Short Communication

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An Estimate of the TNT-Equivalent Net Explosive Quantity (NEQ) of the Beirut Port Explosion Using Publicly-Available Tools and Data

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Abstract: Publicly available video recordings of the explosion in Beirut on August 4, 2020, were examined and from them it was possible, in conjunction with the well-known Google Maps website, to obtain estimates for the locations of the observers' cameras with respect to the blast, and estimates for the blast wave arrival time. A publicly-available blast wave calculator was then used to estimate the size of the explosion in terms of the equivalent quantity of TNT that would produce the same blast wave arrival time at the observers' distance. This work estimates the Beirut explosion to have been equivalent to 637 tons TNT, with a lower bound estimate of 407 tons and an upper bound estimate of 936 tons.

Keywords: Ammonium nitrate · Beirut · Blast

1 Introduction

In August 2020, a fire and explosion occurred in a dockside building in the Port of Beirut. Soon after, it became apparent that a large quantity (estimated at 2750 tons) of ammonium nitrate had been stored in the building, and it was determined that this was the material that had exploded. In this respect, the Beirut explosion is similar to another event that occurred in Toulouse on 21st September 2001 [1], though in that case ~300 tons of ammonium nitrate were stored. Unlike the Toulouse explosion, however, there are several videos of the Beirut blast circulating, and this most likely because many observers were already filming the preceding fire, and so had cameras running at the instant of the explosion.

Kingery & Bulmash [2] collated experimental data from TNT test firings, which have since been compiled into useful blast parameter calculators. Several such calculators exist, for example, the CONWEP programme (which has been in use since 1992); or, more recently, UN SaferGuard [3] web-based calculator. In all of these tools, basic operation allows the user to enter a charge weight and range to blast, and the calculator then produces data, based on the original TNT experiments, for the shock wave parameters, such as the peak overpressure; impulse; shock wave velocity; and shock arrival time. CONWEP has additional flexibility, to allow the user to input two different shock parameters, from which the remainder can be found: for example, one can enter a peak overpressure and charge size, and the software then determines the range at which that pressure would be experienced.

Here we describe some approximate methods by which the evidence from such videos may be used to estimate the range of the observer from the blast at the port, the shock wave arrival time. These estimates can be used in conjunction with a suitable blast wave calculator to estimate the TNT-equivalent explosive charge size of the Beirut explosive event.

2 Experimental

2.1 Estimating the Position of the Blast

The position of the centre of the blast is not easily estimated, mainly because the development of the explosion within the storage building was complex and unobserved. It is therefore not clear from which point the explosion began, nor its direction, nor when full detonation had been achieved. In this paper, it is therefore assumed that the centre of the blast is taken as the geometric centre of the building known to contain the stored ammonium nitrate. Google Maps has a useful feature which displays the lat-

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itude and longitude of a user-selected point on an aerial photographic overlay on a map. Using this tool, the centre of the building, and hence the assumed centre of the blast, is (33.901434 N, 35.518966E).

Visual analysis of publicly-available video evidence can be made using one of the many video player applications freely available, and in this work, the application 'Avidemux' (https://avidemux.org/) was used because it has a convenient time-from-start display calculated from the video frame rate, and allows extraction of the audio track for separate examination.

2.2 Estimating the Position of the Observer

The observer's position can be found using details seen in the video records. For example, one video, referred to here as '1TRiSng', shows a viewpoint from the passenger side of a car travelling along a road, initially with the fire at the port facility visible in the distance. The 'Street View' feature in Google Maps allows roadside features seen on the video to be identified clearly, thus fixing the position of the car in this case. An example of this is given in Figure 1, showing a frame from the video at ~0.5 seconds prior to the explosion, next to a Google Street View image looking north from the corresponding location on highway 51 in Beirut. These images show good agreement in fixed details such as the apparent angle of the tall building in the distance adjacent to the site of the blast; a street sign and bush; and, the grassy region adjacent to the road. This information can

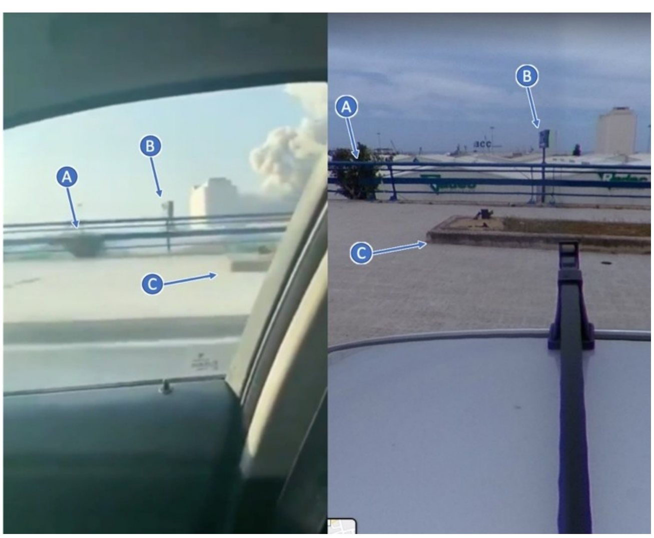

Figure 1. Left: Still image from the 1TRiSng video, showing the view from the moving vehicle window ~0.5 s prior to the initial explosion flash. Right: Google Street View of a position on highway 51 in Beirut, approximately 50 m north west of the Zuhair Murad Building. Common features such as the bush (A), street sign (B) and end of raised grassy area (C) corroborate the location in the video with the position seen on Google Street View.

fix the position of the car at position (33.896351 N, 35.518557E) at the instant of the explosion, with a small uncertainty of $\pm$10 m.

Note that the car is in motion during the '1TRiSng' video, and so this could be a source of uncertainty in the position estimate. However, assuming a road speed of approximately 20 ms^{-1} (~45 mph or 72 $km\,h^{-1}$), and taking a shock arrival time of ~1 second (which will be discussed later) the car had likely changed position along its trajectory by around 20 m during passage of the blast wave to the car. Note, however, that the road route at this position runs approximately perpendicular to the line joining the car and the explosion so that the change in car position would change the distance to the explosion only slightly.

In another video, designated 'zykkj6' the stationary observer's viewpoint is from a terrace bar and is approximately 1100 m from the blast. In this case, it was possible to identify bars and restaurants in the likely vicinity of the observer from the Google Maps view and to examine customer photographs from the publicity websites of these businesses. This allowed identification of the viewpoint, in this case on the terrace of the 'Clap Beirut Restaurant'. Again, the line of the terrace bar, in this case, runs perpendicular to the line-of-sight to the explosion, so that uncertainty in position of the observer within this bar would change the position only by a small amount.

In some videos, however, the determination of the observer's location is more subjective. For example, the early part of the 'zg9oal' video allows straightforward identification of the building from which the video was taken, in this case, an apartment building close to the Pharmacie du Quartier. Further, given a direct line of sight to the explosion, observer must have been on the north side of the building. However, the viewpoint is quite high but it is not possible to accurately determine the altitude of the observer, nor their exact position within the building. Furthermore, using the Google Maps view with the aerial photograph overlay, it is noted that tall buildings are often shown from a slightly oblique viewpoint, making it difficult to accurately place the observer at their ground-level equivalent position. These difficulties require that a larger uncertainty in range-to-explosion be assigned to this, and similar observations.

2.3 Estimating the Shock Arrival Time

The videos run from a short time before the explosion, so that the instant of the explosion can be found, limited by the accuracy of the camera frame exposure length. In most mobile telephone devices, the frame rate is 30 fps, and though the exposure time depends on the camera settings, it can be no longer than 33 ms; since detailed information of the actual exposure time is not present in all of the video records, timing uncertainty is taken here as the longest exposure time, i.e. 33 ms.

There is visual evidence for the arrival of the blast wave seen in the videos, which can be used to determine its arrival time. For example, in the '1TRiSng' video, the car window was broken by the blast wave, and glass fragments are seen. In this case, the video frame at which glass breaking occurs was taken as the blast arrival time, subject to the frame exposure duration uncertainty described above. However in other videos visual diagnostic evidence is not as clear, for example in the 'mcy28f 'video taken from a position approximately 2000 m from the blast.

The videos also contain an audio track, which can be extracted and examined using an audio analysis application, which in this work was called 'Audacity'. In this tool, the waveform of the audio track is visually represented, and the sound of the arrival of the blast wave is then clearly visible as a step change in the waveform amplitude. The 'Audacity' application allows the time since the beginning of the audio sequence to be measured, which is limited by the sampling resolution of the recording device, typically 44.8 kHz. However, selection of the portion of the wave representing the blast arrival is somewhat subjective, so that this method is less certain than the high sampling rate would imply. Furthermore, in some audio tracks, there is evidence of several distinct impulse sounds, which are potentially due to wave reflections from surfaces in the vicinity of the observer, or possibly even sampling compression artefacts. We, therefore, retain the timing uncertainty of 33 ms, as indicated for video frame timing resolution.

2.4 Distance from Observer to Blast

Once the observers positions were found, in the form of six-figure latitude/longitude grid references, a web-based tool [4] was used to find the distance from the blast centre to the observer. The estimated uncertainty in the observer position and the centre of blast position were then applied to this range to give an upper and lower estimate of observer range for each of the video observations.

2.5 Calculation of TNT-Equivalent NEQ

Given the measurements for the distance of each observer from the blast, and the shock wave arrival time relative to the instant of explosion, the UN 'SaferGuard' web-based calculator was used to calculate the explosion NEQ in terms of a TNT-equivalent charge size. Limitations of the SaferGuard tool meant that it was necessary to repeatedly calculate shock arrival times for different input charge sizes, refining the charge size required to obtain the observed shock arrival time at the observer's range from the explosion.

This iterative procedure was performed for the upper and lower estimates of distance to each observer, at the central estimates of shock arrival time, and was again performed at the central estimates of observer distance, for the upper and lower estimates of shock arrival time. This gave, for each observed record, a range estimate of TNT charge sizes that could have produced the observed arrival times at observed distances.

3 Results and Discussion

3.1 Estimates of NEQ

Table 1 summarises the estimates of observer distance. The 'Observer latitude' and 'Observer Longitude' columns allow the reader to locate the approximate observer positions using Google Maps or similar but do not include uncertainty in position. In our work, different workers provided their best estimate of position according to the methodology above, and the uncertainty in observer position is captured in the 'Estimated uncertainty in range' column. Table 2 gives the estimates of wave arrival time, including the uncertainties discussed above. Table 3 gives the minimum, maximum and central estimates of the TNT equivalent charge size for the explosion that would produce the estimated arrival time at the estimated distance.

The central estimate of blast size seems to become larger at shorter ranges to the blast. This is partly explained by the uncertainty in arrival time, which is always fixed at the inter-frame time of the recording camera. For close ranges, and consequent short arrival times, this uncertainty is pro-

Table 1. Observer's estimated position, and range to blast.

Video link	Observer location Lat.	Long.	Range to blast (m)	Error (m)
mcy82f.mp4 [5]	33.896292	35.540627	1996	10
zg9oal.mp4 [6]	33.889115	35.516197	1374	20
zykkj6.mp4 [7]	33.897752	35.507118	1168	15
xmmoa7.mp4 [8]	33.896182	35.522357	655	20
1TRiSng.mp4 [9]	33.896351	35.518557	566	10
DASH_1080.mp4 [10]	33.903115	35.523928	510	15

Table 2. Estimates of wave travel times.

Video link	Central estimat of wave travel time (s)	Min. wave travel time (s)	Max. wave travel time (s)
mcy82f.mp4	5.077	5.044	5.110
zg9oal.mp4	3.294	3.261	3.327
zykkj6.mp4	2.719	2.686	2.752
xmmoa7.mp4	1.303	1.270	1.336
1TRiSng.mp4	1.067	1.034	1.100
DASH_1080.mp4	0.917	0.884	0.950

Table 3. Estimates of TNT equivalent blast size.

Video link	Min TNT equivalent blast (kg)	Max TNT equivalent blast (kg)	Central estimate of blast (kg)
mcy82f.mp4	512,000	860,000	669,000
zg9oal.mp4	407,000	989,000	647,000
zykkj6.mp4	410,500	920,000	625,000
xmmoa7.mp4	344,000	1,068,500	632,000
1TRiSng.mp4	404,500	917,000	621,300
DASH_1080. mp4	363,500	1,028,000	630,000
Average	406,917	963,750	637,383

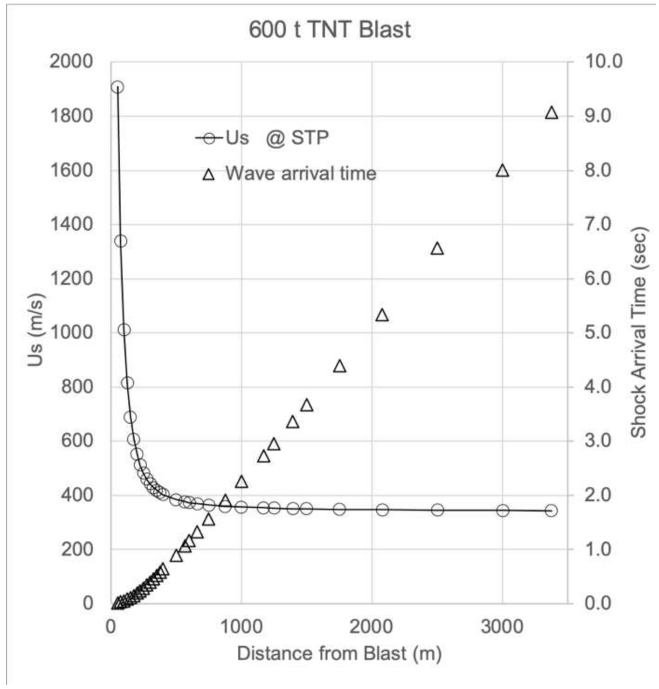

Figure 2. Calculated shock wave velocity and calculated wave arrival time as a function of range to blast, for a 600,000 kg charge size at 288.15 K and 101.3 kPa. Calculations made with the UN SaferGuard calculator.

portionally larger: for example, the frame-duration uncertainty in timing is ~3% in the '1TRiSng' record, but ~0.6% for the 'mcy82f' record.

Nevertheless, the central estimates of blast size are similar for ranges from 510 to 1168 m, being close to 630,000 kg whereas at longer ranges they are larger, and this is likely due the difference in air temperature on the day of the explosion (reported to be 30 °C at 1800 hrs), compared to the normalised temperatures used in the blast wave calculator. All calculations in this work, being based on the same base data set, are normalised to air temperature of 288.15 K.

Figure 2 shows the calculated shock wave speed from the UN SaferGuard calculator, for a 600,000 kg TNT event size. The calculated shock wave speed decreases rapidly from ~2000 ms^{-1} towards the acoustic wave speed in air of 343 ms^{-1} at ranges beyond ~500 m. It is well known that the acoustic wave speed in air increases with increasing temperature, and on the day of the explosion would be 351 ms^{-1}. This means that for the longer range observers at 1374 m and 1986 m, the blast wave propagated approximately acoustically for ~50% and ~75% of its trajectory respectively, and would have travelled more quickly than the SaferGuard calculator assumes. Hence, to reproduce the observed arrival time, it would be necessary to choose a larger charge size in the SaferGuard Calculator.

The TNT equivalence of ammonium nitrate is variously reported in the literature: Merrifield and Roberts [11] gave a figure of 56%, whereas a more detailed analysis by Braithwaite [12] revised this to a theoretical maximum of 42%.

The average of the estimates of TNT-equivalent charge size that explain the observed, blast effects calculated here to be ~637 tons, can be approximately translated into an equivalent mass of AN that contributed to the Beirut explosion. Taking the equivalence to be 42% implies that 1515 tons (or ~55%) of the 2750 tons of stored material contributed to the observed blast effects, while the remainder did not.

There is some similarity to the explosion of 2001 in Toulouse, for which the summary report [1] suggests that 40 to 80 tons of the stored AN underwent detonation and therefore produced blast effects. This corresponds to 13 to 26% of the total stored quantity of material.

In both Toulouse and Beirut, it is clear that the blast effects were less than the total stored quantity of ammonium nitrate would suggest, but that the more recent event was proportionally larger than the Toulouse event. The mechanistic reason for the discrepancy between the stored material quantity and the resulting event size is beyond the scope of this work, though theoretical study of this aspect of large-scale ammonium nitrate explosions is ongoing.

4 Conclusion

It was possible to take advantage of additional details visible in publicly available video records of the Beirut explosion, in combination with information from Google Street view and other public sources, to determine the position of the observer's camera with an accuracy of 10 to 20 m. The limited timing accuracy offered by the standard frame rate in these video records means that, although blast wave arrival times can be estimated, these must be assigned a suitably large uncertainty.

Using a blast wave properties calculator, and given the distance to blast and time of arrival information extracted from the video records, it was possible to obtain estimates for the size of the Beirut explosion in terms of an equivalent quantity of TNT. A minor limitation of the blast calculators (and similar ones based on the same data) was identified, in that these calculators assumed an air temperature of 288 K, whereas in Beirut the temperature, and hence the acoustic wave speed, was higher than assumed by the calculator.

Six independent video records, ranging from 510 m to ~2000 m from the blast, were used to make these estimates, and there is reasonable correspondence between all of them. This work estimates the explosion in Beirut as equivalent to ~637 tons of TNT, with a lower bound of ~407 tons and an upper bound of ~960 tons. This estimate is higher than but comparable to that estimated for a similar explosion in Toulouse in 2001.

Data Availability Statement

The data that support the findings of this study are openly available in the internet sources referred to in the paper.

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