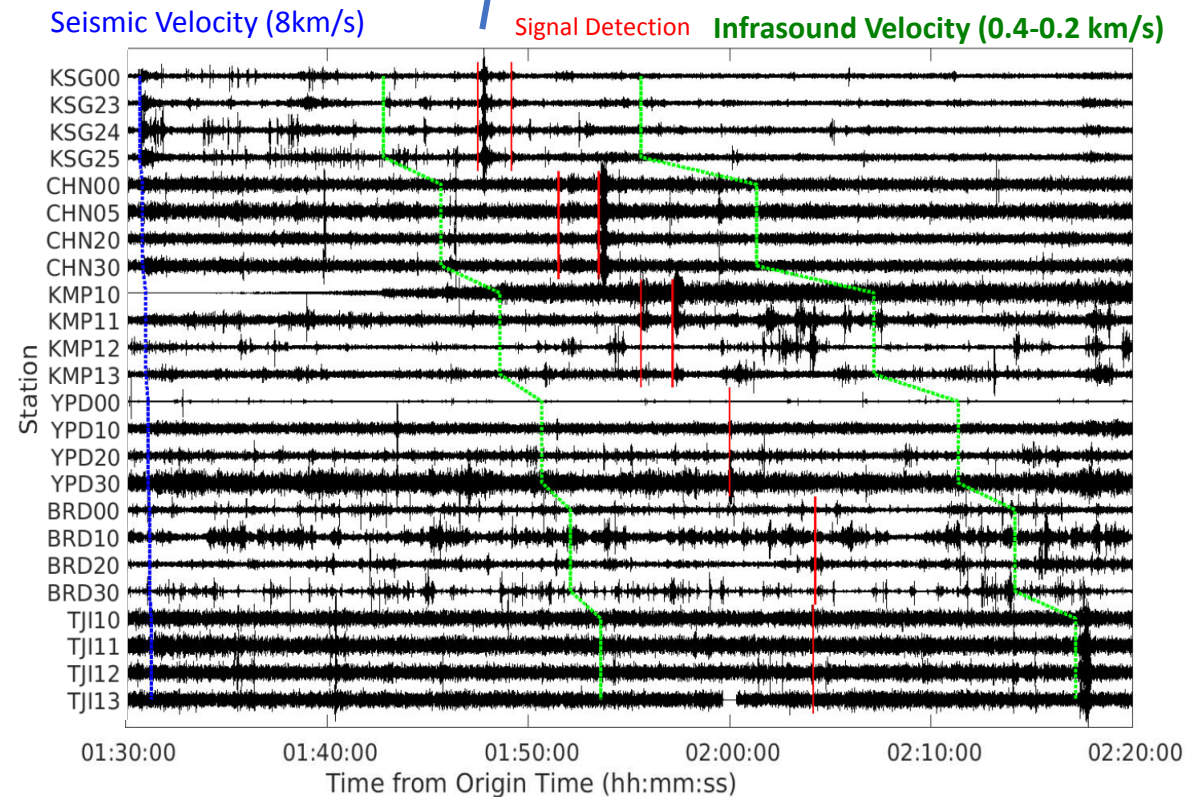
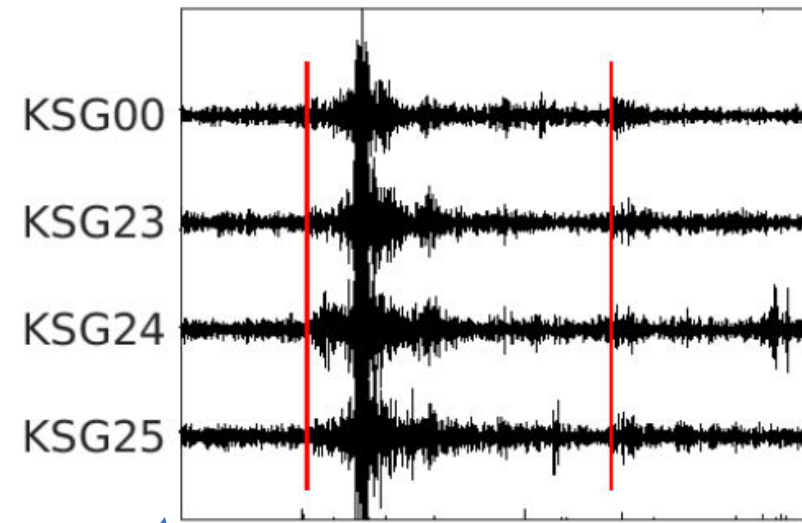
- MM and DJ source models produce different ranges of depth and yield.
- Synthetic seismogram quantify depth effects that may affect spectral ratios at high frequency.
- Analysis of Pg , Sn , and Lg phases may be used to assess direct and indirect source effects (i.e. spall).

Infrasound Signals

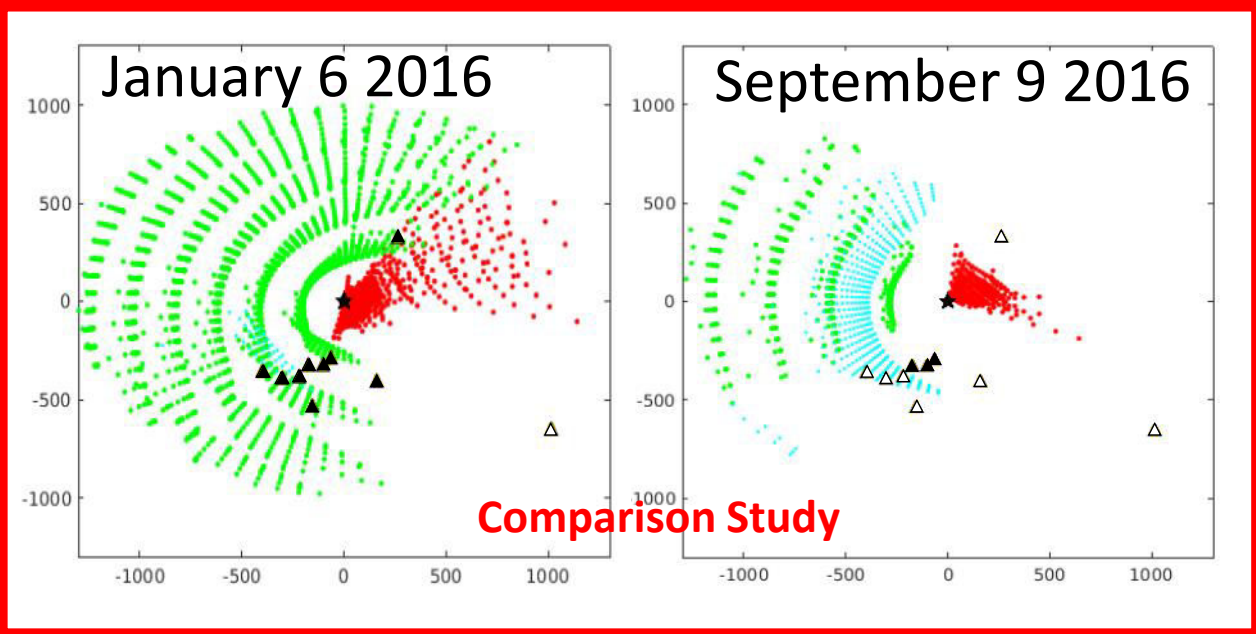
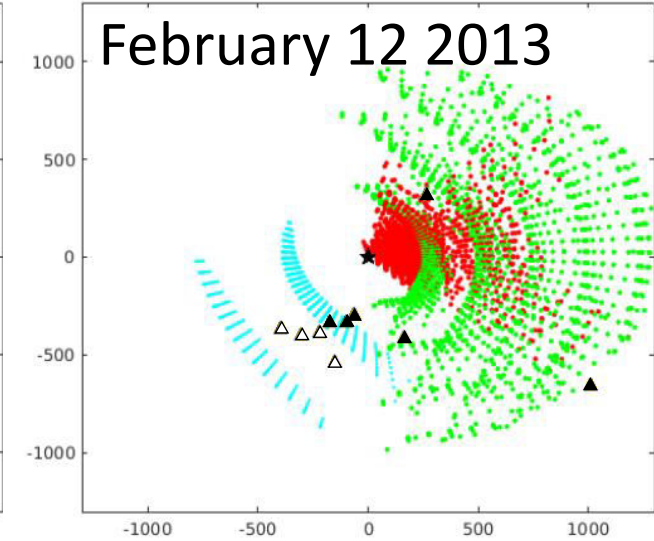
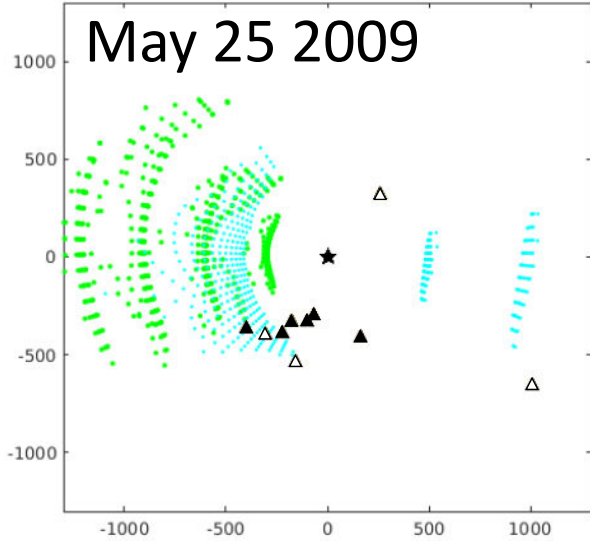
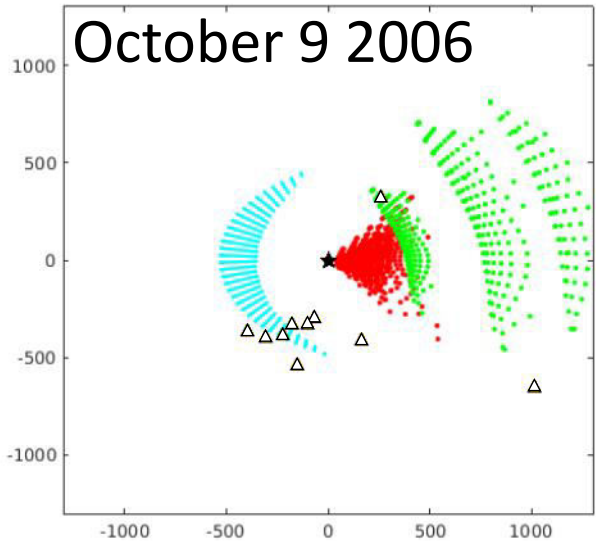
Location Jan 2016 Explosion



- Wind-corrected estimates
- Uncorrected estimates
- ★ Source location



Predictions - Atmospheric Variations

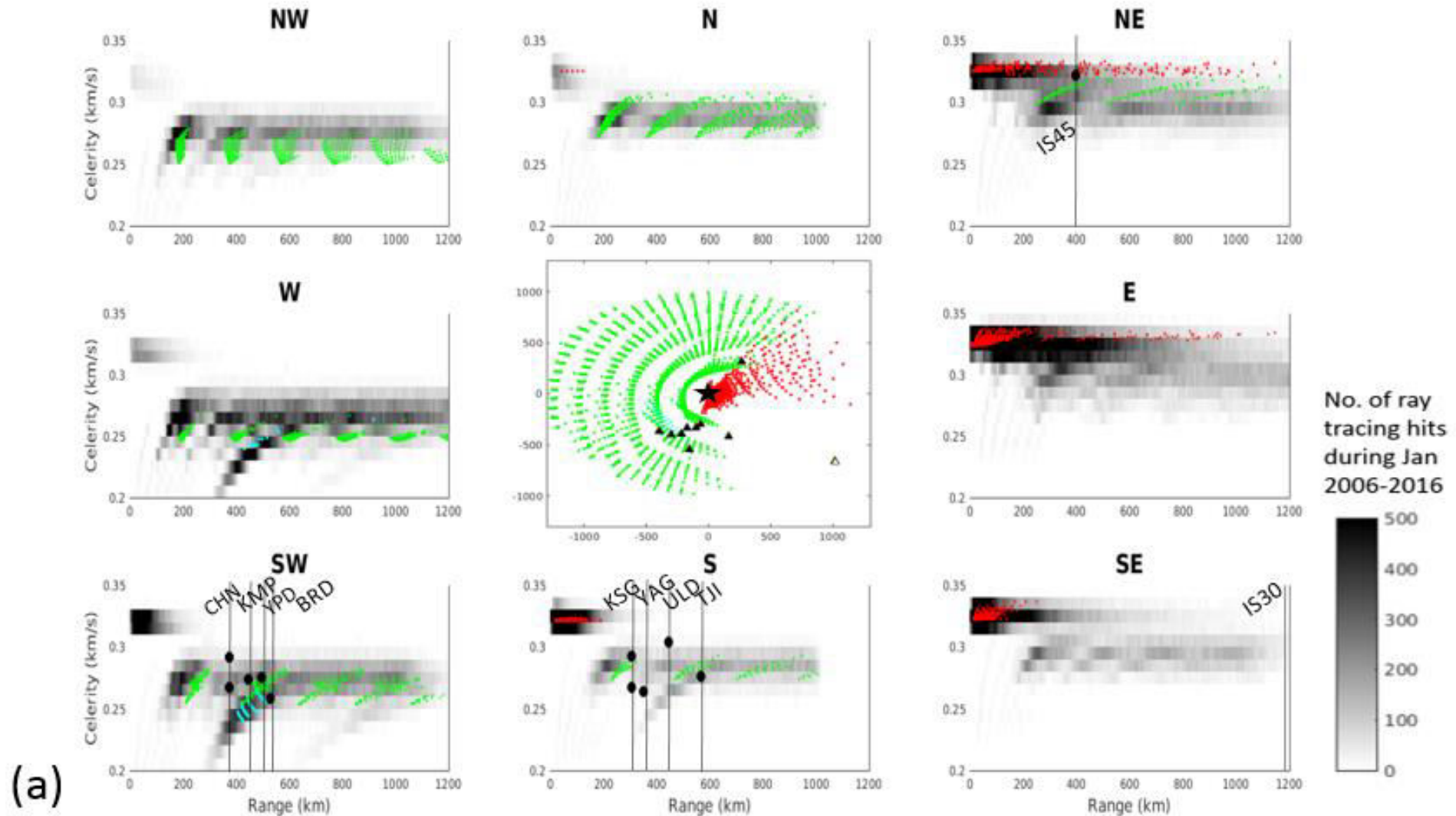


- ▲ Detection
- △ No detection
- Tropospheric
- Stratospheric
- Thermospheric arrivals

Ray tracing using GeoAc (Blom and Waxler, 2012) with Ground-to-Space (G2S) atmosphere (Drob et al., 2010).

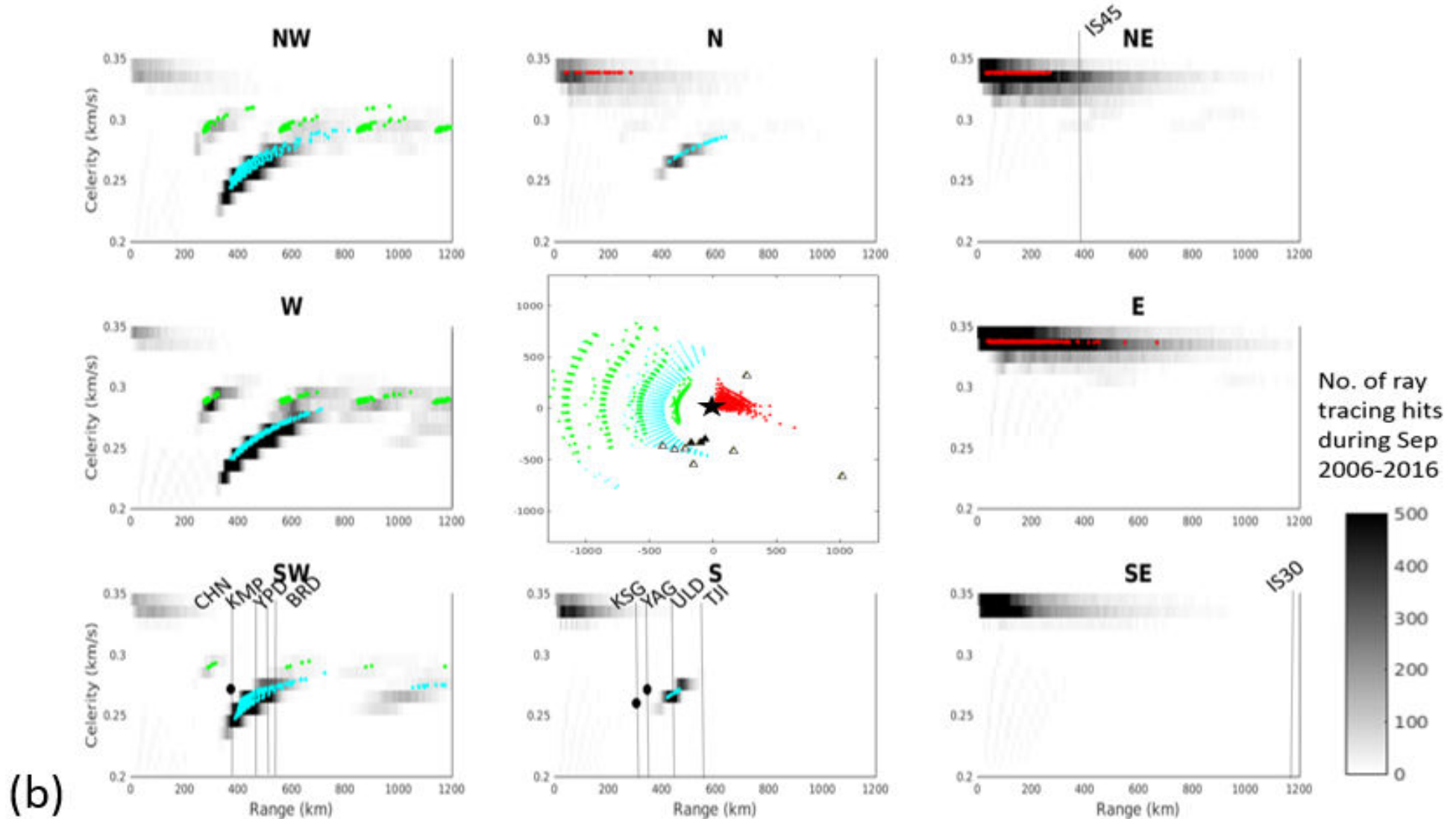
Ray Tracing January 6 2016

Density of Predicted Arrivals, 11 Years



Ray Tracing September 9 2016

Density of Predicted Arrivals, 11 Years



Infrasonic Source Energy

- Empirical yield-scaling from Whitaker et al. (2003)
- Stratospheric phase at closest array (KSGAR)
- Stratospheric wind correction from G2S model
- Equivalent yields:

NKNE	mb	Date	<i>Tons of TNT</i>
1 st	3.9	10/09/06	-
2 nd	4.5	05/25/09	0.6
3 rd	4.9	02/12/13	23.5
4 th	4.8	01/06/16	8.2
5 th	5.0	09/09/16	-

- No clear observations from 2006 explosion and no stratospheric phase at KSGAR for 2016 (Sep) explosion.

Infrasound Summary

- Regional infrasound signals are dependent on atmospheric conditions, as illustrated with G2S model.
- Infrasound equivalent yield estimates are much smaller than seismic yield estimates reflecting containment.
- Atmospheric models are needed for interpreting the infrasonic energy estimates of five explosions.
- Infrasound signals should be modeled linking to predicted near-source ground motions as a function of source depth of burial and seismic yield.