Height Estimation of Hiroshima A-bomb Mushroom Cloud from Photos

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Abstract

The estimated height of the mushroom cloud that formed after the A-bomb explosion at Hiroshima has been a controversial issue for many years. In this work, we have attempted to measure the cloud height from existing photos taken at the time from airplanes and from the ground. First, we determined the precise locations where the pictures were taken. Next, we approximated the three dimensional shape of the cloud using multiple spheroids. Finally, we obtained measurements of the height and width of the mushroom cloud from the approximated cloud shape. Our experimental results suggested that the height reached a maximum of about 16 km.

Introduction

In 1945, the atomic bomb dropped on Hiroshima caused extensive damage. To this day, many people continue to suffer from sequelae related to the event. The affected area has not been specified accurately. There are numerous radiation victims who have never received compensation for their injuries. A weather simulation of the rainfall patterns has been performed in the region where Black Rain fell from the mushroom cloud. In fact, the region estimated by the simulation is narrower than the actual affected area (Maruyama and Yoshikawa 1987). This discrepancy comes from an incorrect presumption of the mushroom cloud height.

So far, various attempts have been made to determine the height of the mushroom cloud. We have estimated the cloud height and width using a technique called synthetic analysis (Ogawa *et al*. 2010). However, in their work, the height was estimated only by visual inspection and quantitative evaluation of the accuracy was not discussed. In this paper, we have estimated the height and width of the mushroom cloud using geometric camera calibration methods. Camera parameters such as the position and the focal length have been determined from the coastline or the horizon. Subsequently, we have approximated the shape of the mushroom cloud and have obtained the height and the width of the cloud.

Target Photos for Analysis

After the atomic bomb was dropped, many photos of the mushroom cloud were taken for various purposes. Several photos that exist to this day portray various cloud features. To perform a meaningful analysis using these photos, the precise location of the camera viewpoint

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is needed in each case. To estimate the point where each photo was taken, geographical features can be used as a means to find the specific locations. Among these features, we have used coastlines, horizontal lines and ridgelines of mountains as clues. We have acquired the geographical features of coastlines from maps and aerial photos taken around the time of the event. Some of our analysis has relied on matching features of the coastline in a photo of the event to the features of the coastline in a control photo. The horizon alone cannot be used as a clue to determine camera position. However, the horizontal line of the horizon can be used as a constraint on the elevation angle so that the horizontal distance from the viewpoint to the hypocenter can be estimated from the photography altitude and the field of view. In addition to these clues, it is necessary that the top of the cloud is included in the photo under examination. There are a limited number of photos that satisfy all of these conditions and can be used to analyze the dimensions of the mushroom cloud. The target photos for our analysis that contain the characteristics mentioned above are listed as follows.

Photos in which coastlines appear

The images in which coastlines appear are shown in Figure 1. The coastline near Kurahashi Island is shown in the Figure 1 (a) and the coastline near the city of Hiroshima is shown in Figure 1 (b). In these cases, the camera position can be estimated by calculating the relationship between the coastline in the photo and the coastline on the map or the aerial photo.

Photos taken with known altitude

These are images that have no clues specifying the location, yet the horizon is clearly indicated and the altitude is known, as shown in Figure 2. These photos were taken from the airplane that followed the bomber Enola Gay, which dropped the atomic bomb. Testimony about the altitude at the time of the photography was obtained from the photographer. From this testimony, the horizontal distance between the hypocenter and the airplane has been estimated.

Photos in which the mountain ridge appears

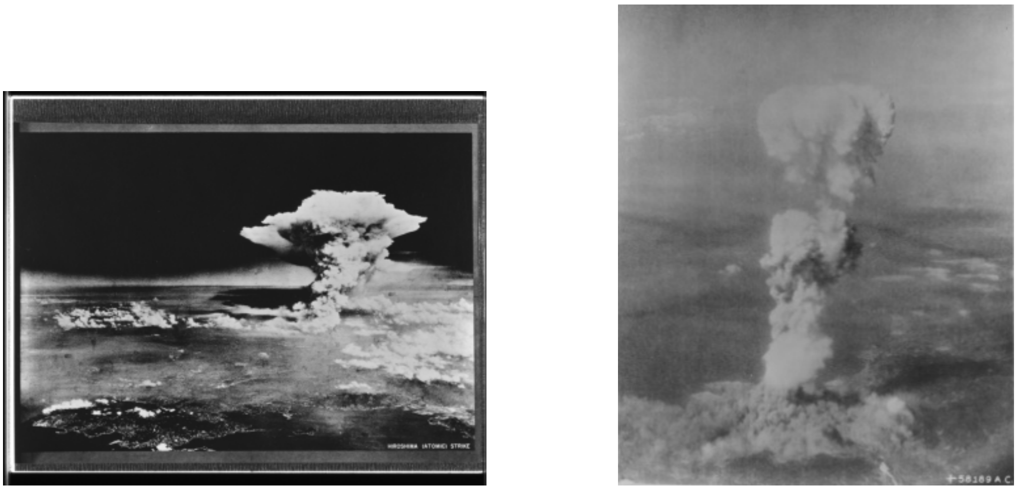
It is difficult to analyze photos taken from the ground because these contain few visible clues to use as a means to estimate the viewpoint. However, there exists an image of the event with a mountain ridge visible in the foreground, as shown in Figure 3. It is possible to use the mountain ridge as a means of comparison to estimate the location of the photo.

Viewpoint Estimation

In this section, we describe the procedure for estimating the viewpoint of the photo of the event. This piece of information is the first stage in estimating the shape of the mushroom cloud.

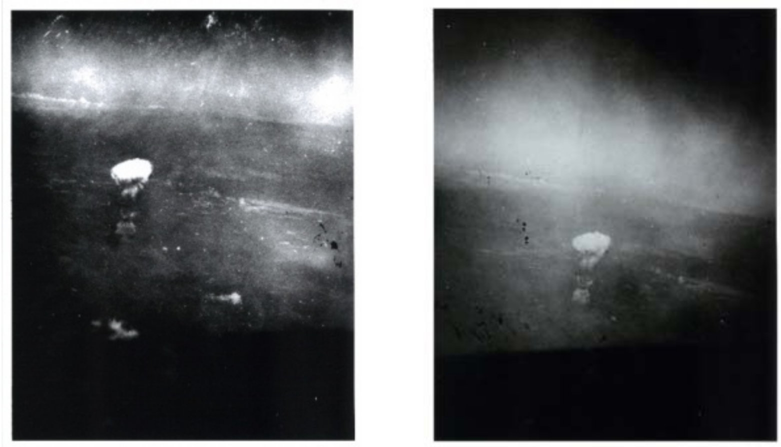
Viewpoint estimation by aligning the coastline

To estimate the cloud size using coastline images, we have acquired corresponding points on the coastline in the image and on the map as feature points. For these feature points, we have obtained the correspondence using the Iterative Closest Point (ICP) method (Besl and McKay 1992). Subsequently, we calculated the homography matrix between corresponding feature points, as shown in Figure 4. We then estimated the position and the focal length of the camera used to take the photos.



(a) Around Kurahashi Island. (b) Picture of Hiroshima bay.

Figure 1 Photos in which a coastline appear.



(a) (b)

Figure 2 Photos in which a horizon appears.

Figure 3 Photo in which a ridge line appears.

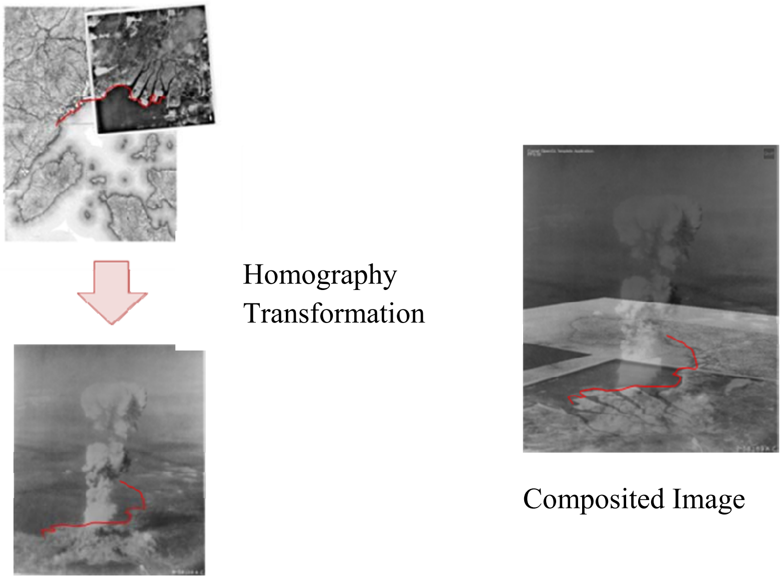


Figure 4 Viewpoint estimation using a homography matrix.

Estimation of horizontal distance from photos of known altitude

As seen in Figure 2, the coastline is not clearly visible, so the estimation method described above could not be used for these photos. Such images lack any clear geological clues, so it is difficult to estimate camera viewpoints. Because information in these pictures is insufficient for making estimates, the key information about the location of the camera comes from the altitude at which the photo was taken. Using the altitude as a constraint, we have estimated the horizontal distance from the hypocenter, rather than the position of the viewpoint.

Mr. Gackenbach, the photographer of the images in Figure 2, gave the following testimony regarding the conditions at the time.

1) The photos were taken approximately one minute after the explosion.
2) The altitude was about 30,000 feet (~9.144 km).
3) The camera used for photo was an "Agfa 620".

Agfa is the make of this German camera and 620 represents the type of film. The Agfa 620 film apparently corresponds to the PB20 model, shown in Figure 5. The focal length of this camera is 105 mm and the film size is 56 × 84 mm.

It turns out that this aspect ratio does not match that of the Figure 2 images. Hence, we have assumed that these photos have been trimmed from their original size. Figure 6 depicts the same image as in Figure 2, except scanned from the original. The image size of this photo is 413 × 605 mm, corresponding to an aspect ratio of about 1:1.5, which matches the size of the original photo before cropping. From this information, the vertical angle of the camera can be calculated as

$$2 \times \arctan((84 / 2) / 105) \approx 43.6 \text{ [deg]} . \quad (1)$$

Since the photos shown in Figure 2 were taken with the same camera, the same correction has been applied to each of these photos in estimating the horizontal distance. We have incorporated these geometric constraints in the estimation of the distance from the hypocenter.

To summarize, because clues such as the coastline are not visible in these images, we have estimated the viewpoints based on information about the camera's focal length, the location of the horizon, the location of the root of the cloud, and the altitude. Since there is no information about the camera direction that can be gathered directly from the photos, we have estimated the horizontal distance from the hypocenter rather than the viewpoint.

That estimation has been made based on information obtained from testimony of the photographer, as well as the images themselves. The constraints are listed as follows.

1) The center of the explosion lies on the straight line connecting the viewpoint and the root of the cloud.
2) The surface of the earth determines the plane consisting of the viewpoint and the horizon.
3) The altitude is 9.144 km.
4) The field of view is approximately 43.6 degrees.

From this information, we have estimated the horizontal distance from the hypocenter by minimizing the following equation.

$$\arg\min_{v} \left| \frac{(\mathbf{l} \times \mathbf{r}) \cdot (\mathbf{e} - \mathbf{v})}{\|\mathbf{l} \times \mathbf{r}\|} - R \right| \quad (2)$$

where ***v*** is the position of the viewpoint, ***l*** is the vector to the left point of the horizon, ***r*** is the vector to the right point of the horizon, ***e*** is the center of the earth, and *R* is the radius of the earth. Figure 7 summarizes the estimation procedure.

Figure 5 Agfa PB20

Figure 6 Original photo of Figure 2(a) before trimming.

Estimation using the viewpoint and the location of the mountain ridge

The image in Figure 3 contains no information about the coastline or the horizon. Thus, the previous estimation methods cannot be used to estimate the viewpoint. However, the photo has a distinctive landscape near the coast and a mountain ridge that can be used to determine the location of the photo.

An image of the present coastal landscape in the direction of the hypocenter, obtained from the Japan Coast Guard Academy in Kure, is sufficiently similar to the photo of the event. We have compared these images and are convinced that the photo of the cloud was taken from the Kure Japan Coast Guard Academy, where the Kure Naval Arsenal was located at that time.

In addition, we obtained information about the camera. This was a Leica with Elmar F3.5

lens of focal length 50 mm; the film size was 24 × 36 mm.

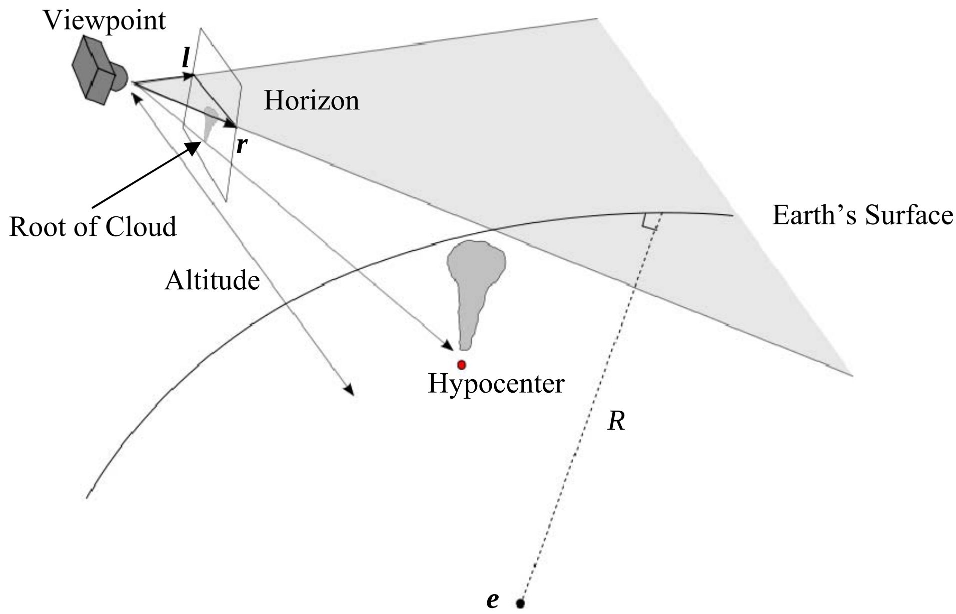


Figure 7 Estimation of the viewpoint for the photo in which the horizon appears.

Shape Estimation of the Mushroom Cloud

In this section, we describe a method for estimating the shape of the cloud, including its height and width, based on the estimated viewpoints. Typically, to obtain a three-dimensional shape, reconstruction techniques using multiple images (McLauchlan, 2000; Dellaert *et al.*, 2000) must be employed. However, because the shape of the mushroom cloud must be obtained from just one image, we have used a technique involving multiple spheroids to approximate the shape of the cloud and have subsequently determined the height and width of the cloud.

Approximation of the area of the cloud using ellipsoids on the image

We have extracted an approximate cloud image by fitting ellipsoids in the zone of the cloud. As shown in Figure 8, we have fitted ellipsoids in various regions of the cloud for regions above a certain threshold in diameter. The procedure is as follows.

5) Determine the ellipsoid containing the largest area that is not enclosed in other ellipsoids.
6) Remove the ellipsoid area from the object region.
7) Repeat the procedure until the area not included in the ellipsoid is below the threshold.

Estimation of the position and shape of the spheroids

We have estimated spheroids in three-dimensional space corresponding to the ellipsoids that were obtained in two-dimensional space. We have assumed that spheroids in three-dimensional space are projected in two dimensions as ellipsoids that approximate the area of the cloud. The silhouette of the spheroid is defined by the viewpoint and the ellipsoid, as shown in Figure 9. The projection plane is defined by the direction of view and the hypocenter.

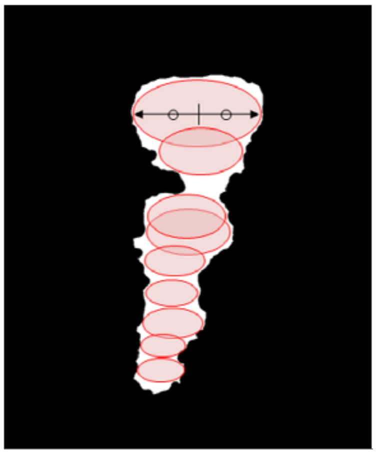


Figure 8 Estimation of the ellipsoids in the cloud region.

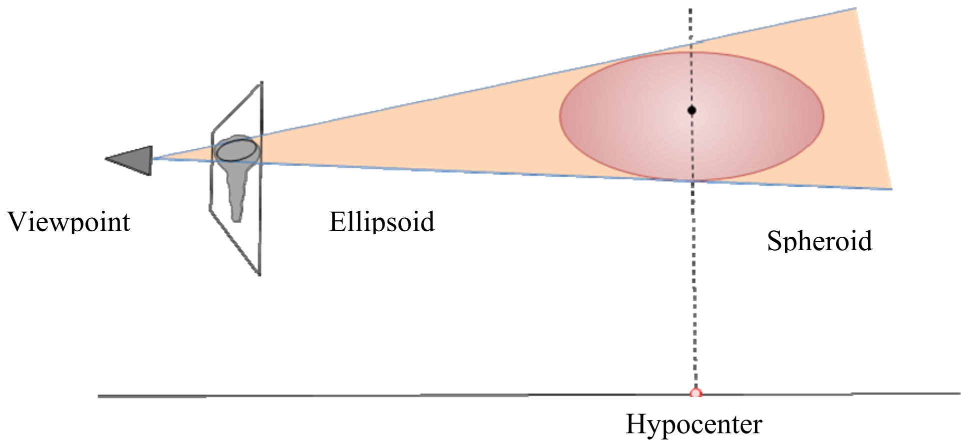


Figure 9 Estimation of the spheroids from the ellipsoids and the viewpoint.

Analysis Results

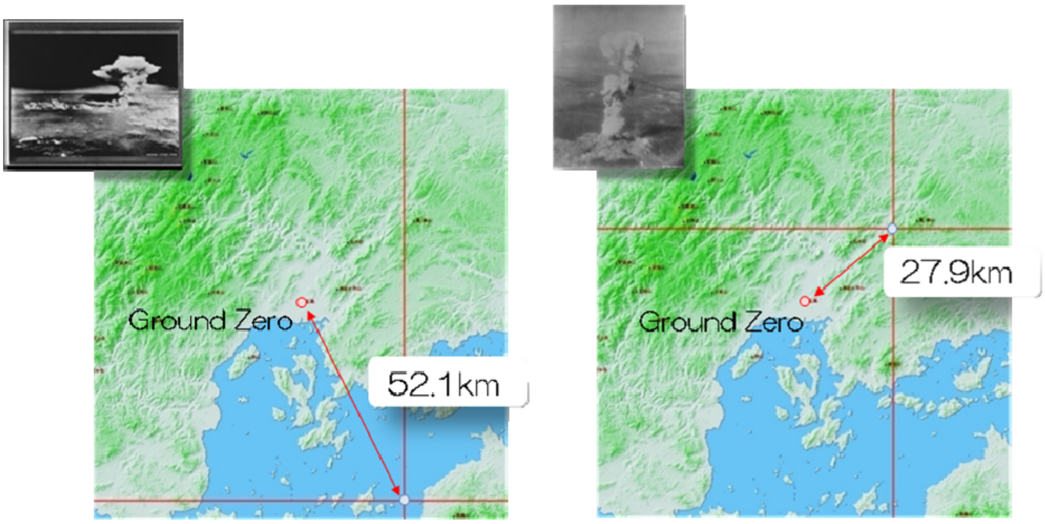
In this section, we discuss our results. First, the results of the estimated viewpoints obtained from the photos are presented. Then, we show the results of the shape estimation of the mushroom cloud, including the height and the width of the cloud.

Viewpoint estimation results

For those photos with visible coastlines, we have estimated the position and focal length of the camera by aligning coastline features in the photo with those on the map. For the photos taken at a known altitude, we have estimated the horizontal distance from the hypocenter. For the photo containing a mountain ridge, we have identified the location where the image was taken by comparison with recent photos of the region.

Estimated results for the photos in which coastlines appear

First, we estimated the position and focal length for the images containing coastlines by aligning the photo and the maps. Largely because of the age and quality of these photos, the coastlines are not clear, so it is difficult to extract the coastlines automatically by using techniques such as segmentation or edge detection. Therefore, we have extracted the coastlines by visual inspection.



(a) (b)

Figure 10 Estimated results of viewpoints and distance from the hypocenter.

We have made corresponding points using the ICP method and have estimated the viewpoint and the focal length. Table 1 shows the results of the viewpoint estimation. The locations of the viewpoints are depicted in Figure 10 as the point where the red lines intersect. The viewpoint for Figure 1 (a) is estimated to be near Nogutsuna Island in Matsuyama, Ehime Prefecture. Furthermore, we know that the image in Figure 1 (b) was taken from the north-east of the hypocenter.

Table 1 Viewpoint estimation results of Figure 1.

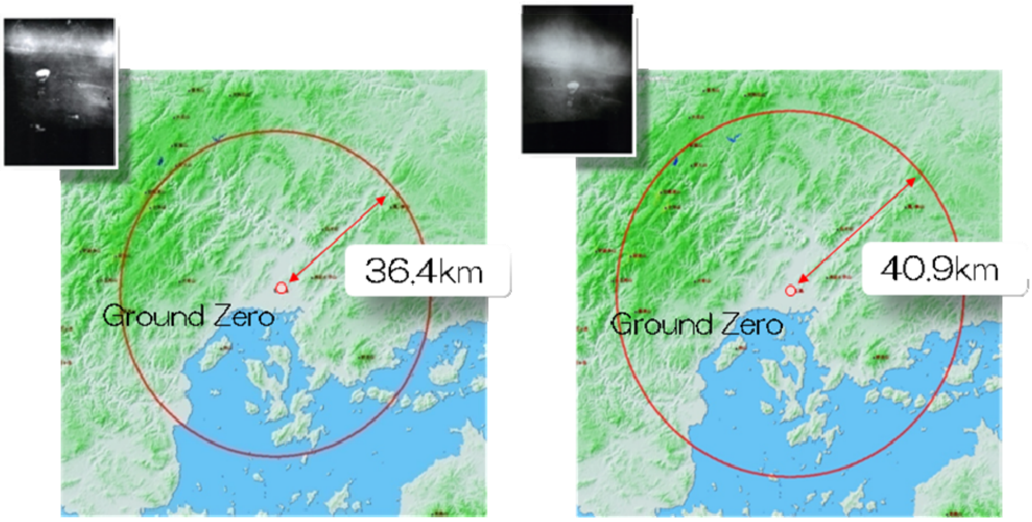
Photo	Fig. 1 (a)	Fig. 1 (b)
Distance from hypocenter in direction of North and South [km]	45.7 South	17.6 North
Distance from hypocenter in direction of East and West[km]	24.9 East	21.6 East
Distance [km]	52.1	27.9
Altitude [km]	8.6	8.1

Estimated results using the photography altitude

Using the geometric constraints given by the known altitude, we present the estimates obtained from photos shown in Figure 2. From the position of the cloud base and the height of the horizontal line on the image, we have estimated the horizontal distance from the hypocenter. Table 2 shows the estimated results of the horizontal distances. These results are shown in Figure 11. Because it is not possible to obtain exact viewpoints, the distance from the hypocenter is represented as a circle in Figure 11.

Table 2 Viewpoint estimation results of Figure 2.

Photo	Fig. 2 (a)	Fig. 2 (b)
Distance [km]	36.4	40.9
Altitude [km]	9.1	9.1



(a) (b)

Figure 11 Estimated results of viewpoint and distance from the hypocenter.

Estimated results for photos with mountain ridges

Presented here are the results of the estimated viewpoint for the mountain ridges contained in the image shown in Figure 3. Although the location of the photo had been uncertain, we have obtained information that leads us to believe that the photo was taken at the Japan Coast Guard Academy in Kure. We took photos from that same location using a digital camera. The camera has an image sensor of area 24 × 36 mm and a lens with a focal length of 50 mm. Figure 12 shows a composite of the image of the event and the photo taken from Kure. As is evident in the picture, an adequate superposition of the landscapes has been obtained. Figure 13 shows the location and the distance from the hypocenter on a map. The horizontal distance obtained from the comparison of the images is shown in Table 3. Regarding the altitude, we have assumed that the photo was taken at a height of about 2 m.

Figure 12 Composite image.

Figure 13 Estimated results of viewpoint and distance from the hypocenter.

Table 3 Viewpoint estimation results of Figure 3.

Photo	Fig. 3
Distance [km]	17.7
Altitude [km]	0.0

Estimation of the shape of clouds

Using the focal length and the viewpoint, we have obtained a three-dimensional shape of the clouds. The height and the width were then estimated using this three-dimensional shape. In addition, we have divided the three-dimensional space into voxels and produced the corresponding surfaces using the Marching Cubes method (Lorensen and Cline 1987). We have divided an area of 50 × 50 km^2 around the hypocenter into voxels of size 0.1 km.

The results of the synthesis for the reconstruction of the shape of the cloud in Figure 1 are shown in Figures 14 (a) and (b). The generated shapes for the images in Figures 2 (a) and (b) are shown in Figures 14 (c) and (d) respectively. In addition, we show the synthesis of the results for the photo of Figure 3 in Figure 14 (e).

The approximated values for the cloud height and width are summarized in Table 4. The height of the cloud in Figure 1 (a) is estimated to be about 16 km. This largely exceeds the 8 km that was previously assumed. For the photos in Figure 2, the height is estimated to be about 5 km, much less than the results for the images containing the coastline. Assuming that the height of the mushroom cloud increases in monotonically, these images are of the mushroom cloud taken soon after the atomic bomb was released. Testimony exists that the mushroom cloud was initially one mass and then separated into two parts. However, as seen in these images, it is clear that this cloud is only one mass and the photos were taken just after the bombing.

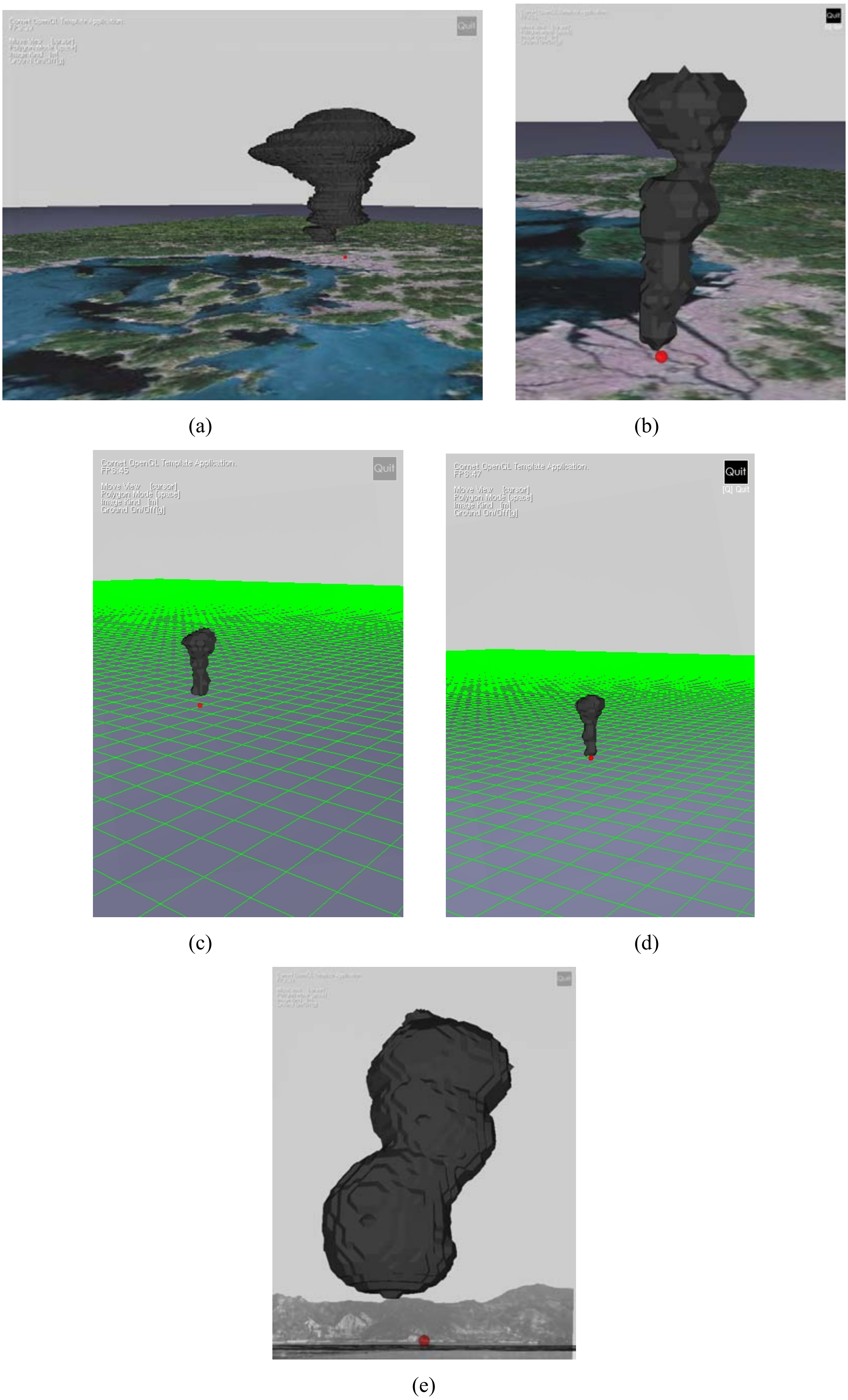


Figure 14 Results of reconstruction of the clouds.

Finally, we mention briefly measurement errors. Generally speaking, the estimated values include some errors. However, it is difficult to evaluate these errors because there are no true values. We evaluate the range of the estimated values by adding Gaussian noise to all feature points for the estimation. Figure 15 summarizes 95% confidence levels of the estimated heights.

Table 4 Summary of the estimation results.

Photo	Fig. 2 (b)	Fig. 2 (a)	Fig. 1 (b)	Fig. 3	Fig. 1 (a)
Height [km]	4.5	4.9	7.8	11.6	15.7
Width [km]	2.1	2.2	3.1	5.6	15.5
Distance [km]	40.9	36.4	27.9	17.7	52.1
Altitude [km]	9.1	9.1	8.1	0.0	8.6

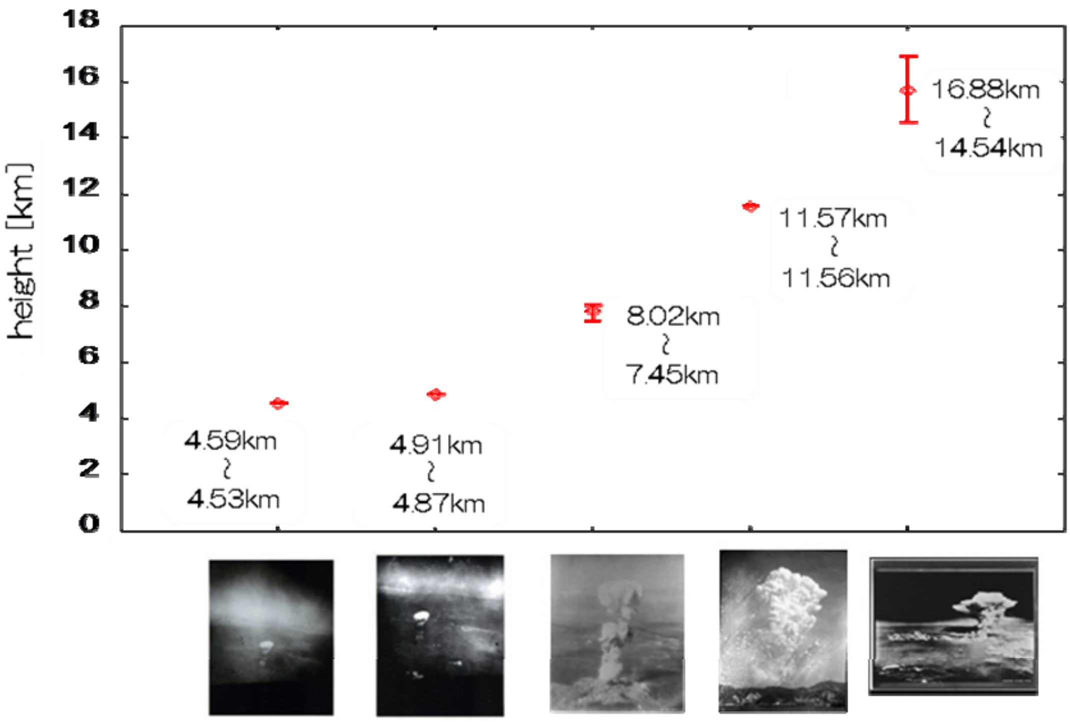


Figure 15 Summary of the 95% confidence level of the estimated heights.

Conclusion

In this paper, we have estimated the shape of the mushroom cloud that formed after the atomic bomb was dropped on Hiroshima in 1945 and have estimated the height of the cloud. We began by classifying the images of the mushroom cloud by their characteristics. We then estimated the locations where the photos were taken. For images with obvious coastlines, the photo viewpoints were estimated by performing an alignment of coastlines between the photos and maps. For photos with information about the altitude, obtained from the testimony of the photographer, we estimated the horizontal distance from the hypocenter from the set of constraints based on the testimonies and horizontal lines on the photo. For the image showing a mountain ridge in front of the cloud, we estimated the location of the viewing point by experimenting with photos taken at locations with a similar view of the mountain ridge. Using the estimated viewpoints, we approximated the three-dimensional shape of the mushroom cloud using spheroids by first finding ellipsoids in two-dimensional space and then projecting the ellipsoids onto the plane corresponding to the three dimensional spheroids. In addition, we divided the spheroids into a set of voxels, producing surfaces using the Marching Cubes method. Our experimental results have suggested that the height was at a maximum about 16 km. This largely exceeds the 8 km that was previously assumed.

Acknowledgements

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