Seismo-Acoustic Analysis of the Gas-Filled Vehicle Explosion in Ulaanbaatar on January 23, 2024

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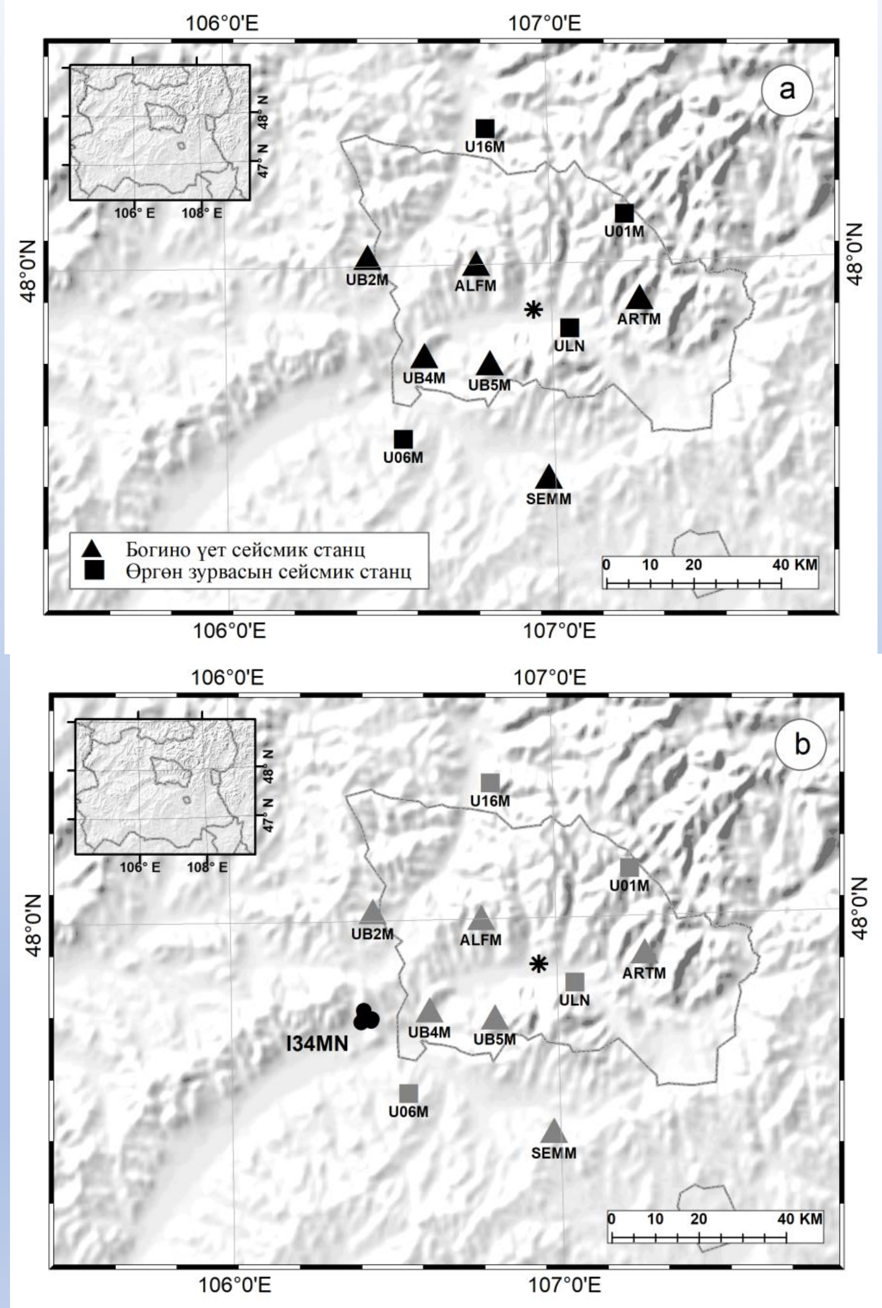
CONTENTS

BACKGROUND

- A 15-ton LPG explosion occurred at 01:21:30 AM in Bayanzurkh District, 26th khoroo.
- Gas leaked from a vehicle, spread over ~10,000 m², ignited, and caused a major blast.
- Resulted in 3 deaths, many injuries, 30+ vehicles destroyed, and damage to buildings.
- The airborne explosion produced infrasound recorded >50 km away and by local seismic stations.
- Acoustic waveform analysis estimated the explosive yield at ~1.5 tons TNT equivalent.
- A tropospheric infrasound phase was observed; origin time (T_0) was identified via infrasound.
- Seismo-acoustic modeling supports the observed wave propagation and source timing.

STATION NETWORK AND WAVE OBSERVATIONS

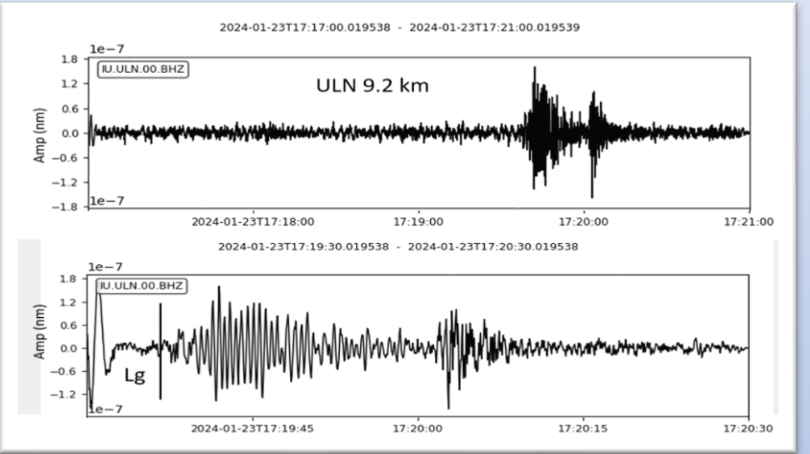
- Lg wave from explosion clearly recorded at stations near Ulaanbaatar (e.g., ALF, ULN)
- Tropospheric phase observed by infrasound stations with strong, clear signals
- Caused by a Vapor Cloud Explosion (VCE) following: Collision between LPG truck and passenger carGas leak → Vapor cloud → Explosion

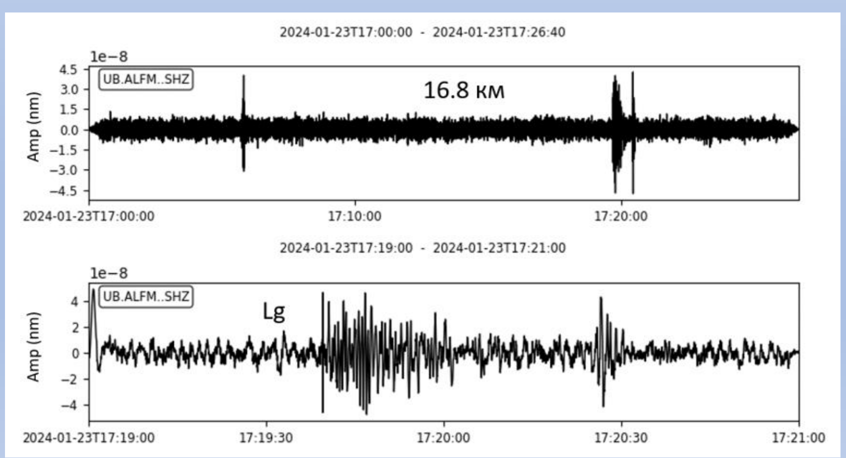


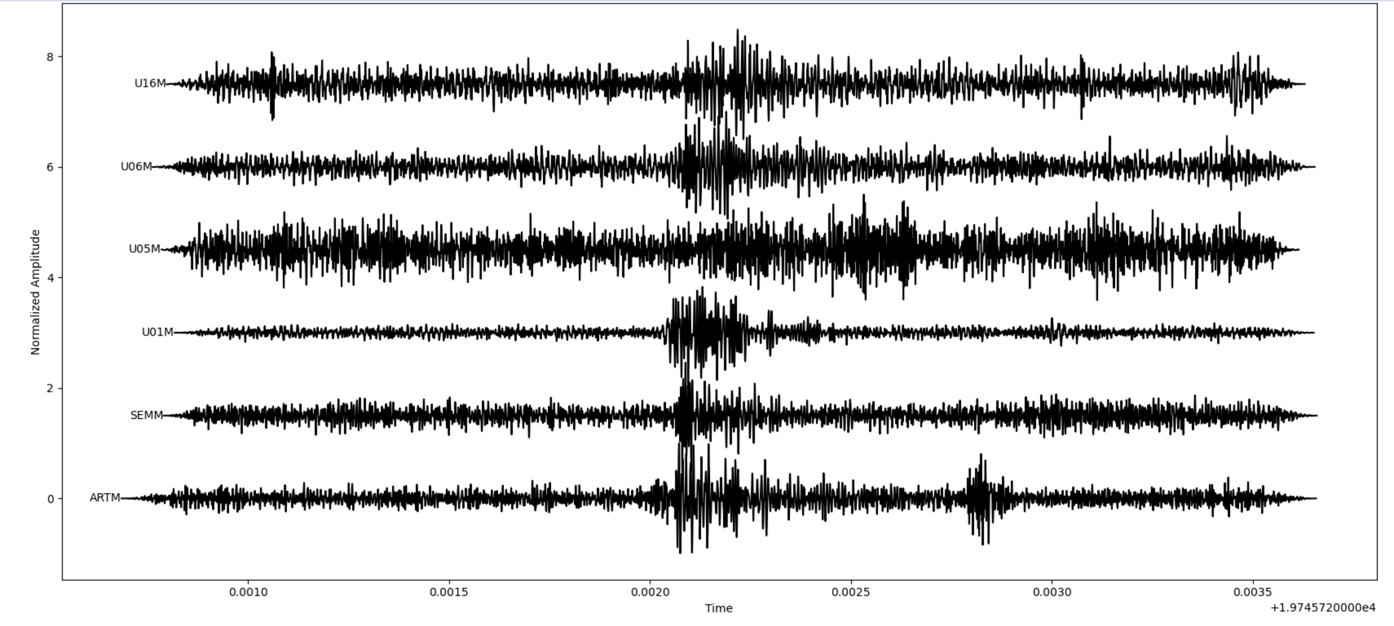
Overview of station locations and observations: (a) General layout of seismic stations where the Lg wave was recorded. Stations with short-period sensors are marked with triangles, while broadband stations are marked with squares. (b) Stations that recorded the acoustic wave corresponding to the tropospheric phase of the atmosphere are marked with circles (I34MN).

RECORDED SIGNALS FROM EXPLOSION: SEISM

This explosion occurred in the air above the ground surface, making it impossible to determine the origin time using seismic methods. Since the location and distance of the explosion are known, the origin time T_0 was determined using the infrasound station.







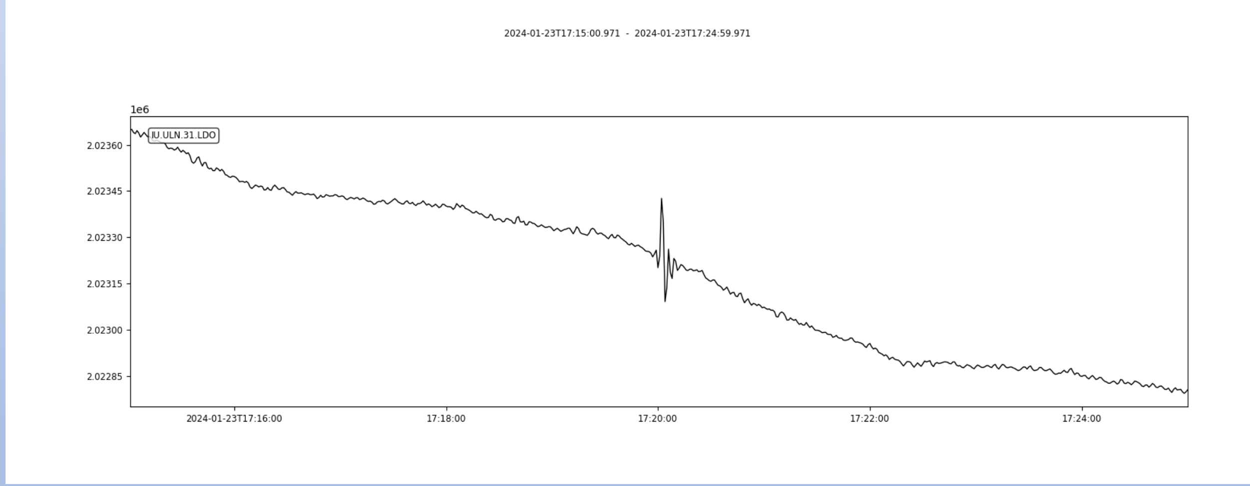
For the seismic stations, seismograms were filtered in the 0.8–5 Hz frequency range. The lower part of each station’s record shows a zoomed-in view.

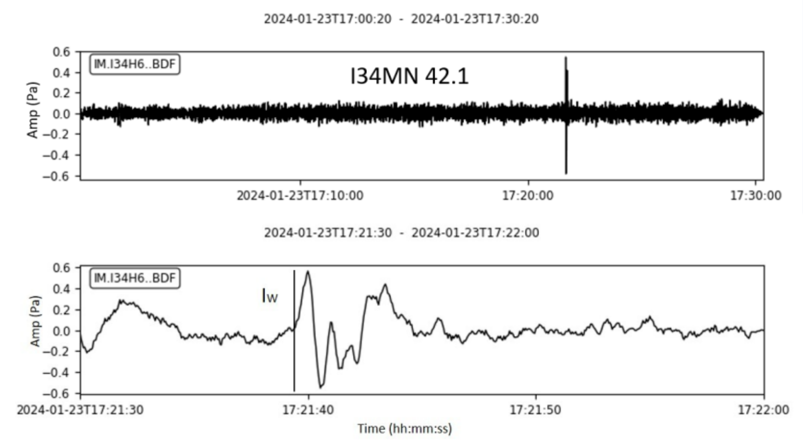
RECORDED SIGNALS FROM EXPLOSION: ACCOUSTI

. Since the location and distance of the explosion are known, the origin time T_0 was determined using the infrasound station.

$$T_0 = \frac{\Delta}{C_i} - (t_A - t_i) \qquad [1]$$

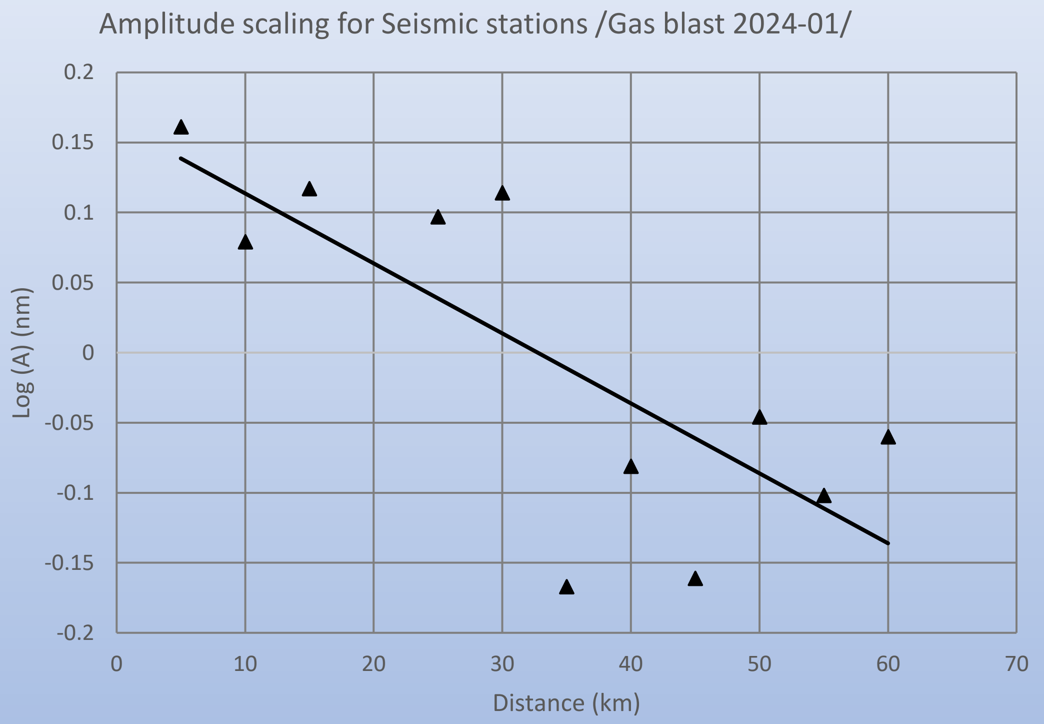
This includes: T_0 — the origin time at the source, C_i — the acoustic wave velocity (celerity, km/s), t_A — the seismic arrival time, and t_i — the infrasound arrival time. When the distance to the source is known, the above equation is used to determine the origin time T_0.





As an example of the explosion, Sound waves recorded at Pressure sensor ULN (9.2 km), as well as Iw waves recorded at the infrasound station, are shown. The acoustic Iw signal generated by the gas explosion was recorded with an amplitude of 0.54 Pa, displayed in detail at the bottom.

AMPLITUDE SCALING FOR SEISMIC STATIONS



Comparison of the maximum amplitude displacement of surface Lg waves observed at seismic stations within the 1–20 Hz frequency range as a function of distance.

Using Wood-Anderson simulations at a total of seven stations (ranging from 9.2 to 54.9 km), the local magnitude (ML) was calculated as 0.6 based on the average of the largest amplitudes from 13 Lg wave phases. The Hutton & Boore (1987) equation was used:

$$Ml = \log(A) + 1.11\log(D) + 0.00189 * D - 2.09 \qquad [2]$$

(A) amplitude nm and (D) distance km.

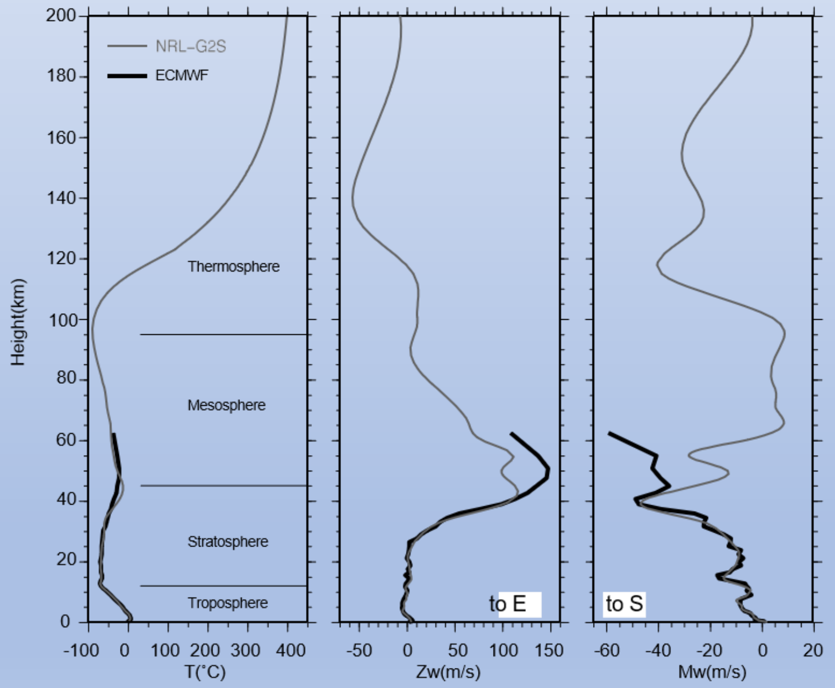
Compared to the magnitude of typical mine blasts, this explosion corresponds to approximately 1.2 ML.

Although the Hutton & Boore (1987) local magnitude equation was originally developed for S-wave amplitudes, it was applied here to Lg wave amplitudes as an approximate estimate, due to the absence of P and S phases from this atmospheric explosion

INFRASOUND PROPAGATION

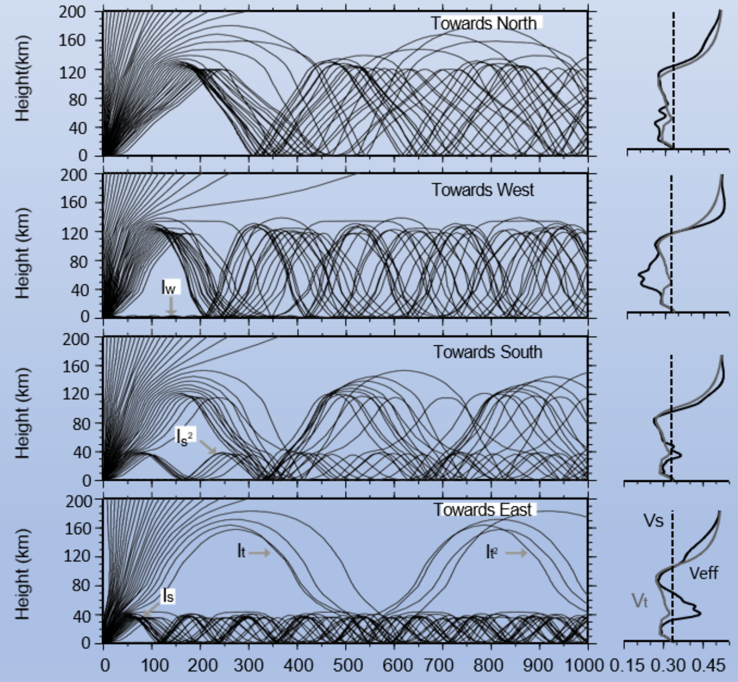
Since the propagation speed of the infrasound wave does not depend on frequency, it is expressed by the following formula, similar to ordinary sound.

$$C_{eff} = \sqrt{\gamma_g RT + \hat{n} \cdot \vec{u}}$$



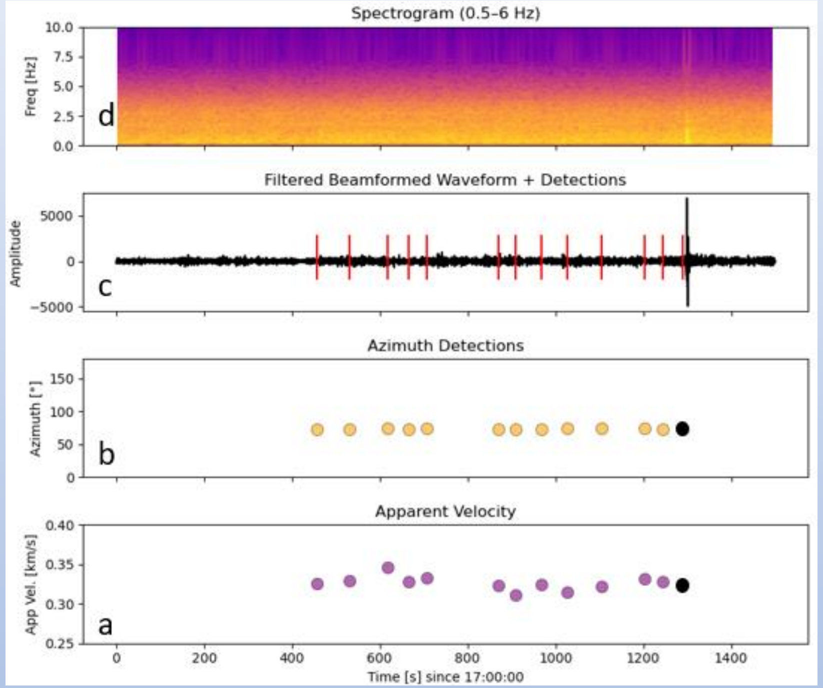
Atmospheric zonal and meridional winds and temperature at 17:00 on January 23, 2024, at longitude 47.8° and latitude 106.4°, modeled using ECMWF and NRL-G2S.

In seismology, the tau-p method (Buland & Chapman, 1993) is used to treat the atmosphere as a moving medium, as reformulated by Garcés et al. (1998). The NRL-G2S model was used to show the propagation trajectory of the infrasound waves.

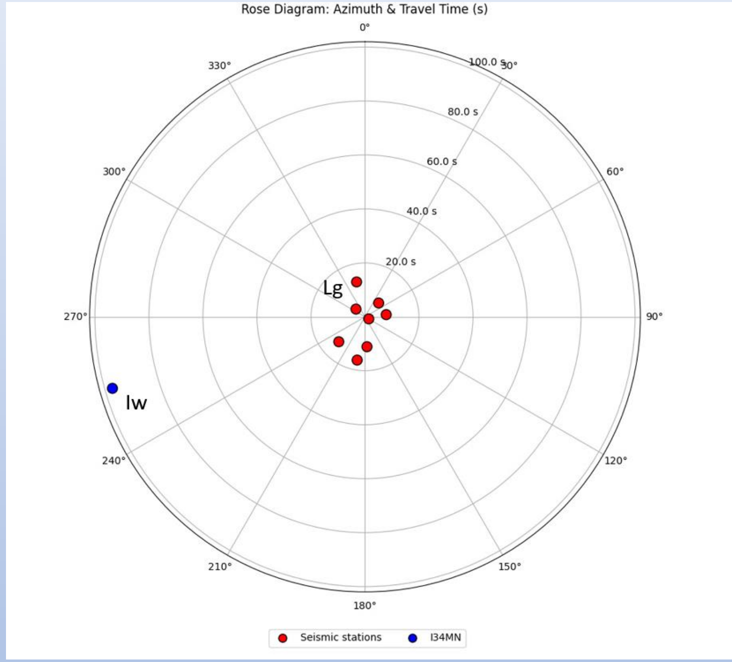


The effective sound speed (V_{eff}) arriving from atmospheric layer boundaries in a region is used to denote the propagation phases through the atmospheric troposphere as I_w, the stratospheric phase as I_s, and the thermospheric phase as I_t (Brown et al., 2002).

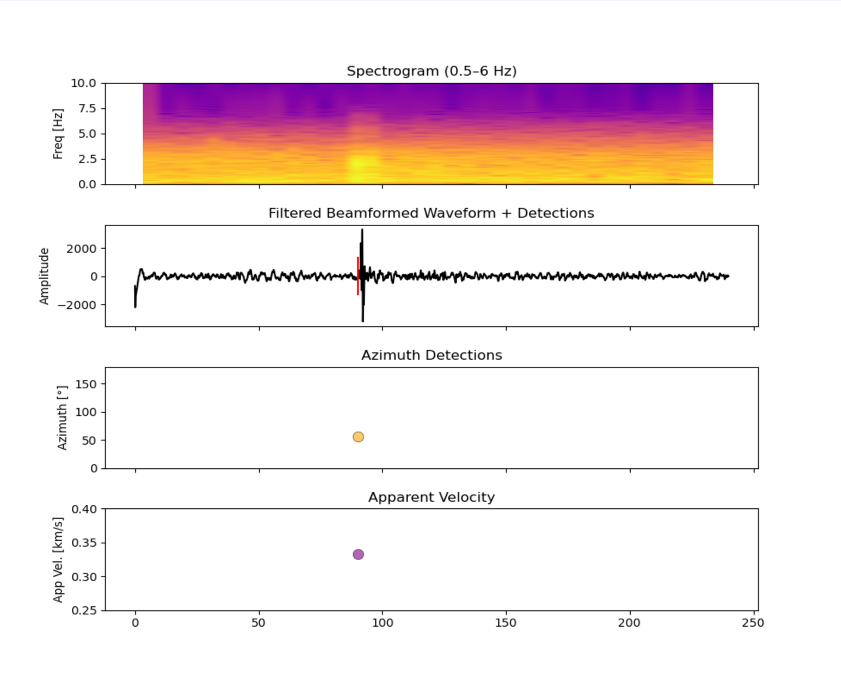
INFRASOUND DATA ANALYSIS



Gas blast



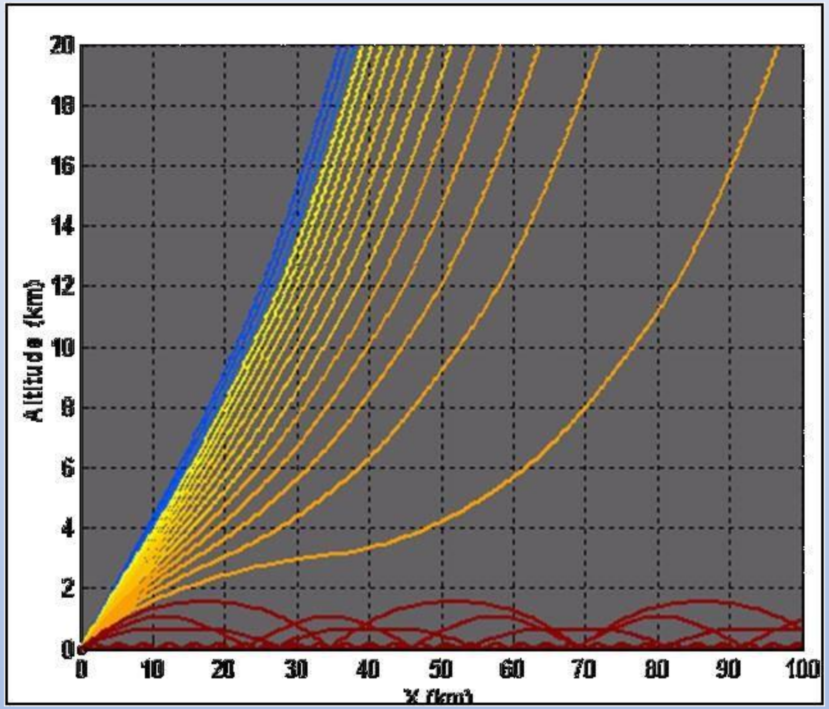
Surface wave observations were shown using colored dots based on their recorded arrival times: blue dots represent arrivals at the infrasound station, and red dots represent Lg wave arrivals at seismic stations.



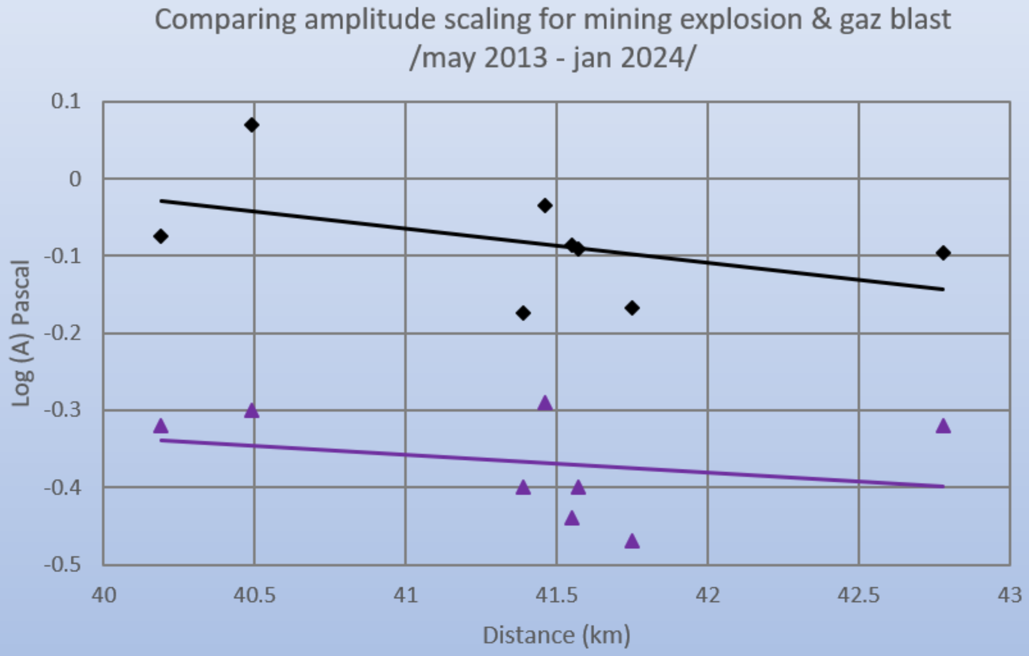
Mining blast

The explosion recorded at the infrasound network station was compared to a nearby quarry blast by processing both signals in the 0.5–6 Hz frequency range. The comparison is based on 30 minutes of signal following the explosion, with the starting time set at 17:00:00. The lower panels show: (a) apparent velocity of 0.330 km/s, (b, c) the azimuth from the explosion location to the station and the amplitude recorded at the station, and (d) frequency-based separation of the wave signals.

COMPARING GAS BLAST AND MINING EXPLOSION



Temperature inversion and heterogeneity between altitudes of 0–15 km generate waves in the tropospheric layer called $\boldsymbol{I_w}$ (these were not included in the experimental model calculations).



Results of the root mean square amplitude calculation for acoustic waves arriving from the troposphere, showing the amplitude from the gas explosion of diamond JD024/2024 and, for comparison, the smaller mine blast near the city represented by triangle JD013/2013.

YIELD ESTIMATION FROM INFRASOUND RECORDS

Using the data available in our own database, we applied the LANL equation from Stevens et al. (2002).

- $\log(P) = -1.54 + \log(W) - 0.5\log(R sin\Delta)$, *Pierce and Posey*
- $\log(P) = 0.92 + 0.5\log(W) - 1.47\log(\Delta)$, *Clauter and Blandford* 1998

$\log(P) = 3.37 + 0.68(W) - \log(R)$, LANL formula

- $\log(P) = 3.00 + 0.33\log(W) - \log(R)$, *used by Russian*

Here, P is the pressure value from zero to peak in Pascals, W is the yield in kilotons, and R is the distance expressed in kilometers and degrees.

The energy release calculated from the infrasound station recordings corresponds to 1–1.5 tons of TNT. The intensity was determined by comparing observed amplitudes from data recorded at the 8 elements of infrasound stations. However, there are no infrasound stations in directions other than the source of the explosion, so measurements were not made in those directions.

PUBLICATION

УЛААНБААТАРТ ХОТОД 2024 оны 01 сарын 23 нд, ХИЙ АЧСАН АВТОМАШИНЫ ДЭЛБЭРЭЛТИЙН СЕЙСМО-АКУСТИК АНАЛИЗ

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Хураангуй

2024 оны 01 сарын 24 ны шөнө Улаанбаатарын цагаар 01 цаг 21 минут 30 секундэд БЗД ийн 26 хороонд 15 тонн хий дэлбэрсэн байна. Дэлбэрэлт нь зөөврийн хийн түлш (LPG) зөөвөрлөдөг автомашинаас анх үүсэлтэй ба нийт 20,000 м^2 талбай буюу 100 метрын радиуст хий тархаж гал авалцан дэлбэрэлт болсон байна. Дэлбэрэлтийн ойр орчимд их хэмжээний хохирол учирч тухайн үед нийт 3 хүн нас барж, олон тооны хүн түлэгдэж, 30 орчим машин техник шатаж, орон сууцны барилгад их хэмжээний хохирол учирчээ. Хохиролын хэмжээ цаашид нэмэгдсэн байна. Тухайн дэлбэрэлтээс үүссэн дуу чимээ нь агаар мандлаар тархан Улаанбаатарыг тойрсон сейсмик станцад бүртгэгдэхээс гадна хотоос баруун тийш 50 гаруй км зайд байрлах инфра авианы станцад бүртгэгдсэн байна. Уг дэлбэрэлтийн дууны долгионы сейсмик бичлэгээс *P* долгионы бүртгэсэн хугацааг 17:19:37.53 +/-0.5 (UTC) тодорхойлсон (origin mime). Бүртгэсэн хугацааг тодорхойлсоноос хойш 15 сек дараа сейсмо-акустик долгионы бүртгэгдсэн байна. Инфра авианы станцад бүртгэгдсэн акустик долгион (17:21:12.2 +/-10 (UTC сек) байх ба үргэлжлэх хугацаа нь 60 секундээс бага байв. Дэлбэрэлтээс үүсэх акустик долгион нь Улаанбаатарыг тойрсон сеймик станцуудаас цөөн хэдэд бүртгэгдсэн байна (ALFM, ULN). Анхдагч акустик долгионы зайнаас хамаарсан энергийн функцыг тооцохын тулд амплитудыг тодорхойлсон. Тухайн орчимд дэлбэрэлтийн хүчийг тооцохын тулд дууны долгионы сигнал дээр хэмжилт хийсэн ба уг хэмжилтийн үр дүнд ойролцоогоор 1,5 тнт эквивалентын хүчтэй дэлбэрэлт болжээ. Температур, салхины хурд, чиглэл зэргээс шалтгаалж, атмосфертын давхрагаар тархах акустик долгионы тархалт өөрчлөгддөг ба тархалтын замыг тодорхойлохын тулд цацрагийн аргыг ашиглан (atmospheric ray-trace) загварчилсан. Энэ дэлбэрэлтээс үүссэн долгион агаар мандлын тропосфер, стратосферын шууд болон хугарсан долгион ажиглагдсан бөгөөд тархалын хугацаа тооцоолоход хоорондоо тохирч байв. Агаар мандлын загварчлалаар ажиглагдсан тархалтын хугацааг тайлбарлахад хангалттай ба дэлбэрэлтийн сейсмо-акустик долгионы боловсруулалтын үр дүнгээр нотолсон.

1. ОРШИЛ

Монгол улсын нийслэл Улаанбаатар хотод 2024-01-23-нд шөнийн 17:19:37 цагт (UTC) хэрэглээний хий (LPG) тээвэрлэж явсан зориулалтын автомашин дэлбэрч ихээхэн хэмжээний хохирол учирсан байна (бүх цаг хугацааг ОУЦ). Уг дэлбэрэлтээс үүссэн сейсмо-акустик долгион Улаанбаатар орчим ажиллаж байгаа сейсмик болон инфра авианы станцуудад бүртгэгдсэн байна. Хагас цагийн дотор үйл явдал болж өнгөрсөн ба гол дэлбэрэлтээс өмнөх үеийн хугацааны жижиг бичлэгүүд нь газар хөдлөлтийн станцад бүртгэгдээгүй бөгөөд энд зөвхөн судалгаандаа гол дэлбэрэлтийг авч үзсэн. Гол дэлбэрэлт нь хий тээвэрлэж явсан автомашин, суудлын автомашинтай мөргөлдсөны улмаас тухайн орчинд хий алдагдснаар хийн мананцар үүсэж дэлбэрэлт (Vapour Cloud Explosion) болох үндсэн шалтгаан болжээ.

Дэлбэрэлт нь газрын гадаргуу дээр болсноор акустик долгион нь агаар мандлаар болон газрын гадаргуугаар тархан сеймик болон инфра авианы станцад хоёуланд нь бүртгэгдсэн. Гэсэн хэдий ч, дэлбэрэлт нь ойр

CONCLUSION

The combined analysis of seismic and acoustic observations demonstrated that it helps reduce uncertainties in estimating the timing and yield of the explosion.

Since the location of the explosion is known, currently used models were applied, which also facilitate a better understanding of uncertain explosions in the future.

The main results of this work are as follows:

- The origin time (17:19:37.53 ± 0.5 UTC) and the initiation time at the source were determined using the infrasound station to define T_0.
- The explosion yield estimated from recordings at the I34MN infrasound station corresponds to an equivalent of 1.5 tons of TNT.
- The acoustic waves observed at seismic stations and the infrasound network were successfully interpreted using atmospheric propagation models, demonstrating the feasibility of monitoring atmospheric explosions via their seismo-acoustic signals.
- The observed acoustic wave types included those refracted through the troposphere, stratosphere, and thermosphere. The azimuth and range functions of the acoustic waves were explained by atmospheric modeling during the explosion.