

Response to Referee #2

RC2: '[Comment on egusphere-2026-3997](#)', Shingo Watada, 21 Sep 2026

Review of “Measurement report: Geostationary satellite and ground-based video observations of cloud brightness variations triggered by the 2022 Hunga Lamb wave” by Horváth et al. submitted to EGU sphere

The authors extended the work of Horváth et al. (2025) which studied the Lamb waves from the 2022 Hunga Tonga eruption using geostationary weather satellite multiband imagery. This manuscript includes near source and far-field regional image scans for L1 and up to L4 Lamb wave arrivals, near-field and far-field surface pressure records, and ground-based videos near the source.

The brightness temperature (BT) and reflectance (R) consistently correlated with the local pressure variations positively and negatively, respectively. Second time derivatives of BT and R are always remarkably anti-correlated. This manuscript collectively documents the Lamb waves captured by the geostationary weather satellites.

One thing I would like to emphasize is the cause of the asymmetry of L1 (and all following L-waves). The Green's function of a point source in a 2D space, either on the plane or on the sphere, has a tail, unlike Green's functions in 1D and 3D spaces which lack this feature. I agree that there is a tail caused by nonlinear gas dynamics as described in Appendix A, but the tail here is a different origin. The origin of tail is $\pi/4$ phase advance of the 2D Green's function, i.e., in all frequencies, at one wavelength away or more from the source, the wave phase advanced by $\pi/4$ compared to the phase of waves traveling over a source-station distance with a constant phase speed of the wave. The phase shift typically appears as far-field asymptotic forms of the Bessel function (or the Hankel function) as $\sqrt{2/\pi k r} \cos\{(kr - \pi/4)\}$ on a plane and Legendre function as $\sqrt{2/\pi (n+1/2) \sin \theta} \cos\{((n+1/2) \theta - \pi/4)\}$. The polar phase shift $\pi/2$ is added to this initial phase $\pi/4$ at every passage of the poles (at source and antipode). L1 wave is advanced by $\pi/4$, L2 wave $3\pi/4$, L3 wave $5\pi/4$, L4 wave $7\pi/4$, so on. These phase advances are the same for all frequencies and change the waveforms to be asymmetric in time.

We thank Referee #2 for his constructive review. Our answers to the specific comments are given in blue below.

Specific comments

1) L 96 I cannot access Data S1 in the Supplement. Where is Data S1?

The zenodo archive containing the supplements was restricted. However, we provided a private link to the archive in the Cover Letter at submission. Apparently, this private link (see below) was not communicated to the Reviewers.

https://zenodo.org/uploads/20591199?token=eyJhbGciOiJIUzUxMiJ9.eyJpZCI6ImRIYWUwMmQxLTlTYTltNDBkYi04OTFiLWlzNzY5MTkxODdhNSIsImRhGEiOnt9LCJyYW5kb20iOiI2MzdjYjRiYjM4NWYwNWlzMjlmNGRiNmI3ZDc1ZjliNyJ9.VyNyjpg-KqFtpLD4Km04xa7-0BN38Z0FauhFtn-wV6Dt-B9Ag8KRRh_4XZVaMiiHUjP8kWhoXjWK7hvQQID2Cw

We have made the zenodo archive public.

<https://doi.org/10.5281/zenodo.20591199>

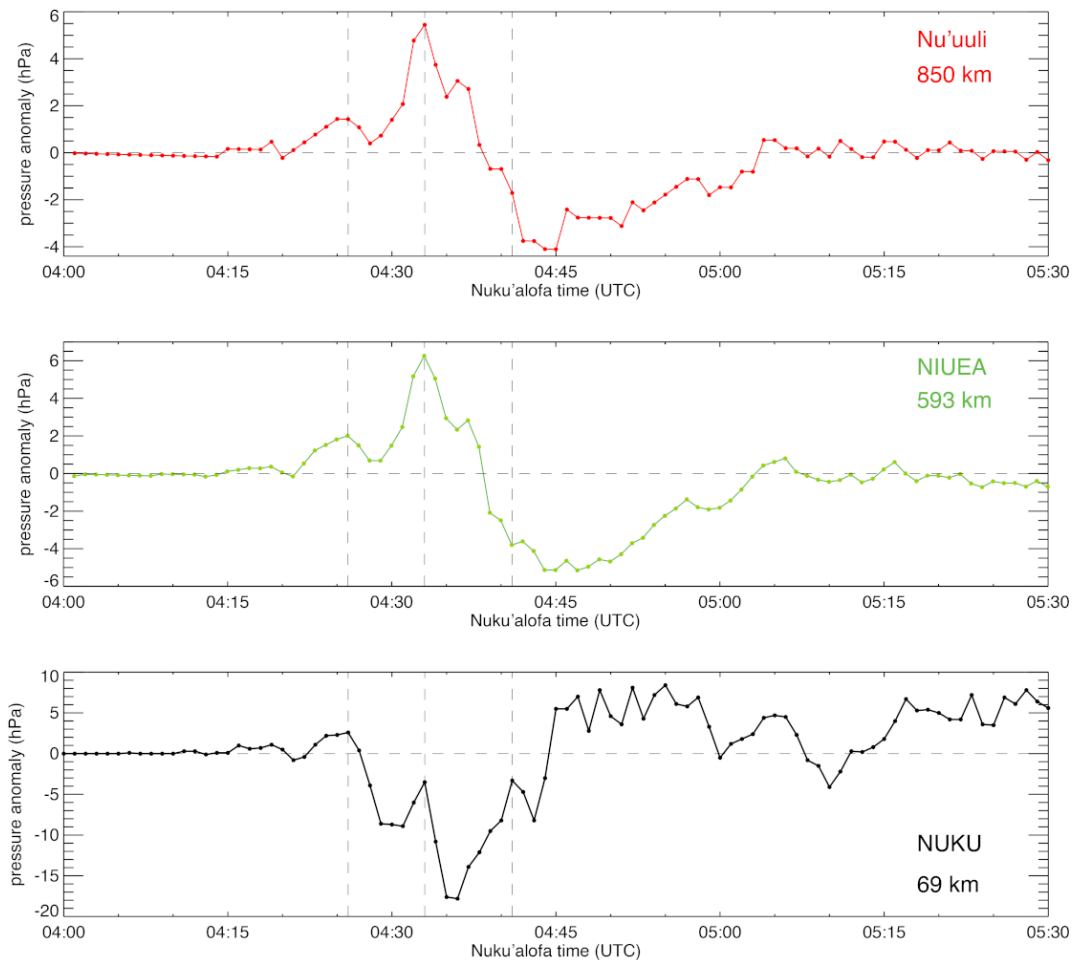
2) L 108-115 This paragraph requires corrections and the description of the initial phase shift of $\pi/4$, which I wrote in the general comment above.

We thank the Reviewer for pointing out the initial phase shift of 2D surface waves leaving a point source, which is also mentioned in Brune et al. (1961). We agree that the initial phase advance is largely responsible for the appearance of the trailing low-pressure trough behind the compressional pulse. Accounting for this initial phase shift, however, is most important when inverting the source time function and determining the exact origin time of the explosion from far-field records, which is beyond the scope of the current paper. For a relative comparison between two far-field stations, it is sufficient, in our opinion, to track the cumulative $\pi/2$ shifts from caustic passages.

In addition, the violent volcanic updrafts (with vertical speeds in the core up to 200–400 m/s in our numerical simulations), generated a significant low-pressure zone around Hunga, which dynamically altered the near-field waveforms. This is evident in the closest NUKU pressure record obtained in Nuku'alofa. The salient feature of the NUKU data (see figure below) is an 18 hPa pressure deficit. The NUKU record differs from all other L1 pressure records collected further away, which are remarkably similar and show (at least) two precursor pulses followed by the main Lamb pulse.

The figure below plots the next closest high time-resolution (1-min) data from Niue airport (NIUEA), 593 km from the source and the Nu'uuli data used in our manuscript; the barographs were time-shifted to approximately line up their precursor peaks with those of the NUKU record. Stations between NIUEA and Nu'uuli—FUTU (Maopo'opo,

Futuna, 744 km), MSVF (Monasavu, Fiji, 754 km), and AFI (Afiamalu, Samoa, 823 km)—show very similar waveforms.



To the best of our knowledge, the emergence of the 'outlier' NUKU record, including the effect of the low-pressure zone on the waveform and phase shifts, has not been explained yet. In general, the near-field wave propagation is a very challenging problem for the complex Hunga eruption, which involves convective dynamics. We have performed large-eddy simulations of the eruption with the ICON-ART (ICOsaedral Nonhydrostatic model with Aerosols and Reactive Trace gases) model, which, although being far from perfect, managed to reproduce important features of the NUKU record, including the low-pressure zone. This, however, is the subject of an upcoming paper.

The figure above also indicates that the atmospheric waveform had largely stabilized, at least for the components captured in 1-min pressure data, by the time it reached Niue and, thus, the Nu'uuli record can be considered 'far-field' for the discussion in our manuscript.

Finally, we note that an idealized, instantaneous point source might not be the best model to fully explain the atmospheric waves. Published simulations that successfully reproduced various aspects of far-field pressure records used a variety of source models. For example, Zhang, S. et al. (2025) uses an explosive point source 50 km above the surface, Zhang, J. et al. (2026) assumes an explosive point source at an altitude of 1 m, Watanabe et al. (2022) and Suzuki et al. (2023) impose a 100 K temperature anomaly of 280 km diameter over Hunga between 850–400 hPa (~2–8 km) at 04:30 UTC, while Tonegawa and Fukao (2023) argue that the Lamb wave and the coupled thermospheric waves are best explained by a finite-sized (6 km Gaussian half width), upward-moving ($W = 8$ m/s) pressure source rising between 58–70 km over a duration of 1500 s (25 min). Moreover, all these studies rely on an imposed, synthetic source, rather than one that ‘naturally’ emerges from the simulation of atmospheric thermodynamics. In sum, it’s fair to say that source size, duration, altitude, and origin time are issues far from settled.

Suzuki, T., Nakano, M., Watanabe, S., Tatebe, H., & Takano, Y. (2023). Mechanism of a meteorological tsunami reaching the Japanese coast caused by Lamb and Pekeris waves generated by the 2022 Tonga eruption. *Ocean Modelling*, 181, 102153. <https://doi.org/10.1016/j.ocemod.2022.102153>

Tonegawa, T., and Fukao, Y., Mesospheric pressure source from the 2022 Hunga, Tonga eruption excites 3.6-mHz air-sea coupled waves. *Sci. Adv.*, 9, eadg8036(2023), 2023. <https://doi.org/10.1126/sciadv.adg8036>

Zhang, J., Gao, Y., & Hu, H. (2026). Analytically-based rapid modeling of global traveling acoustic-gravity waves generated by the 2022 Hunga-Tonga volcanic eruption. *Journal of Geophysical Research: Atmospheres*, 131, e2026JD046333. <https://doi.org/10.1029/2026JD046333>

Zhang, S., Wang, R., Chen, X., Yang, Y., Dahm, T., & Hou, Y. (2025). Dispersion of Lamb waves from the 2022 Hunga Tonga–Hunga Ha'apai volcanic eruption reveals coupling between lower and upper atmospheric layers. *Geophysical Research Letters*, 52, e2025GL115294. <https://doi.org/10.1029/2025GL115294>

We have added the following paragraph to briefly summarize the discussion above and draw attention to the initial phase shift.

“Crucially, an initial phase advance of $\pi/4$ (45°) occurs for two-dimensional surface waves propagating away from a point source (Brune et al., 1961). This initial phase shift is largely

responsible for the formation of the trailing low-pressure trough behind the primary compressional pulse, and it must be accounted for when inverting the source time function from far-field records. For the Hunga eruption, violent volcanic updrafts additionally generated a low-pressure zone that dynamically altered near-field waveforms. While these near-source hydrodynamic complexities remain outside the framework of the current study, accounting for the cumulative polar phase shift is sufficient when evaluating the relative phase relationships across our barographic datasets."

3) Figure 2, Line 185-188 The pressure peak and the energy peak of L1 wave are marked at the same timing. Because the phase of L1 wave advanced by $\pi/4$, the pressure peak and the energy peak (or envelope of the entire L1 wave) arrive at different times. The difference reflects the $\pi/4$ phase advance. If you compute the envelope of entire L1 pressure wave, you will see the envelope peak is behind the pressure peak. Please label the P_{peak} and E_{peak} of L1 wave at different times reflecting the $\pi/4$ phase advance. Also, timing of L4 P_{trough} , E_{peak} labels should reflect the $7\pi/4$ phase advance.

We have removed the E_{peak} labels from Figure 2 and their corresponding references in the text, as our initial interpretation was incorrect. We have kept the P_{peak} and P_{trough} labels because they simply mark the observed arrival times in the station data.

4) L 258 paroxysmal means something to start and stop abruptly and repeatedly. Do you really mean the Hunga Tonga explosion to be paroxysmal? If not, please think moving or rephrasing paroxysmal.

The explosion that produced the prominent Lamb pressure peak was variously referred to in the literature as 'climactic', 'phreatoplinian', or 'paroxysmal'. We prefer paroxysmal, because 'climactic' is too general and can easily be misread as 'climatic', although Hunga has no significant climate effect, unlike the 1991 Pinatubo eruption, and 'phreatoplinian' mainly refers to the interaction of magma and external water, not the explosion's sudden and short nature.

The APARC (2025) Hunga report, cited in our manuscript, also uses paroxysmal to describe the 15 January 2022 eruption (e.g., the term is used 10 times in Chapter 01). In general, the term is often used in papers about the Hunga event, a few examples are listed below.

Genareau, K., Paredes-Mariño, J., Cronin, S. J., Harkema, S. S., Schultz, C. J., Murphy, K. M., & Naeger, A. R. (2026). Volcanic ash affected by lightning during the Hunga 2022

eruption. *Journal of Geophysical Research: Atmospheres*, 131, e2025JD044700.
<https://doi.org/10.1029/2025JD044700>

Le Bras, R., Bittner, P., Kuśmierczyk-Michulec, J. *et al.* TIMING Analysis of the Multiple Passages of the Pressure Wave Generated by the 2022 Hunga Tonga-Hunga Ha'apai and Comparison with the 1883 Krakatoa Pressure Wave. *Pure Appl. Geophys.* 182, 1–28 (2025). <https://doi.org/10.1007/s00024-024-03507-y>

Smart, D. (2022), The first hour of the paroxysmal phase of the 2022 Hunga Tonga-Hunga Ha'apai volcanic eruption as seen by a geostationary meteorological satellite. *Weather*, 77: 81-82. <https://doi.org/10.1002/wea.4173>

5) L 261 Tongatapu is not a point but a finite area. The interchangeable use of "Tongatapu" and "Nuku'alofa" confuses readers. We know "Nuku'alofa" means a video in Tongatapu. But "Tongatapu" means an island with a width of 20 km. All "Tongatapu"s at L79, L261, L283, L238, L264, L354, L356, and L938, refer to the video recorded at Nuku'alofa. Can you use Nuku'alofa instead of Tongatapu at these lines?

Done.

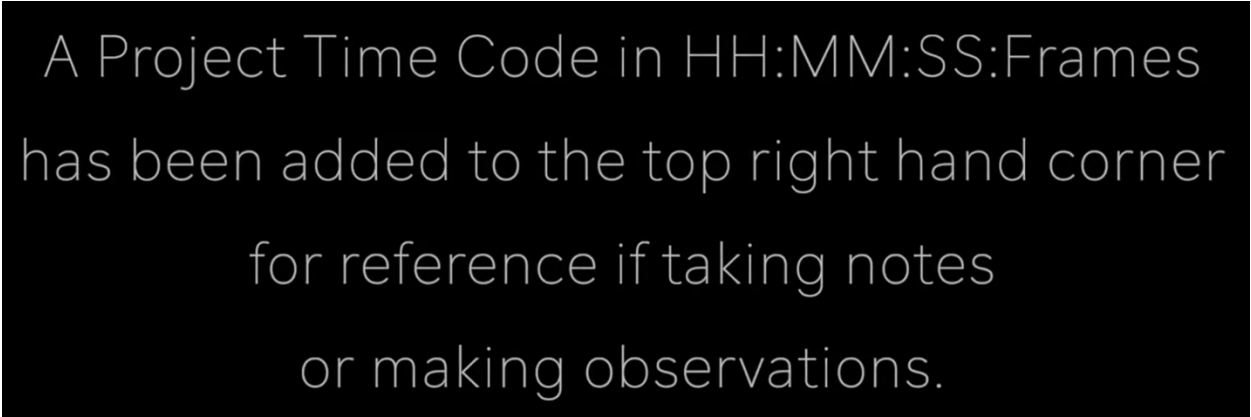
6) L 340 What are the "project times"? What does HH:MM:SS mean? since when? Does it different from video frame times in Figure 4?

The term "project time code" or "project time" is used by B. M. MacDonald (@MolisiDelmar), who recorded, cut, arranged, and time-coded the video footage uploaded to YouTube. We use the same terminology for compatibility and the precise identification of frames within this video.

The description given below the YouTube video is as follows (emphasis ours):

*"This video is for those interested in gaining more insights into the eruption. This video incudes all the video I have of the Jan 15 Hunga Tonga Hunga Ha'apai Eruption as seen from my window facing HTHH from the beginning of the eruption until the fall of the rocks and ash. Footage includes full time lapse of the Eruption's beginning until dark and additional footage shot on my phone and Canon dslr. **The footage has been arranged in a sequential manner according to camera and time as much as possible and is labeled accordingly.** I have included a little of the satellite footage of the about the same time period covered in my footage from the ground as watched it about 73 kilometre's from my lounge window. Enjoy."*

The project time is described at the beginning of the video at the 0:14–0:19 YouTube time mark, as this screenshot demonstrates (henceforth, we refer to the YouTube video time as “mark”; it’s basically the MM:SS part of the “project time”).



A Project Time Code in HH:MM:SS:Frames
has been added to the top right hand corner
for reference if taking notes
or making observations.

The project time allows the accurate determination of the relative time difference between individual frames. Absolute times, however, can only be assigned at certain points within the video and only approximately, when there is a timestamp shown. For example, at the 1:45 mark, the absolute time is given in the bottom left corner of the frame as “Circa 521pm”, i.e., ~17:21 local Tonga Time (UTC+13) or ~04:21 UTC. This is the first timestamp in the DSLR time lapse. The project time is continuous, whereas there are cuts in the absolute (local) time, because the video is compiled from several segments covering different periods post eruption.

The accuracy of the absolute timestamps is stated at the end of the video between the 19:54–20:07 mark. Specifically, the accuracy of the DSLR timestamps used in our study is given as “within a minute or two” at the 19:57 mark. It is also stated that, where possible, data points were cross referenced with the iPhone timestamps (up to a claimed accuracy of 1 minute).

Figure 4 shows a 22-s segment between video project times 00:04:46–00:05:08, as stated in the text in parenthesis. To assign an *approximate* absolute start time to this segment, we used the closest timestamp in the video, which is 05:28 pm local Tonga Time or 04:28 UTC, flashed on the screen (as 528 pm) between project times 00:04:29–00:04:36 (or YouTube time mark 4:29–4:36), i.e., 10–17 s before the start of the segment. We cannot be more precise about the absolute time, because the provided Tonga timestamps do not include seconds.

In Figure 4, we refer to the frames with their elapsed time (in seconds) since this approximate ~04:28 UTC start time. In Figure 5, however, we reference the exact video project times for the precise identification of the frames used and for the

reproducibility of this quantitative plot. The longer, 1-min segment shown in Figure 5 is approximately between 04:28–04:29 UTC.

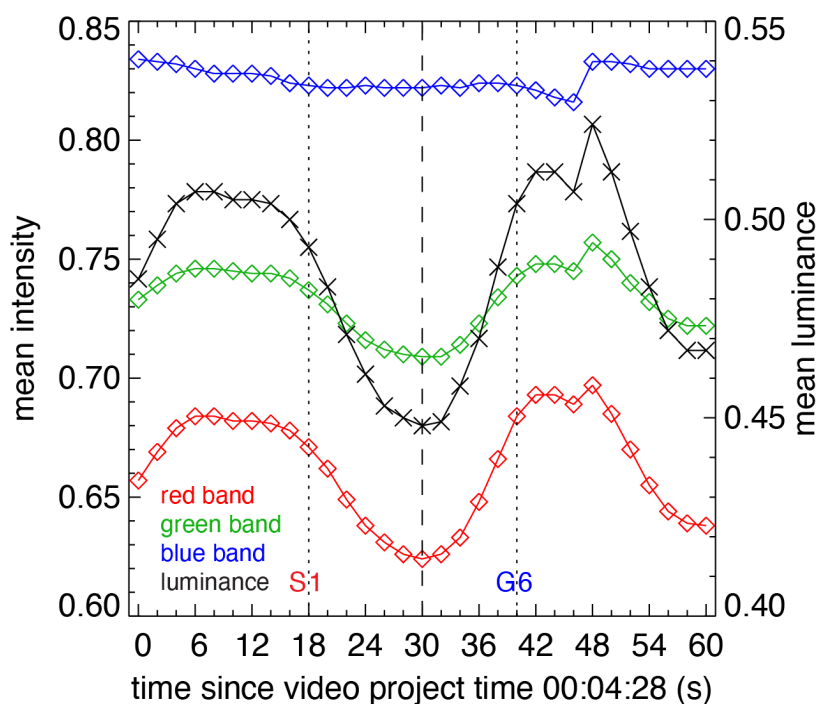
For improved clarity, in section 2.2, the description of the ground-based video, we have replaced “*local time*” with “*local Tonga Time*” when referring to the timestamps. We have also rephrased line 340 as follows:

“... (video project time 00:04:28–00:06:48, given in HH:MM:SS format, where HH, MM, and SS are the two-digit hour, minute, and second, respectively).”

One must keep in mind that this is an amateur video—not a calibrated scientific dataset—whose owner was kind enough to go the extra mile to time reference the footage, as accurately as possible, and share it with the wider community. A commendable effort.

7) L348 How does Figure 5 depict the blue (B) remain constant? I do not see blue plot in Figure 5.

Because the blue band intensity remained nearly constant, it was omitted from the original Figure 5. We have added the blue band to the revised figure shown below.



8) L353-354 "which reached Tongatapu a few minutes later at ~04:33 UTC" confused me. The Figure 4 caption says that "camera in Nuku'alofa Tongatapu" indicating Nuku'alofa and Tongatapu are at the same location. Please describe the detailed location information of Nuku'alofa within the Tongatapu Island to avoid confusion among readers.

As indicated in our answer to 5), we have replaced Tongatapu with Nuku'alofa throughout the manuscript. In the Figure 4 caption, we have deleted Tongatapu and added the geographic coordinates of Nuku'alofa in parenthesis.

9) L355 "at 05:07–05:08 UTC (Fig 2) Considering a ~45 min travel time to Nu'uuli (assuming a phase speed of 315 m/s)" In this traveltime estimate, do you consider the phase advance of $\pi/4$ at Nu'uuli? If the wave period is short, less than one minutes, we can ignore the phase advance.

We did not consider the initial phase advance in estimating the travel time to Nu'uuli and assumed an average phase speed of 315 m/s. The apparent phase speed derived from barograph records or satellite images varies with azimuth, distance from source, the stations used, as well as the time resolution of the input data (1-min vs. 10-min). The published range of speed estimates is 288–325 m/s, the slowest speeds observed around Japan. For example, Matoza et al. (2022) estimated 300 m/s, Díaz and Rigby (2022b) derived 309 m/s, and Wright et al. (2022) obtained 318 m/s from the closest NUKU pressure observations.

We also derived apparent phase speeds from the 1-min GOES-17 MESO images, which cover the backazimuth range of 330°–360° and 0°–70° and include Nu'uuli. These speed estimates vary between 310–327 m/s, depending on azimuth. In the direction of Nu'uuli, our estimate is ~315 m/s. Over the CONUS, satellite- and barograph-based regional speed estimates for 15 January are significantly higher, 325–365 m/s, due to the effect of strong winds. However, this is beyond the scope of the current work and will be discussed in a future paper.

Gusman and Tanioka (2025) applied a multiple time window inversion method to estimate the source time function of the Hunga Lamb wave, using barograph data. They emphasized that the closest NUKU pressure data were excluded from the inversion, because "*the Lamb wave propagation process in the near field is too complex.*" They performed the source time function inversion for Lamb wave speeds of 288–325 m/s and found little sensitivity to the assumed speed. Their final result assumed a speed of 320 m/s and indicated a main explosion starting around 04:15–04:20 UTC, ending at 04:30 UTC.

Given the still not fully understood near-field complexity and the uncertainties in the phase speed estimates, the Nuku'alofa video timestamps, the effect of winds, and the exact time of the main explosion, we think assuming a 315 m/s apparent phase speed to Nu'uuli, which is at least anchored in local satellite images, is adequate for the level of discussion in a Measurement report.

Nevertheless, we have introduced more uncertainty regarding the timeline in the first two sentences of this paragraph:

*"The cloud fluctuations captured by the Nuku'alofa video around ~04:28 UTC **appear unrelated to** the primary Lamb pulse, which **likely** reached the city a few minutes later at ~04:33 UTC. Instead, **these variations were probably driven** by the lower amplitude precursor observed in the Nu'uuli pressure trace at 05:07–05:08 UTC (Fig. 2)."*

We have also revised the last sentence of the paragraph to explicitly note the limitations of this approximate timeline:

"When interpreting this approximate timeline, several limitations must be noted: the video timestamps are accurate only to within 1–2 minutes, and uncertainties exist regarding both the phase speed estimates and the exact origin time of the main explosion (e.g., Díaz and Rigby, 2022b; Matoza et al., 2022; Gusman and Tanioka, 2025; Wright et al., 2022). Moreover, a precise calculation requires explicitly accounting for the initial phase advance."

"Gusman, A. R., and Tanioka, Y. Atmospheric Lamb wave inversion from the 2022 Hunga Tonga–Hunga Ha'apai eruption for tsunami prediction. Geosci. Lett. 12, 32 (2025). <https://doi.org/10.1186/s40562-025-00404-7>"

Finally, we have introduced more uncertainty in the first sentence of the subsequent paragraph.

*"The arrival of the primary Lamb pulse **is likely represented** in the video between project times 00:07:25–00:07:37."*

Nevertheless, we still infer that this specific video segment captures the arrival of the primary Lamb pulse, as both the loudest audible boom and the largest pressure increase occur within this period.

10) L429 Where is Supplement Animation 1?

See our answer to 1).

11) L429 "channel 2 reflectances" What is the wavelength of channel 2 of GEOS-17 ?

This information is already provided in Section 3.1.2; nevertheless, we have repeated it here for clarity. The GOES-17 channel 2 is the 0.64- μm visible red band.

*"Supplement Animation 1 shows channel 2 (**0.64- μm visible red band**) reflectances at full resolution (0.5 km) from 04:00 UTC until sunset at 05:59 UTC."*

12) L495 Again where is Supplement Animation 2?

See our answer to 1).

13) L798-799 "trough-peak-trough sequence" L4 wave has a $3\pi/2$ wave advance relative to the L1 wave. Please remember that the L1 wave has a $\pi/4$ advance in all frequencies so the shape of L1 wave not time symmetric, even for a simple point source. Therefore, L4 wave phase advanced $7\pi/4$ which makes the waveform "trough-peak-trough sequence" asymmetric in time.

Here and in Figure 14, we present the BT", R", and the pressure anomalies that were actually observed at Santa Barbara. The Hunga eruption was not a pure, single pulse, it had at least two smaller precursor pulses, which also affected the final, emergent signal. There are other complicating factors, such as dispersion and accumulated wind effects. The source might not have been symmetric either, e.g., a fast rise followed by a slower decay. It is not our intention to invert a source function that explains all observed wave passages. The focus rather is on connecting the measured pressure fluctuations with the measured BT and R fluctuations.

Nevertheless, here and in Section 2.1, we have refined the description of the observed L4 waveform as follows:

*"... the L4 waveform is characterized by **a small peak followed by a trough-peak-trough sequence** ..."*

14) Figure 14. Current timing of P_trough and P_peak labels are as if the waveforms are symmetric in time. These L4 wave should reflect $7\pi/4$ phase advance so the waveforms are not symmetric in time, but the phase advance $7\pi/4$ is difficult to be noticed in the Figure 14.

As discussed above at 13), this figure plots the actual pressure anomalies at Santa Barbara and the observed arrival times of the dominant troughs and peak. We mark these pressure arrival times to help interpret the corresponding BT and R variations.

15) L881 The climatic eruption phase of the 1991 Pinatubo volcano unrest continued for at least a few hours (e.g. Watada and Kanamori 2010). The prolonged source time function with a lower source intensity makes the detection of L2 and L3 waves difficult compared to the 2022 impulsive Hunga Tonga source.

We have addressed this point by adding the following sentence to the manuscript:

"In addition, the longer duration (≥ 2 h) and lower intensity of the 1991 Pinatubo explosion make its Lamb waves more difficult to detect than those from the impulsive Hunga source (Watada and Kanamori, 2010)."

Citation: <https://doi.org/10.5194/egusphere-2026-3997-RC2>