Can we use infrasound data from bolides to constrain global celerity models?

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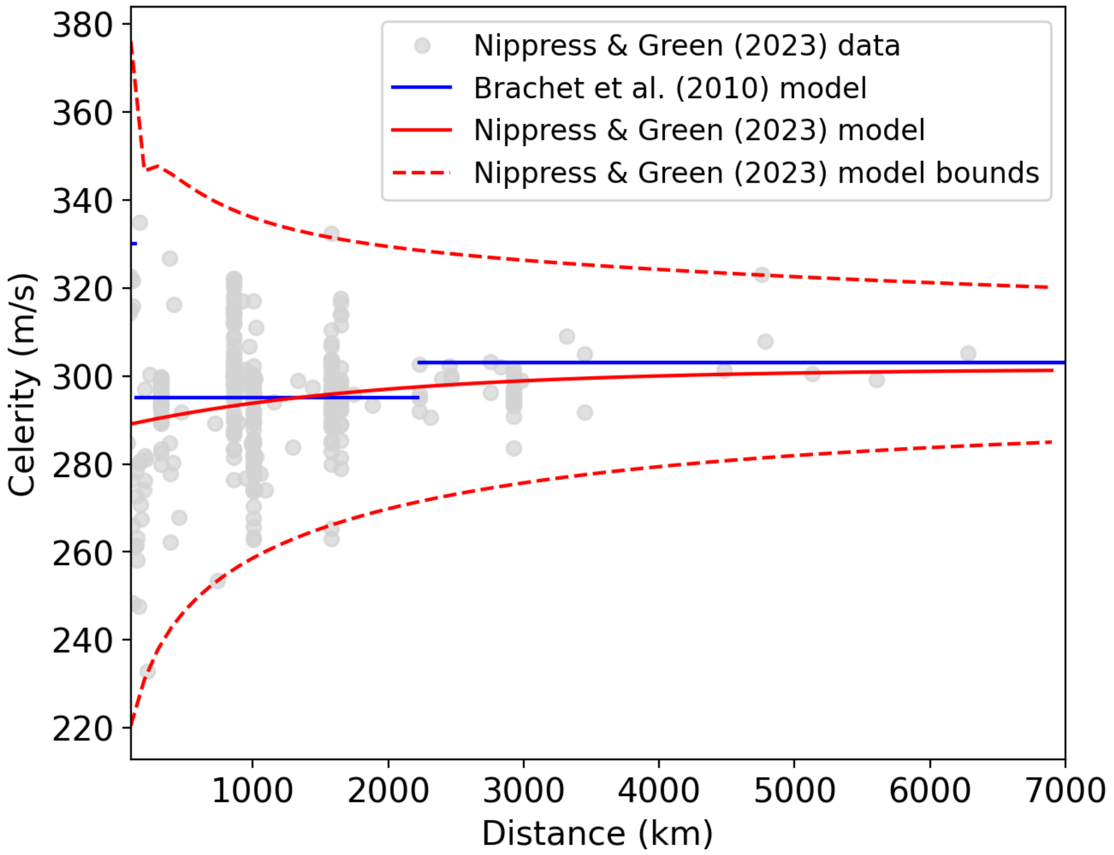
Motivation

- Global celerity and back azimuth deviation models are used within infrasound detection association and event location estimation algorithms.
- Brachet et al. (2010) model – used at the CTBTO.
- Infrasound Global Empirical Model (InfGEM) developed by Nippress and Green (2023)
  - Derived from a database of ground truth mine blast and chemical explosions.
  - Using the arrival time of the maximum peak-to-trough amplitude to calculate the celerity.
  - **Limited data at ranges greater than 2000 km.**



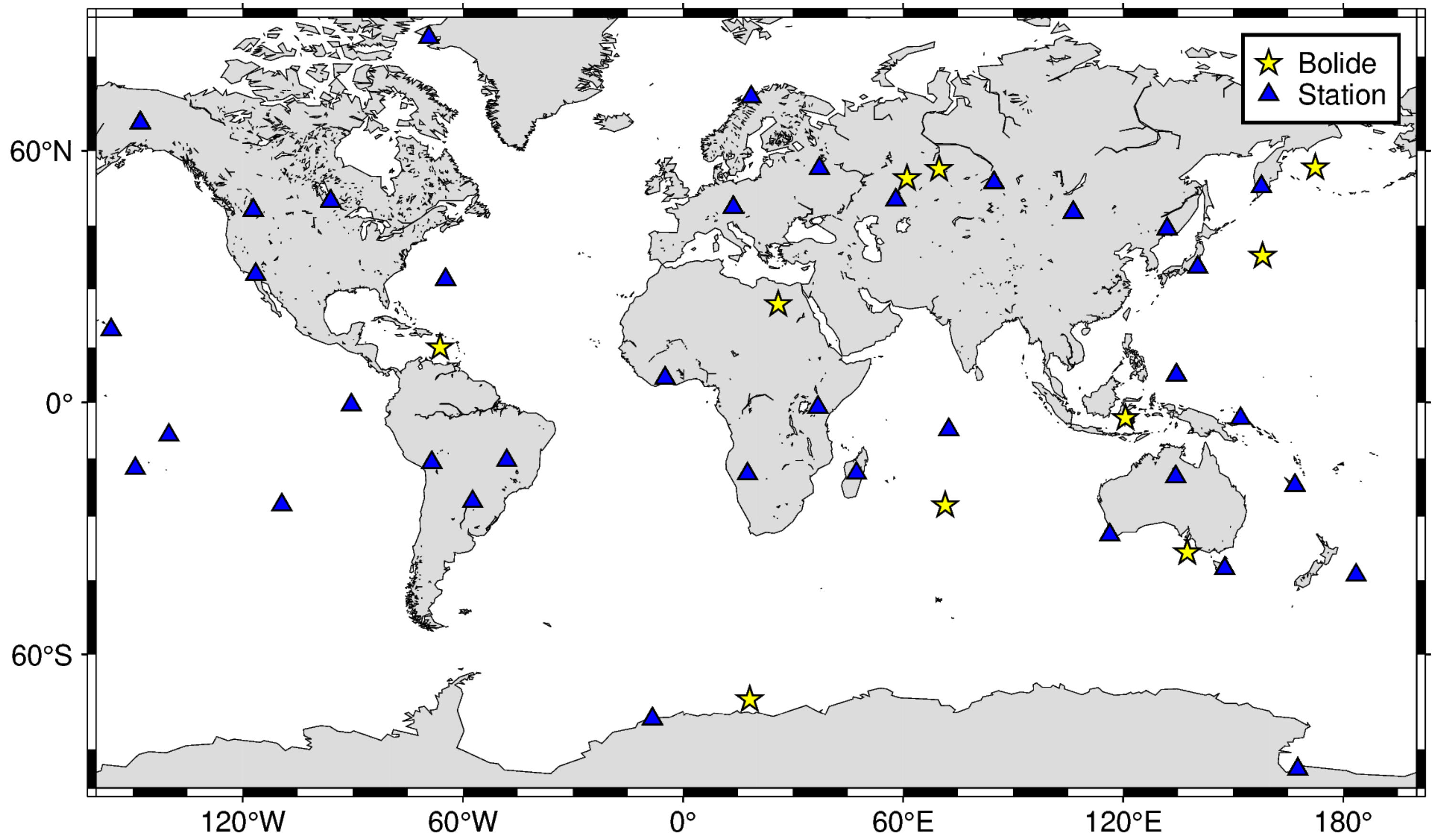
Bolide Review

- A bolide is a meteor that explodes in the atmosphere producing an infrasound signal that is often detectable at long ranges.
- Bolides are an opportunity to input celerity estimates into InfGEM at longer ranges (> 2000 km).
- Chose 10 of the largest bolides using information from NASA's Centre for Near Earth Observation Studies (CNEOS). See previous literature: Gi & Brown (2017), Pilger et al.,(2020).
- Seven of these bolides are included in the REB (*).

Bolide	Location	Date and time	Altitude (km)	Total Impact Energy (kt)
Antarctic	67.7S 18.2E	2004/09/03T13:07:22	31.5	13
Indian Ocean	27.3S 71.5E	2004/10/07T13:14:43	35.0	18
Northeast Africa*	26.2N 26.0E	2006/12/09T06:31:12	26.5	14
Central Russia*	56.6N 69.8E	2009/02/07T19:51:32	40.0	3.5
Sulawesi*	4.2S 120.6E	2009/10/08T02:57:00	19.1	33
Pacific Ocean*	38.0N 158.0E	2010/12/25T23:24:00	26.0	33
Chelyabinsk*	54.8N 61.1E	2013/02/15T03:20:33	23.3	440
Bering Sea*	56.9N 172.4E	2018/12/18T23:48:20	26.0	49
Australia*	38.8S 137.5E	2019/05/21T13:21:35	31.5	1.2
Caribbean Sea	14.9N 66.2W	2019/06/22T21:25:48	25.0	6

List of bolides used in this study. Bolide parameters from CNEOS.

Bolide Detections



- The CTBTO International Monitoring System (IMS) stations that detected a bolide signal.
- 61 detections on 37 stations from the 10 bolides out to a range of ~13,000 km.

Processing Method

Data gather from IMS stations.

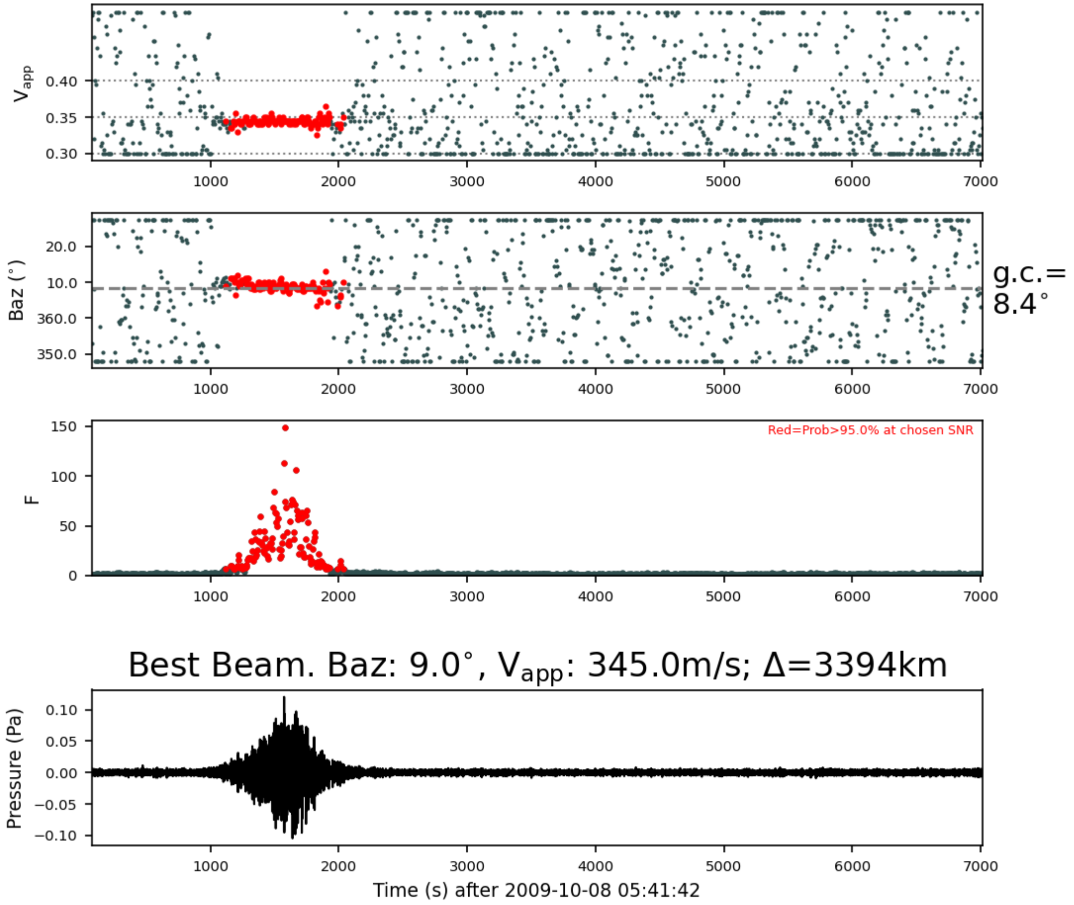
Automatic and interactive quality check on data.

Beamformed data over a combination of backazimuth (baz) and apparent velocity (v_{app}) parameters. Beamformed for passbands 0.32 to 1.28 Hz and 0.04 to 0.16 Hz.

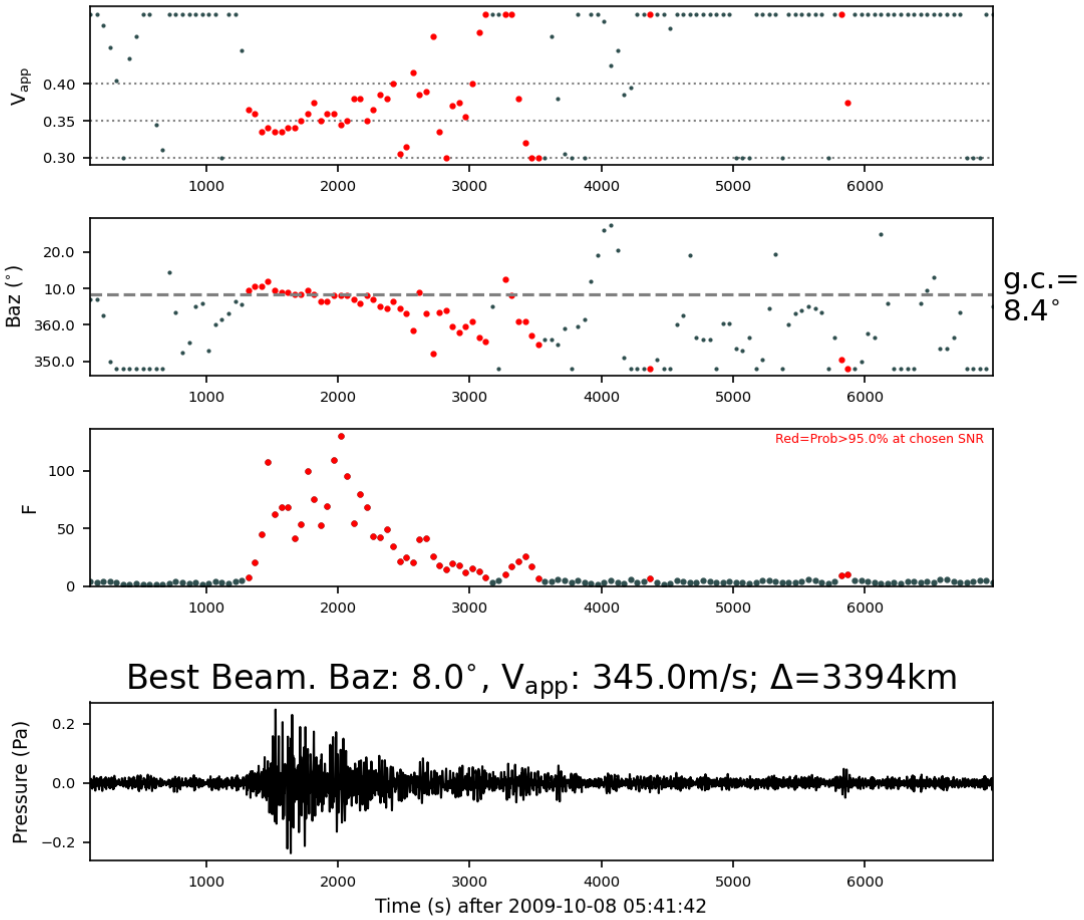
Picked best beam baz and v_{app} based on F-statistic with a SNR of >2 and 95% confidence bounds.

Picked the maximum peak-to-trough amplitude arrival on the best beam to determine celerity and back azimuth.

Processing example – Sulawesi Bolide (Alt.=19.1 km)



IS04, 0.32 to 1.28 Hz



IS04, 0.04 to 0.16Hz

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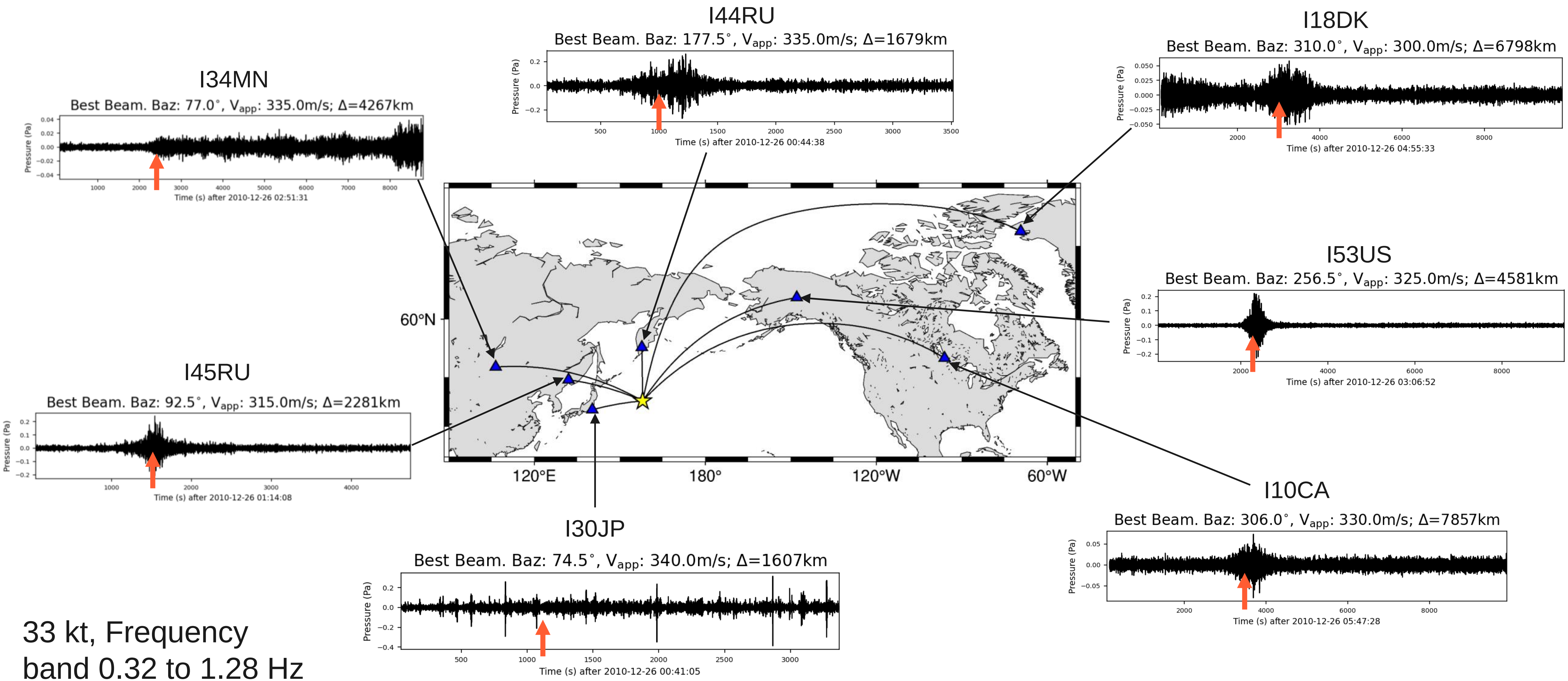
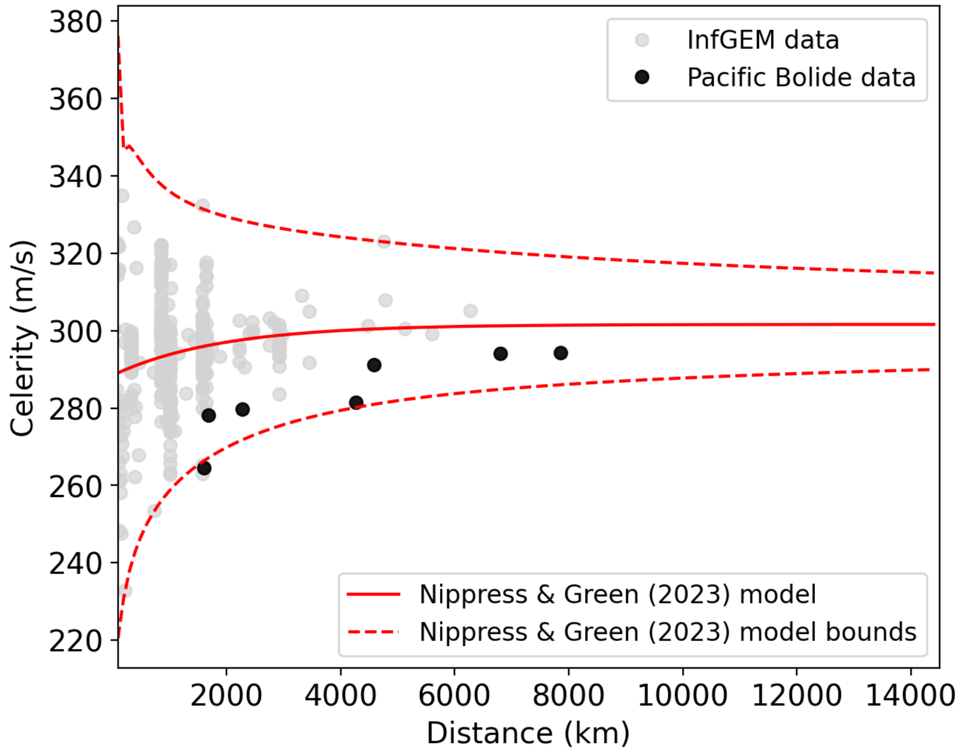
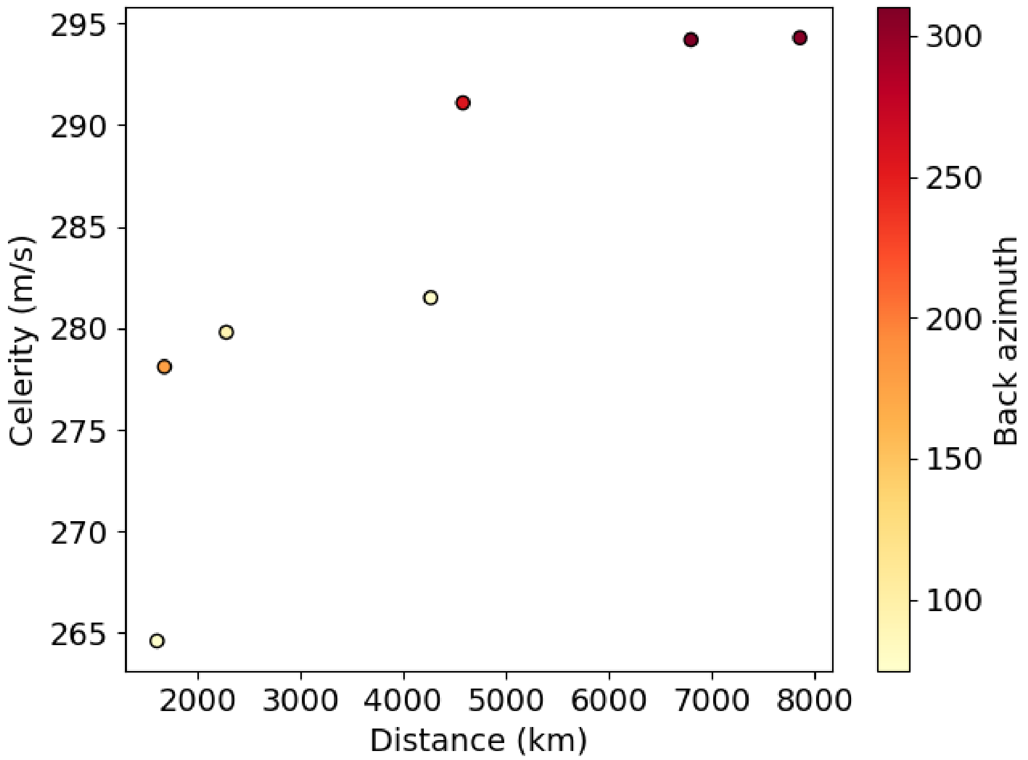
Pacific Ocean Bolide (25/12/2010, Alt.=26 km)



33 kt, Frequency band 0.32 to 1.28 Hz

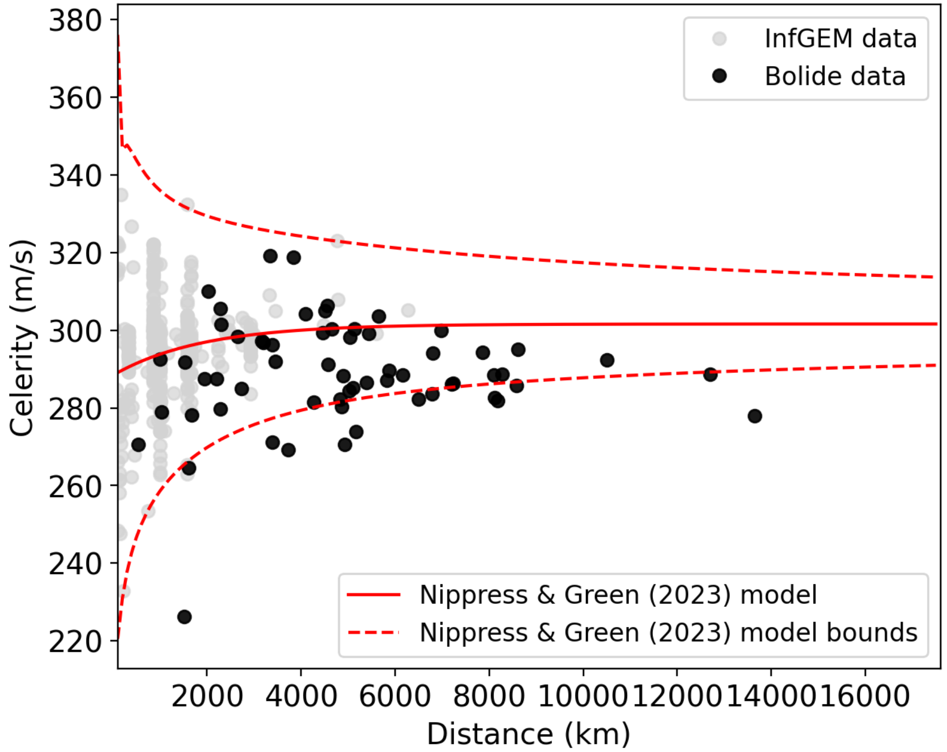
Pacific Ocean Bolide (25/12/2012, Alt.=26 km)

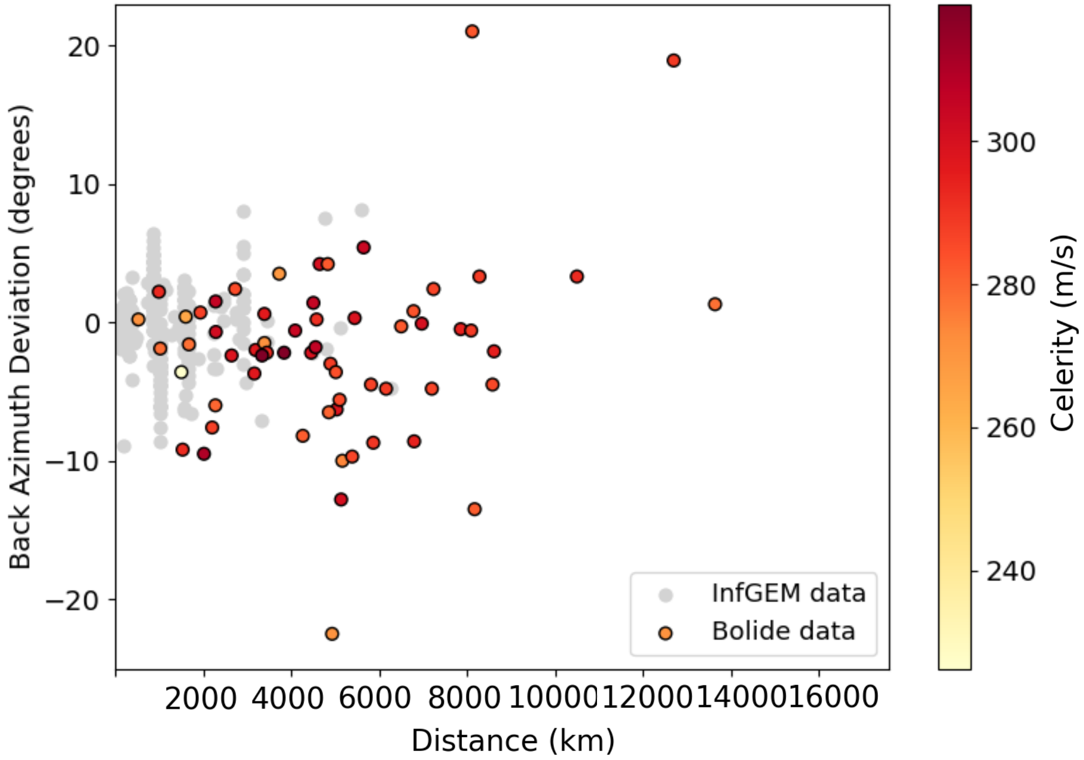




- 25/12/2012 Pacific bolide celerities are on average slower than the InfGEM median model would predict, but the majority of celerities are within the model confidence bounds.
- We see slower celerities to the West and faster celerities to the East.

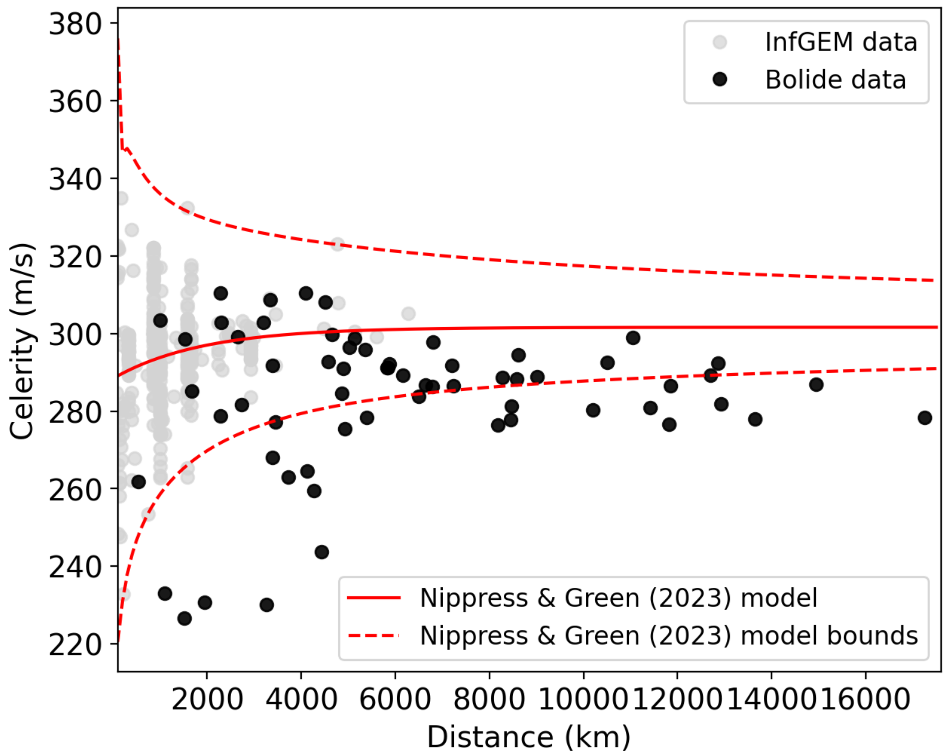
InfGEM and Bolide data – 0.32 to 1.28 Hz

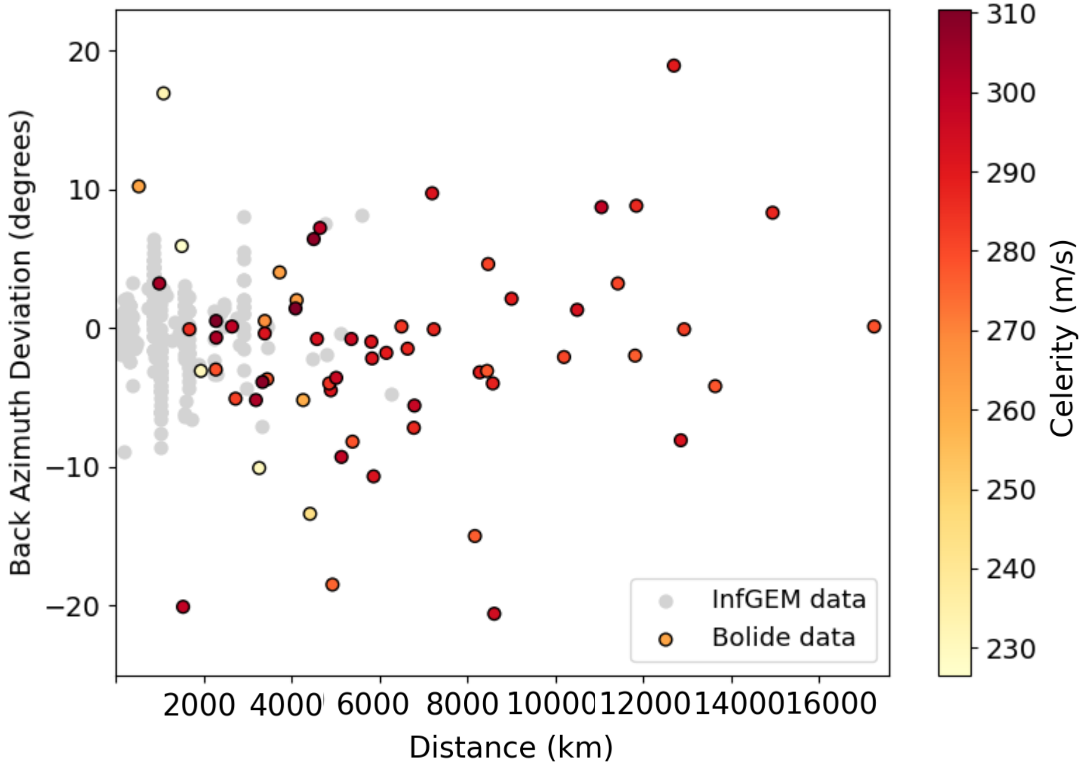




- For all 10 bolides, 79% of celerities are slower than the InfGEM median model. 21% of celerity estimates are lower than the InfGEM 1% quartile bound.
- 10% of the arrival's back azimuth deviations are >10°.

InfGEM and Bolide data – 0.04 to 0.16 Hz



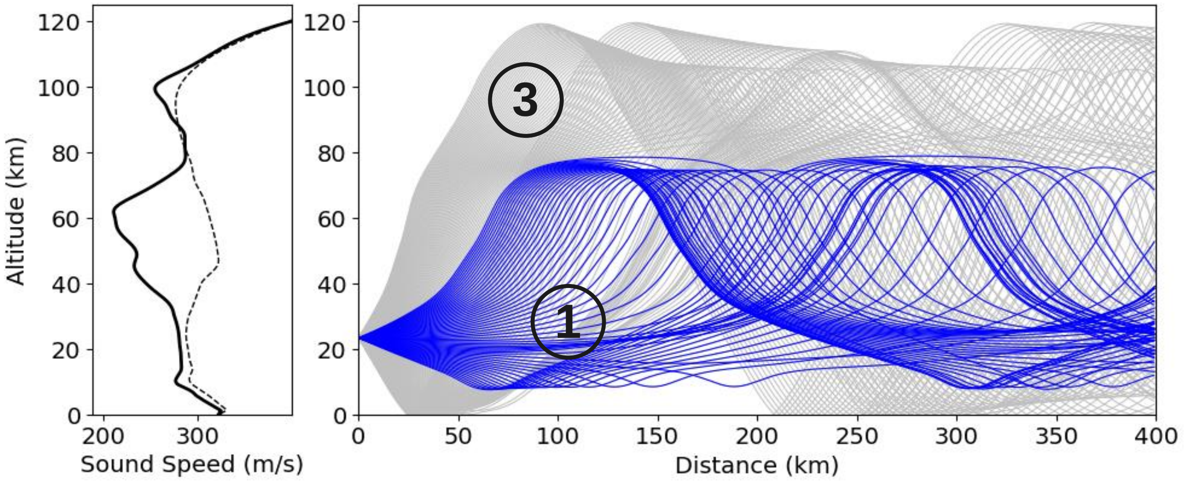


- For all 10 bolides, 83% of bolide celerities are slower than the InfGEM median model would predict. 37% of celerity estimates are lower than the InfGEM 1% quartile bound.
- 17% of back azimuth deviation measurements are >10°.

Range Independent Propagation Modelling

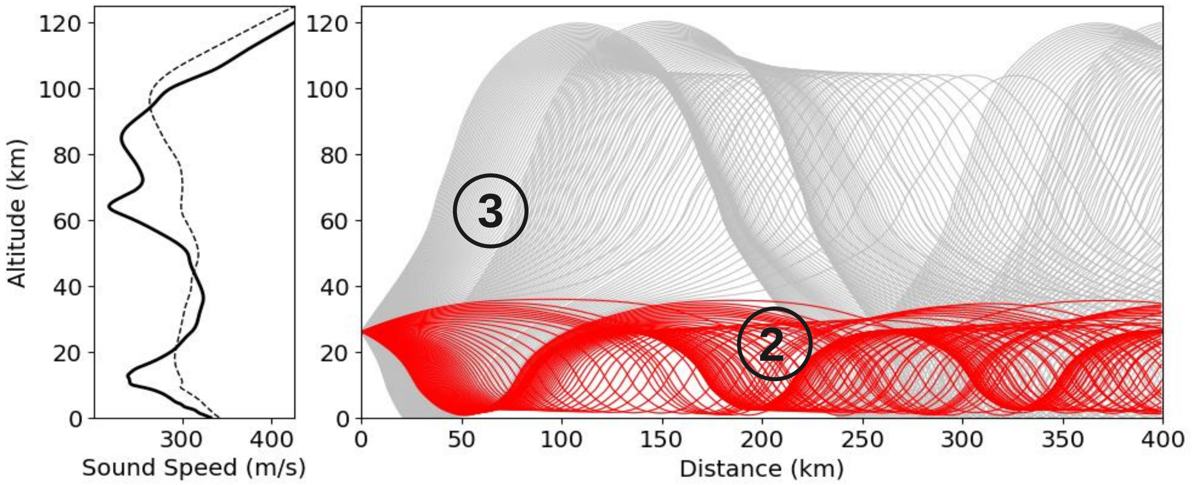
Do elevated sources potentially generate infrasound along slower paths than sources on ground?

Chelyabinsk towards IS43



Observed celerity 226 m/s, Modelled celerity ~240-260 m/s

North Pacific towards IS30



Observed celerity 264 m/s, Modelled celerity ~270 to 290 m/s

Elevated mesospheric ducts (1)

- More likely along paths that propagate upwind w.r.t. stratospheric jet.
- Slower observed celerities than ground-to-stratosphere ducts.

Elevated stratospheric ducts (2)

- Slower observed celerities than ground-to-stratosphere ducts.
- Require mechanism for energy to reach ground from the elevated duct.

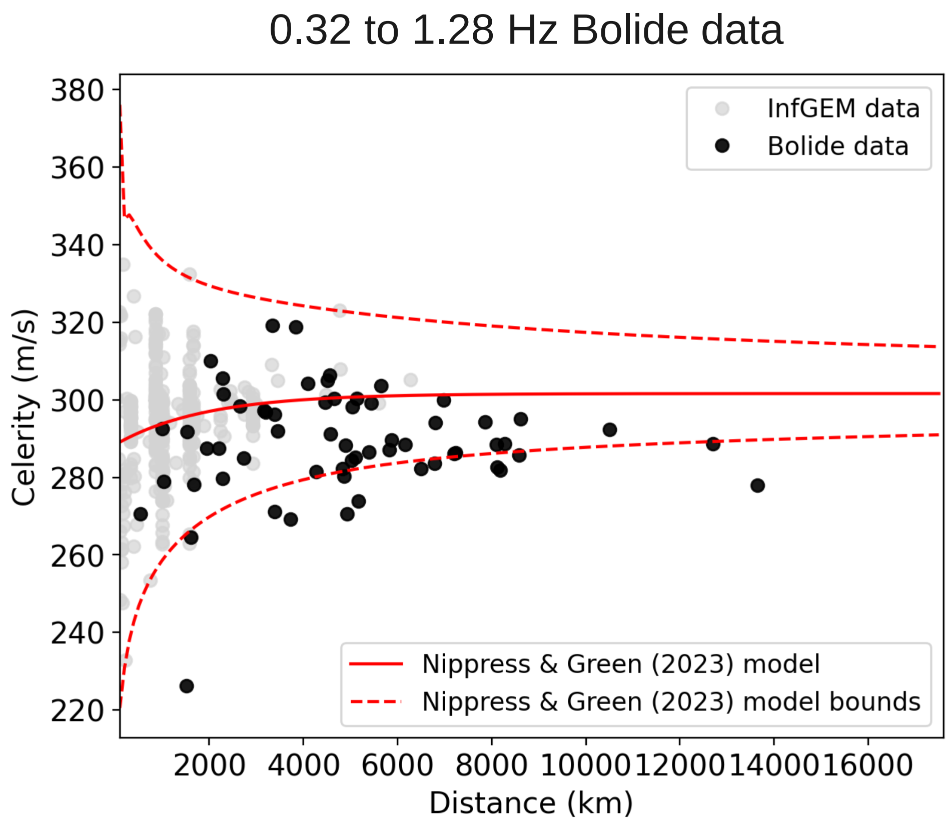
Thermospheric arrivals with shallow inclination angles (3)

InfraGA software (Blom, 2019)

[Modelling, using G2S specifications, only shown out to 400km distance to illustrate possible paths]

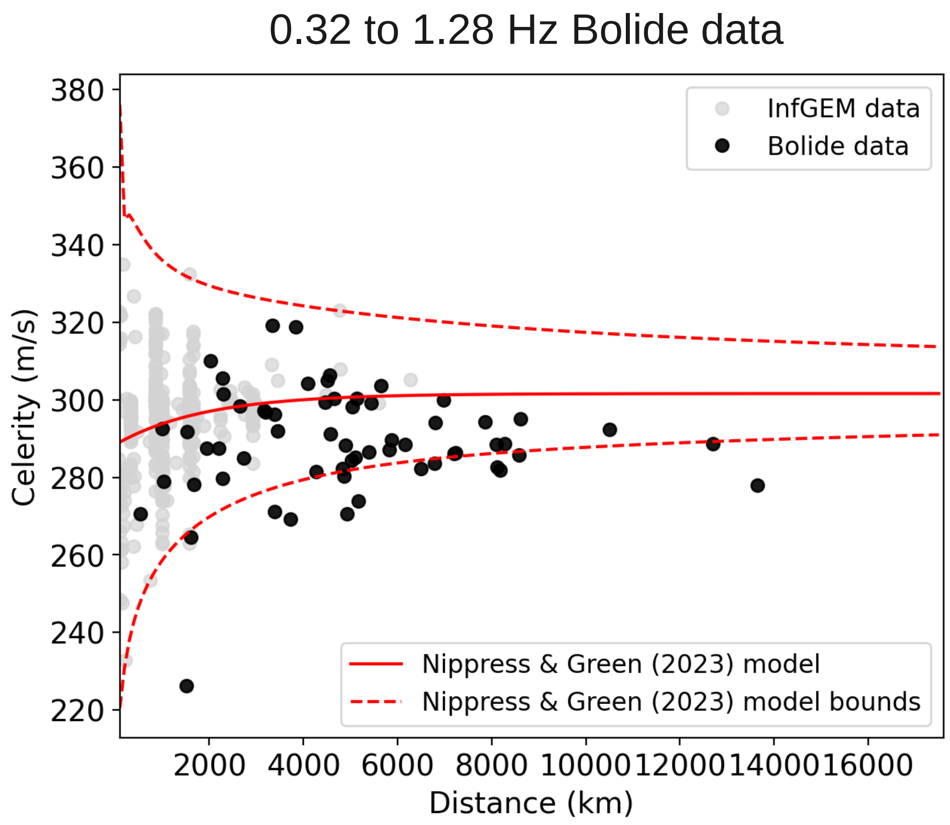
Summary

- Ground-truth studies of ground-based sources (e.g., InfGEM) include few long distance (>2000 km) paths.
- Observations from 10 bolides at altitudes between 20 to 40 km increase the maximum source-to-receiver distance of celerity and back-azimuth measurements in the 0.32 to 1.28 Hz passband to 13000 km.
- Bolide celerities are on average slower than both InfGEM and the Brachet IDC model would predict. Back azimuth deviation has a greater variation than InfGEM data.
- Propagation modelling suggests that infrasound from elevated sources may propagate along slower paths than the often observed ground-to-stratosphere ducts.
  - e.g., elevated mesospheric ducts, elevated stratospheric ducts.



Future Work

- Expanding the bolide database to confirm the trend of lower celerity measurements.
- Reanalyse the InfGEM model to include bolides – or create a separate one?
- Continue with propagation modelling to further understand:
  - Slower celerity observations.
  - Large back azimuth deviations.



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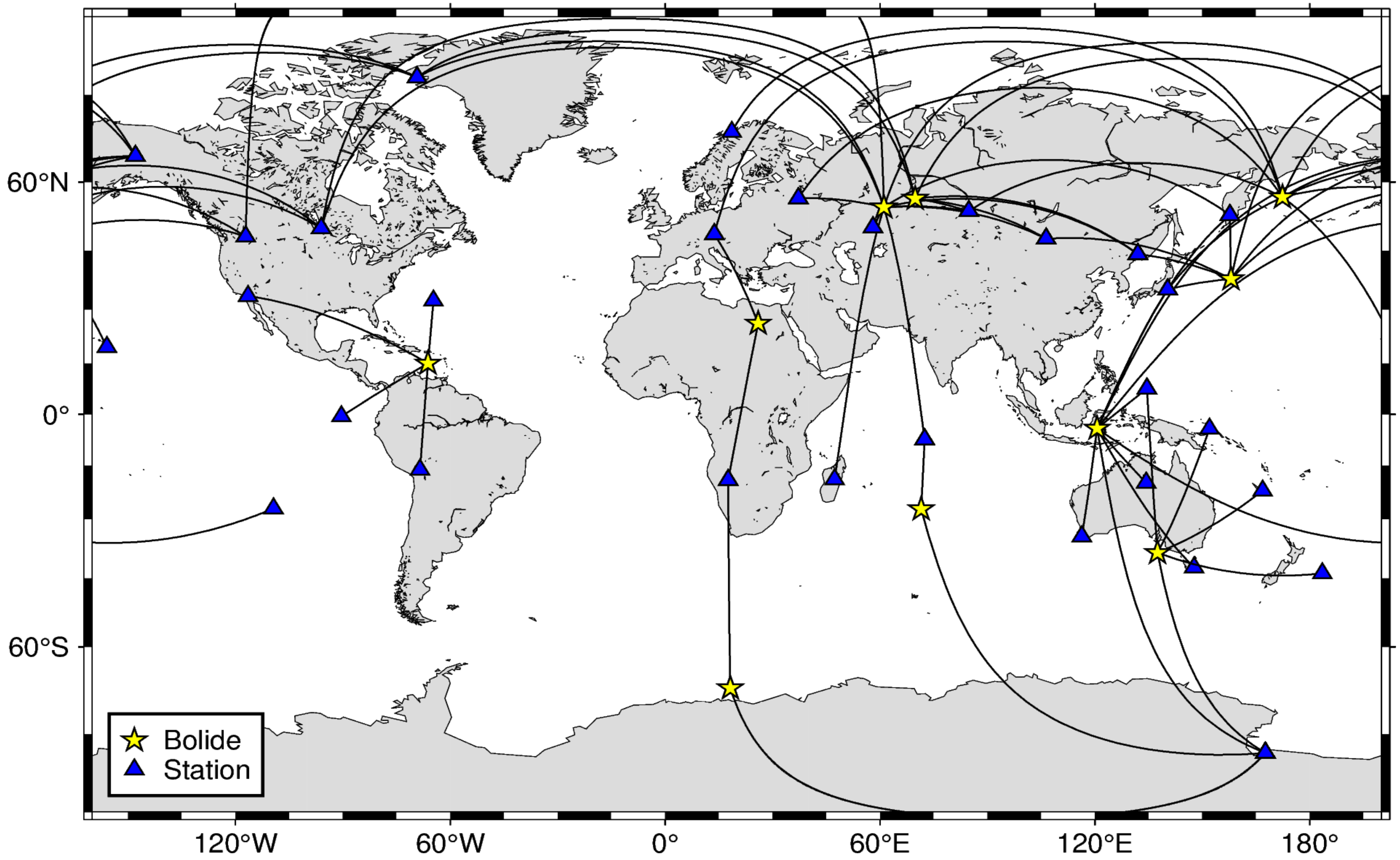
Pilger, C., Gaebler, P., Hupe, P., Ott, T., & Drolshagen, E. (2020). Global monitoring and characterization of infrasound signatures by large fireballs. *Atmosphere*, *11*(1), 83.

Extra Slides

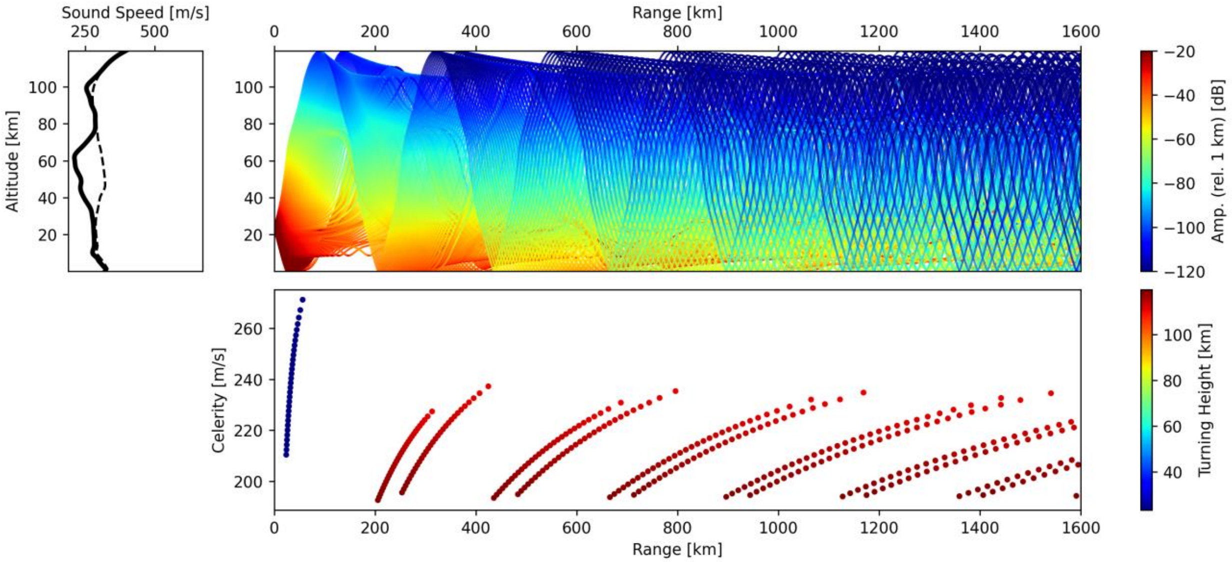
Bolide Paths



Range Independent vs Dependent modelling

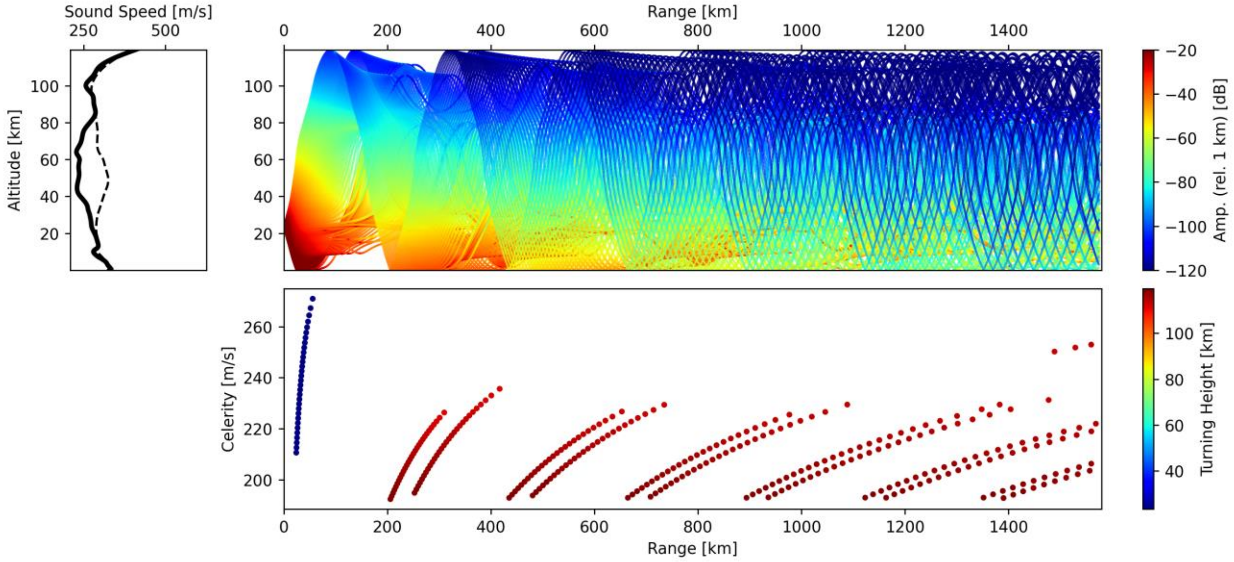
Chelyabinsk bolide

Range Independent model for IS43



Alt. = 23.3 km

Range Dependent model for IS43



Alt. = 23.3 km

[Modelling, using G2S specifications]

InfraGA software (Blom, 2019)

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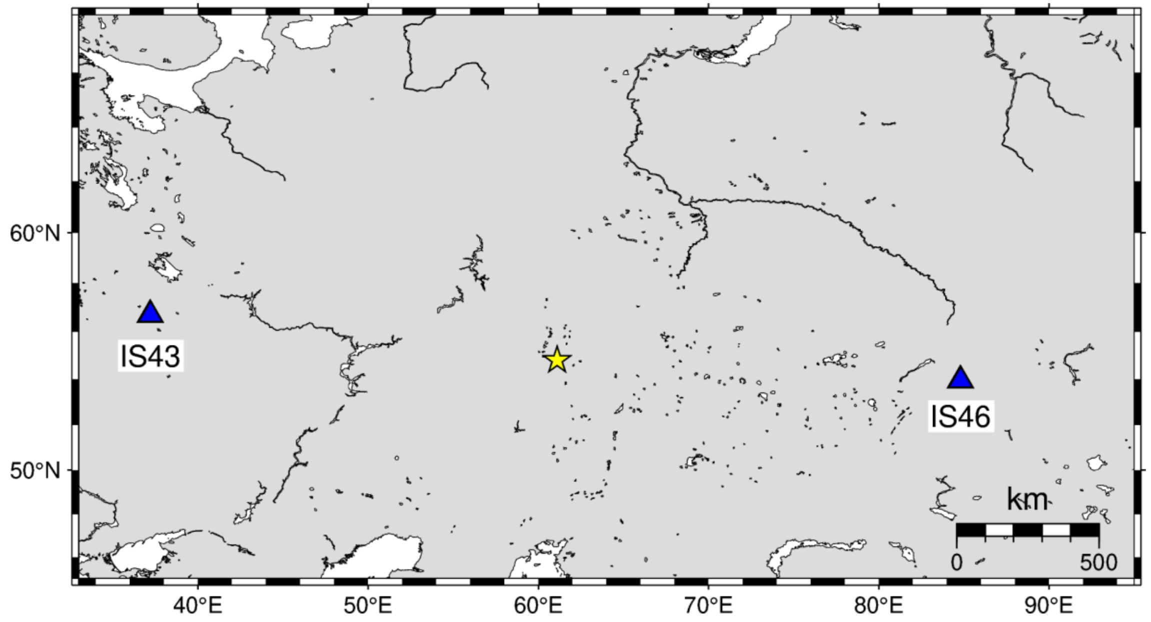
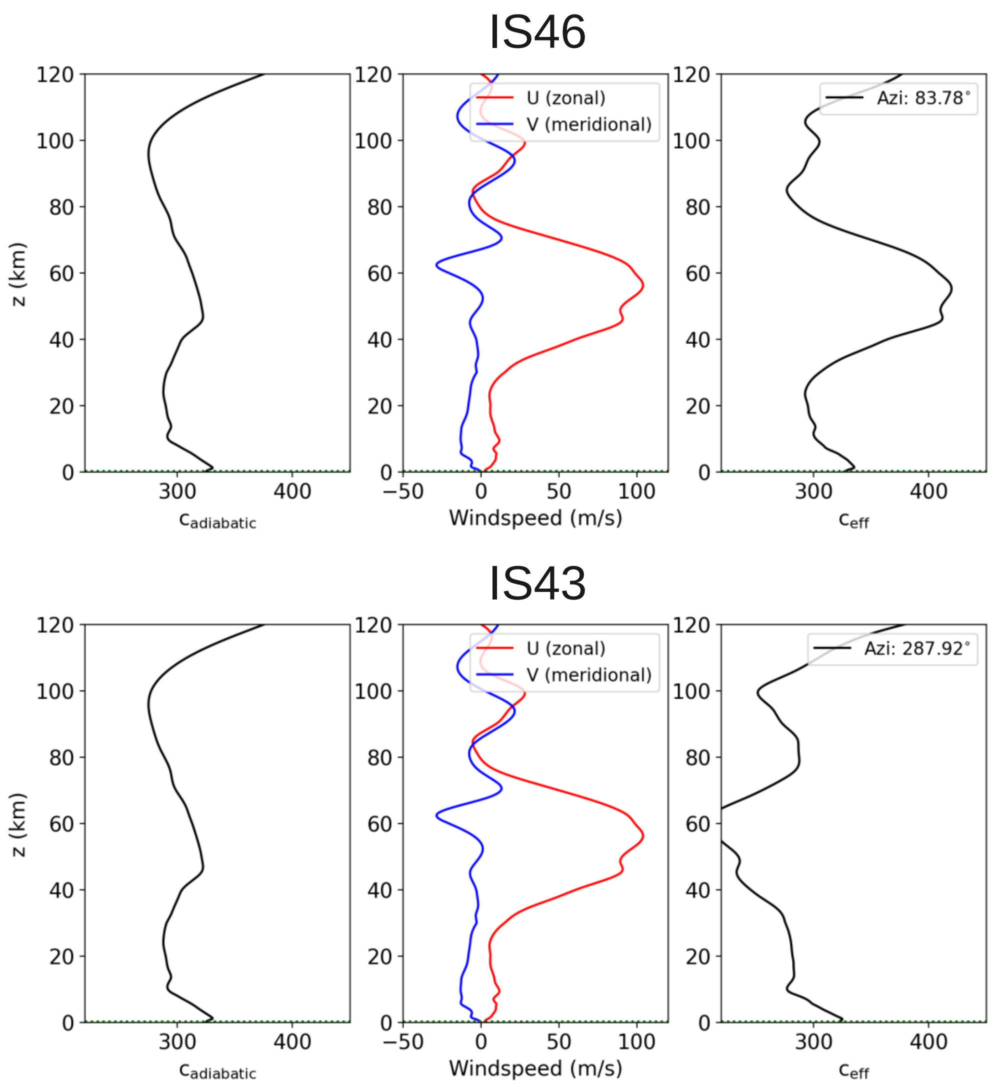
Modelling – Chelyabinsk Bolide

- IS46 observed celerity: 291.8 m/s
- IS43 observed celerity: 226.3 m/s.

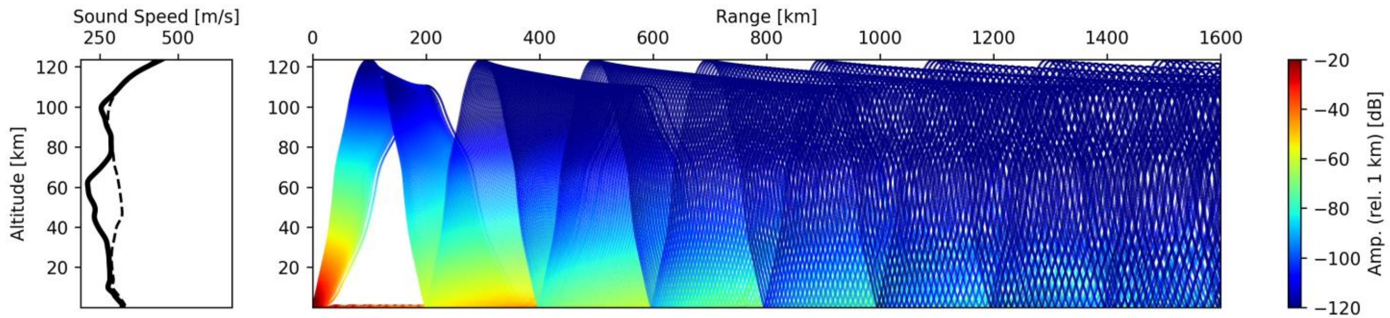


2013/02/15 03:20:33, 440 kt, Altitude ~23 km

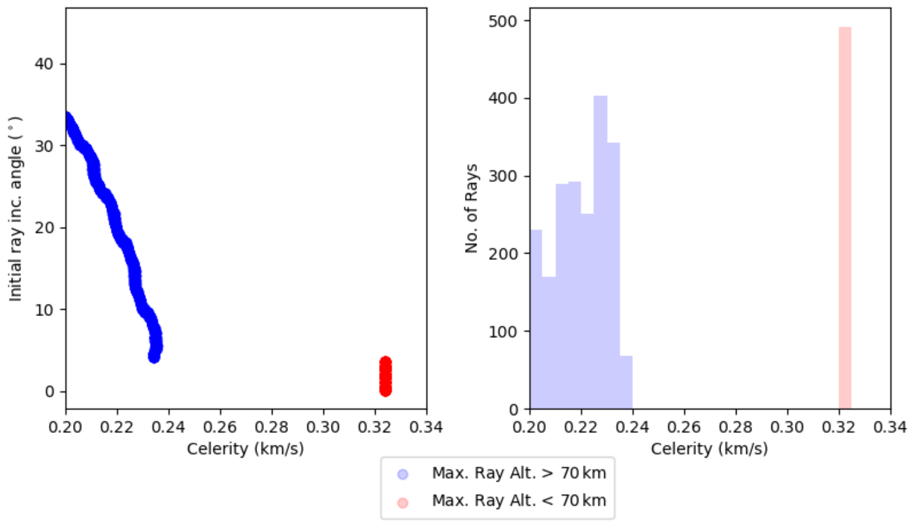


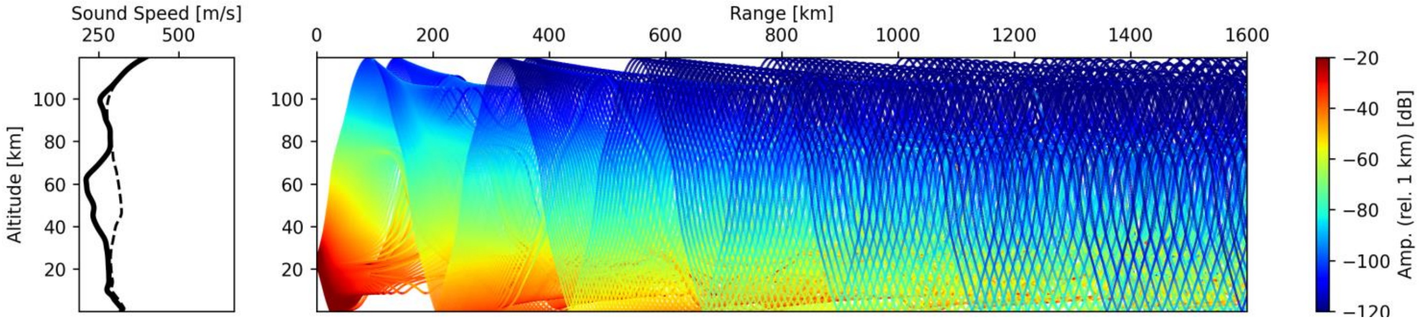
Modelling Chelyabinsk Bolide – IS43

Measured celerity: 226.4 m/s

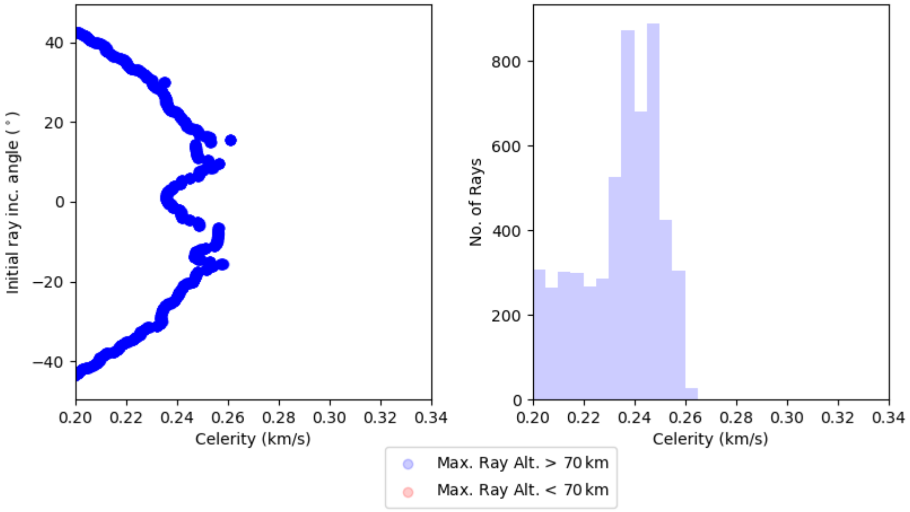


Alt.=0 km





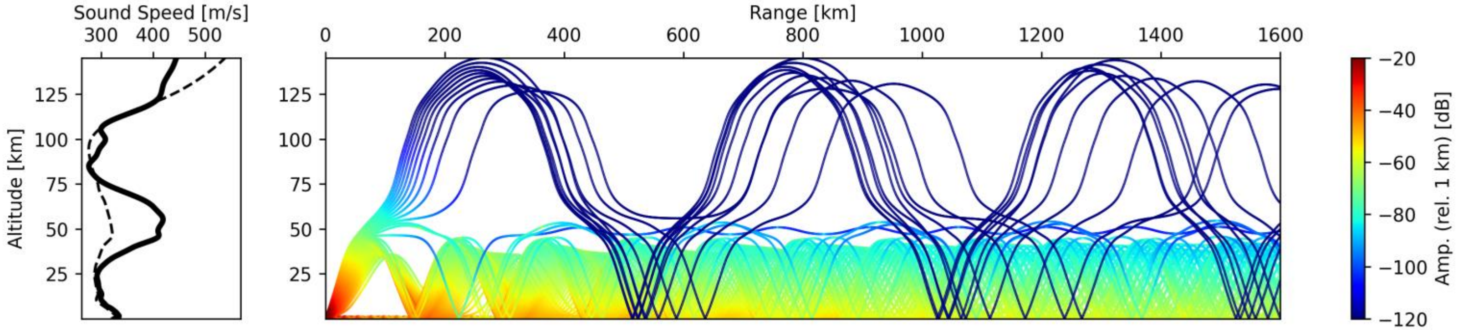
Alt.=23.3 km



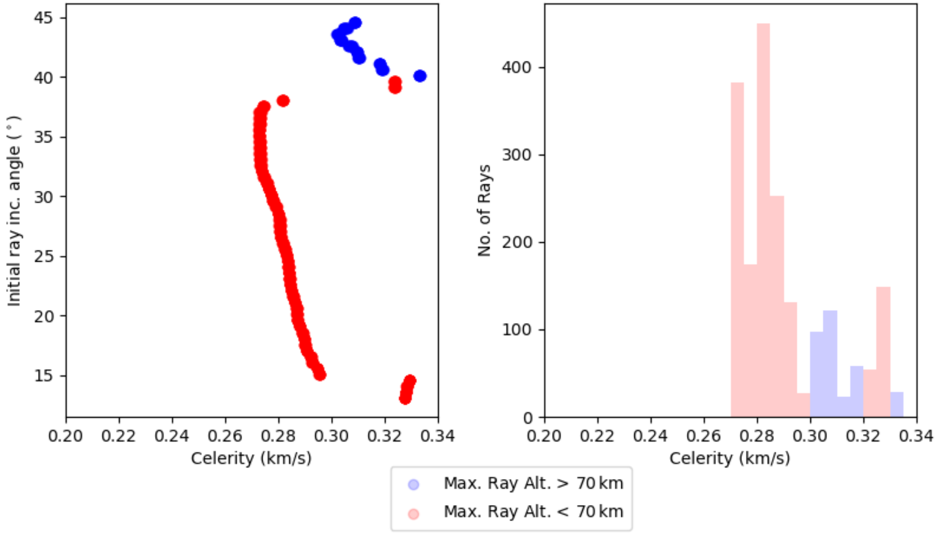
[Range Independent Modelling, using G2S specifications in InfraGA (Blom, 2019)]

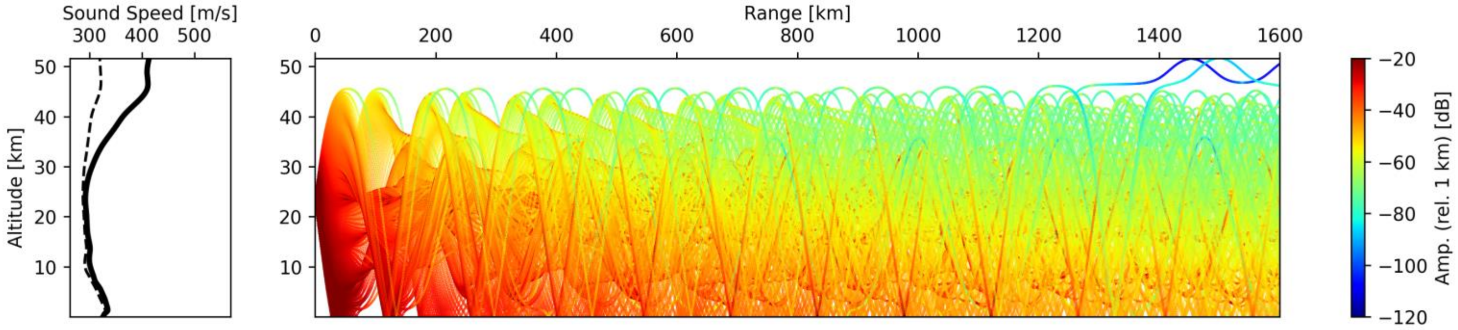
Modelling Chelyabinsk Bolide – IS46

Measured celerity: 291.8 m/s

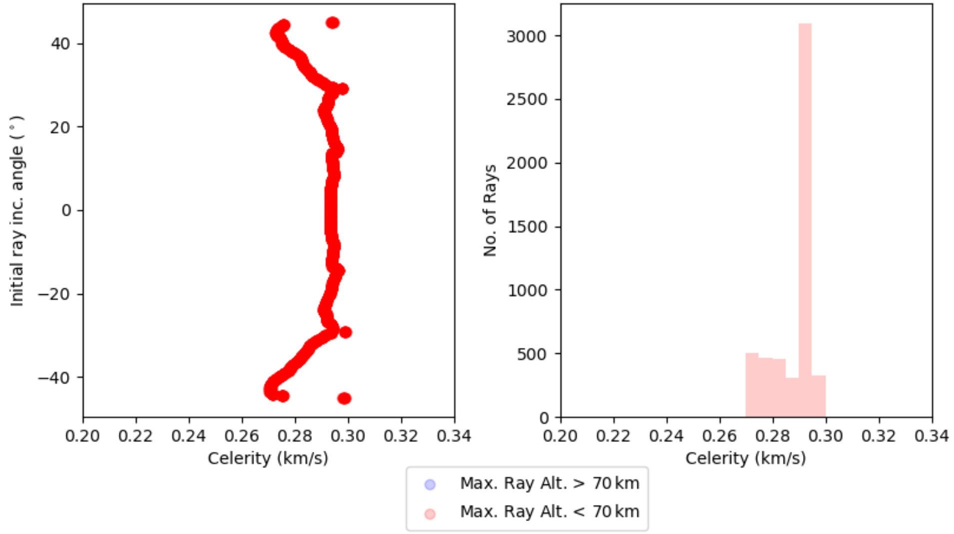


Alt.=0 km





Alt.=23.3 km



[Range Independent Modelling, using G2S specifications in InfraGA (Blom, 2019)]