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# The V1 (Flying Bomb) attack on London (1944–1945); the applied geography of early cruise missile accuracy

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ABSTRACT

In a 291 day period in the latter stages of WW2 (1944–45) 10,386 V1 cruise missiles were launched against the UK from ground ramps in France and Holland, and from modified He-111 bombers flying off the south and east coasts of England. The attack mainly targeted London and despite a highly effective British campaign of in-flight interception, 2420 V1 missiles (23% of those launched) made explosive impact on the London target area resulting in significant loss of life and massive damage to London's housing stock. Using data from *The National Register* of 1939 we reconstruct the target geography of London and utilising a vast body of archival data from The National Archives we also reconstruct the V1 impact geography; in doing so we evaluate the accuracy of the V1 attack. Most missiles struck near the centre of the London target in areas of high population density; 40% of the missiles fell on the County of London forming the inner core of the London Civil Defence Region containing 38% of its 1944 population in only 16% of its area. The overall Mean Point of Impact is within 3.5 km of the centroid of the County of London. V1 impact density showed similar Clarke-like distance-decay relations to population density in relation to an assumed Central London aiming point. We also determine the accuracy metrics for the V1 attack. Our results verify the idea that high-resolution accuracy is moot when missile systems with relatively low accuracy are launched against large area targets, such as large cities. Although compared to modern missile systems the V1 was "inaccurate", we find that the German cruise missile system fulfilled the operational accuracy requirements to achieve its terror and urban damage objectives.

## 1. Introduction

### 1.1. The German missile attacks on London (1944–1945)

The German missile attacks on London during the latter stages of WW2 (1944–45) were the first such attacks in modern war. The missiles deployed against London were the V1 cruise missile (also known as the Flying Bomb and colloquially as the "Doodlebug"), developed by the German Air Force, and the V2 ballistic missile (also known as the A4 rocket or the Long Range Rocket Projectile) developed by the German Army (Barber, 2017; Hölsken, 1994; Irving, 1964; Pocock, 1967; Young, 1978; Zaloga, 2005). The German missile attacks took place in a 291-day period between June 12, 1944 and March 29, 1945 (Campbell, 2013; Collier, 1957, 1964; Longmate, 1981; USSBS, 1947a). In the V1 attack (June 12, 1944 to March 29, 1945), 10,386 V1 cruise missiles were launched against the UK from ramps in France and Holland, and from modified He-111 bombers flying off the south and east coasts of England (Evans and Delaney, In Review; Smith, 2006). 7573 V1 missiles (73% of those launched) were considered non-abortive and thus presented a net threat to British defences; of these, 3986 missiles (38% of those launched) were destroyed in flight by British countermeasures (Hill, 1948, pp. 5585–5617; Evans and Delaney, In Review) while 2420 V1 cruise missiles made explosive impact on the London target area (23% of those launched; Table 1). By comparison, in the V2 attack (September 8, 1944 to March 27, 1945) 1403 rockets were launched into ballistic trajectory against UK; 1054 impacted British soil of which 517 made explosive impact within the London target (39% of those launched; Table 1).

Both missiles were autonomous. They were conceptualised as terror weapons for use against civilian populations in urban areas and were designed to damage/destroy the built environment on impact; their impact occurred essentially without warning to the population at risk

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**Table 1**
Comparative summary data on V1 cruise and V2 ballistic missiles (reproduced from Evans and Delaney (In Review)).

| | V1 | V2 |
|---|---|---|
| Range (km) | 255 | 352 |
| Launch Weight (kg) | 2180 | 12,700 |
| Fuel Weight (kg) | 702 | 8410 |
| Warhead Weight (kg) | 848 | 735 |
| Average speed (km/hr) | 555 | 3600 |
| Number of missiles constructed by Germany | 32,750 | 6550 |
| Total number of missiles launched by Germany | 22,480 | 3170 |
| Number of missiles launched against NW Europe | 12,094 | 1767 |
| Number of missiles launched against UK | 10,386 | 1403 |
| Number of missiles striking London Civil Defence Region | 2420 | 517 |

and high-explosive warheads (Table 1) were fused for maximum blast effect and thus maximum surface damage (Hellmold, 1999; p. 219). In this first distal war, German missile impacts accounted for 26% of London's fatalities due to aerial bombardment during WW2 and resulted in massive damage to London's housing stock (data in Titmuss, 1951; Kohan, 1952). The attacks took place despite an aggressive Allied bombing campaign beginning in 1943 designed to interrupt engineering development, suppress production and supply, and destroy launching sites and supply depots associated with the V1 and V2 missile systems across a broad expanse of France, Holland and Germany (Overy, 2013; USSBS, 1947b).

### *1.2. Conceptual scope and objectives*

Here we examine the V1 cruise missile attack and explore both the target and impact geography of the attack on London. In comparing the two geographies we investigate the accuracy of the V1 attack through mapping the interface of two spatial patterns generated by the interaction of an attractor (missile target) and a driver (missile impacts). Missile impacts mark the end point of a flight trajectory; thus the impact geography is filtered by such factors as launch success, flight reliability, and guidance accuracy (e.g., Mackenzie, 1990). Importantly, missile launch may be suppressed by pre-emptive action while missile trajectory can be interrupted by in-flight interception or system malfunction. These actions modify missile impact geography; as described in detail by Hill (1948, pp. 5585–5617) these were key determinants on the distribution of impacts of the V1 (launch suppression and flight interception).

Contemporary government documents concerning the V1 offensive (e.g., TNA AIR 19/417), and subsequent historical accounts of the attack (e.g., USSBS, 1947c, Collier, 1957, pp. 396, 432–433; 1964, p. 139–142; Ordway & Sharpe, 1979, pp. 244–245; Howard, 1990. p. 180) frequently refer to the “inaccuracy” of the German cruise missile system; despite this assertion, the damage to the built environment of London by V1 impacts was considerable and the loss of life substantial. In this paper, we examine this paradox through an analysis of the target geography of London and the impact geography of the V1 attack on the British Capital. Our objectives are to (i) outline the geographic and demographic characteristics of the London urban target in 1944–45, (ii) determine the impact geography of the cruise missile attack, (iii) estimate the population at risk (and its density) in the London target area, iv) explore the interface between the impact geography of the V1 missile attack in relation to target characteristics (urban geometry and population), v) examine the accuracy of the attacks and outline the implications for the geography of missile warfare. This paper forms part of a larger work investigating the response of physical and human elements of the urban environment to conventional missile attack, i.e., the geography of missile warfare conditioned by high-explosive impact.

### *1.3. Data sources and methods*

Remarkably, no official history (based on original documents and data) of the V1 attacks, documenting its scale, chronology, geography, and effects has ever been prepared. However, the occurrence, impact and effects of the missile attacks on London were meticulously recorded by different British military and local government organisations, documented in the field, and analysed in depth by British government investigators in documents now held at The National Archives (TNA) at Kew. This large body of declassified material represents a unique documentation and analysis of the response of a densely populated urban landscape to conventional missile attack and provides the basis for an applied geography analysis. However, these records remain relatively inaccessible in scattered locations within the collections of The National Archives. For this work, we located, reviewed, and extracted a large volume of this fragmentary data from documents at The National Archives. In addition we extracted population and geographic data from *The National Register* of 1939 (HMSO, 1944). Geospatial data from these sources was synthesised, georeferenced, and analysed using ArcGIS software.

## 2. The London target I - geometry

In the V1 offensive against the United Kingdom, Germany almost exclusively targeted London (Collier, 1957, 1964; Hölsken, 1994). In TNA documents, missile incident/impact data for the offensive is reported for the affected English counties as they were defined in 1944–45, and the wartime London Civil Defence Region (Civil Defence Region 5; O'Brien, 1955) which we abbreviate as LCDR (Fig. 3). London is therefore defined here in terms of the LCDR as mapped in Fig. 1.

The area of the LCDR thus defined (Fig. 1; Supplementary S1), calculated from the area of the 95 administrative units given in *The National Register* of 1939 (Table I in HMSO, 1944), was 1869 $km^2$, equivalent to a circle with a radius of 24.4 km. Using the same data, the County of London, forming the inner core of LCDR, had an area of 303 $km^2$ (16% of the area of LCDR), equivalent to a circle with radius of 9.8 km. This extensive urban footprint of the British capital and its inner core represented the primary target of the German missile offensive (Fig. 1).

With reference to a Central London aiming point for the V1 offensive, two aiming points are given in published sources and archival documents, i.e., Tower Bridge and Charing Cross Station (see discussion in Supplementary S2). Published sources (e.g., Howard, 1990; Hölsken, 1994, p. 198; Jones, 1978, p. 422; Werrell, 1985, p. 47; Woolven, 2002; Young, 1978, p. 82, p. 56) give Tower Bridge as the aiming point whereas a number of archival documents assume the aiming point for the V1 attack was Charing Cross Station “or thereabouts” (e.g., TNA AIR 20/4261; TNA CAB 80/86; TNA WO 291/305). These aiming points are within a circle of 1.7 km radius in Central London. We have been unable to find confirmation or detailed definition of missile aiming points in primary official sources in The National Archives although, as discussed below, there is archival evidence suggesting that in the final phases of the main V1 offensive several aiming points in Central London were used by the German missile batteries, rather than one (see for example, TNA AVIA 11/60 and discussion in Supplementary S3).

Thus, for the purposes of this paper we assume a nominal primary aiming point for all V1 missiles launched against the London target to be Tower Bridge at 51.505°N/0.075°W (Fig. 1). The distance from the nominal aiming point to the centroid of the County of London (51.489732°N/0.079676°W) is 2.15 km (Fig. 1).

[1] This alphanumeric code is the reference number for the document in The National Archives (TNA) online catalogue at http://discovery.nationalarchives.gov.uk/.

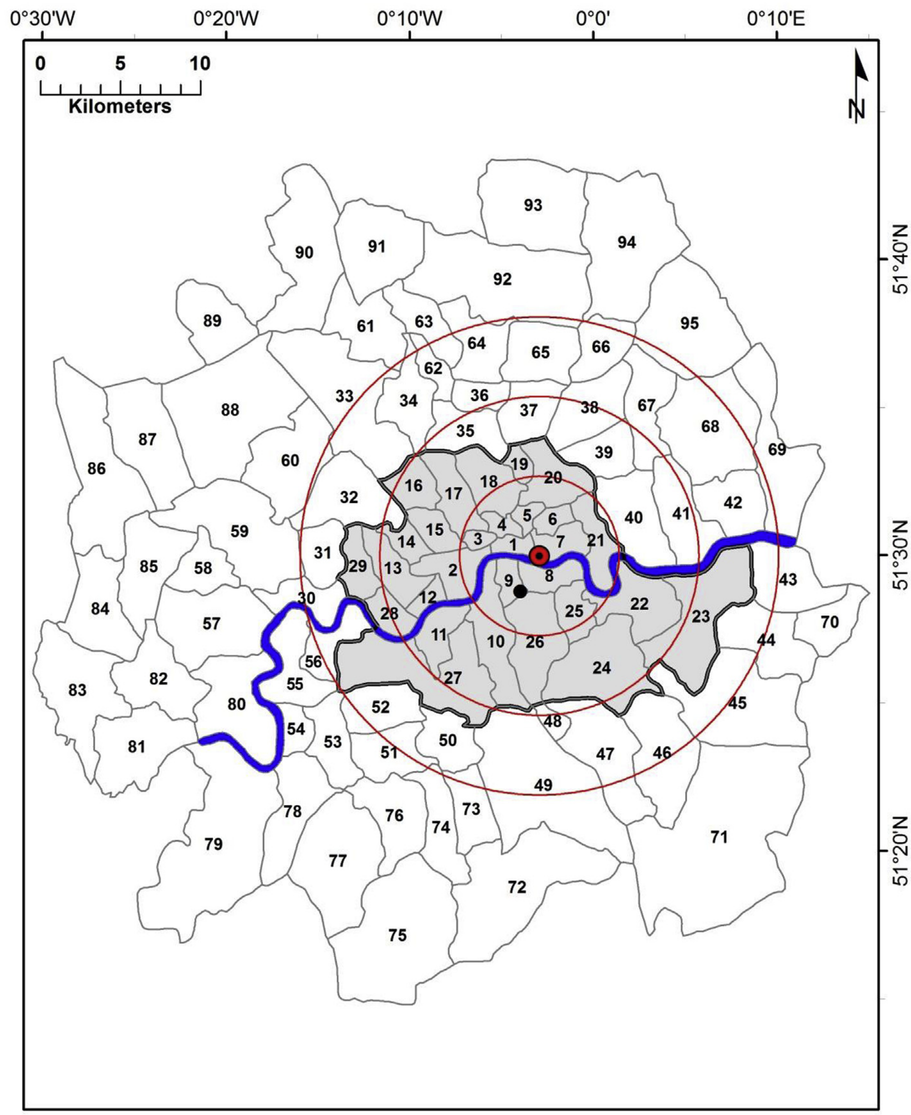


**Fig. 1.** Key map of the 95 administrative units (boroughs and districts) of the wartime London Civil Defence Region (LCDR) as constituted in 1944–45 during the German missile offensive (source - maps in TNA HO 193/54[1]). Key to administrative unit numbers in Supplementary S1. Area of LCDR was 1869 $km^2$ (radius of equivalent circle = 24.4 km). The County of London, made up of the 28 Metropolitan boroughs and the City of London (area = 303 $km^2$; equivalent radius = 9.8 km) and forming the core of the LCDR, is shaded grey and outlined by heavy black line. Concentric red circles are 5, 10, 15 km radius from Tower Bridge, the nominal aiming point in Central London assumed for the missile offensive as discussed in text (red dot). Centroid of the County of London is black dot. River Thames, flowing from west to east, is shown in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

## 3. The London target II - population

The estimation of the population of the LCDR at the time of the missile attacks in 1944–45 is a complex problem because of non-uniform (in space and time) demographic disturbances in the form of civilian evacuation and return following the initial mass exodus in early September 1939 (Titmuss, 1951). Three waves of large scale evacuation of the civilian population from Inner London took place between 1939 and 1944 and this population was either resettled in the outer areas of LCDR or moved out of the LCDR altogether to reception areas in other regions of Britain. Many evacuees returned to their home areas at various stages in the war but the dynamics of the return phases were not well quantified (Titmuss, 1951). In addition to official recorded evacuation there was considerable unrecorded private or voluntary departure from the designated areas which Titmuss (1951; Appendix 2) believes in the September 1939 exodus at least, to have exceeded official evacuation by a factor of 2. The population of LCDR was thus affected by a number of phases of mass population change which resulted in the successive redistribution of the urban population of LCDR from September 1939 to September 1944.

Key population data is recorded in *The National Register* which was taken on September 29, 1939 (HMSO, 1944) for the purposes of enumerating the number of civilians in the United Kingdom; the document gives the night-time civilian population of the boroughs and districts of the LCDR on that date. However, the population on September 29 had already been affected by significant evacuation and resettlement within the LCDR beginning in the summer of 1939 as war approached. Significant official and private evacuation had taken place in the exodus beginning on September 1, after war seemed inevitable (Titmuss, 1951; O'Brien, 1955; HMSO, 1944) to the extent that the population of the LCDR enumerated by *The National Register* was 17.5% less than the Registrar General's estimate of the ambient population in mid-1938 (HMSO, 1944; Fig. 2; see data in Supplementary S1).

Data in TNA HO 198/245 contains estimates of the 1944 population of the administrative units of the LCDR made by the Registrar General (Fig. 2C; see data in Supplementary S1). These data show that the population of LCDR as a whole declined by 685,821 (10%) between 1939 and 1944 as a result of further evacuation. In the same period, the population of the County of London, forming the Inner Core of the capital, declined by 560,196 (19%). Thus, compared to the Registrar General's estimate of the pre-war 1938 population (HMSO, 1944), the 1944 population of the 29 administrative units of London's Inner Core, had declined by 1,600,690 (39%); the population of some units had declined by 60% or more (Fig. 2D).

Visual comparison of Fig. 2A–D indicates that despite evacuation "thinning-out" of the denser populated areas, the broad population density distribution of LCDR was largely unchanged, i.e., the densest population was still found in the Inner London core at the centre of the

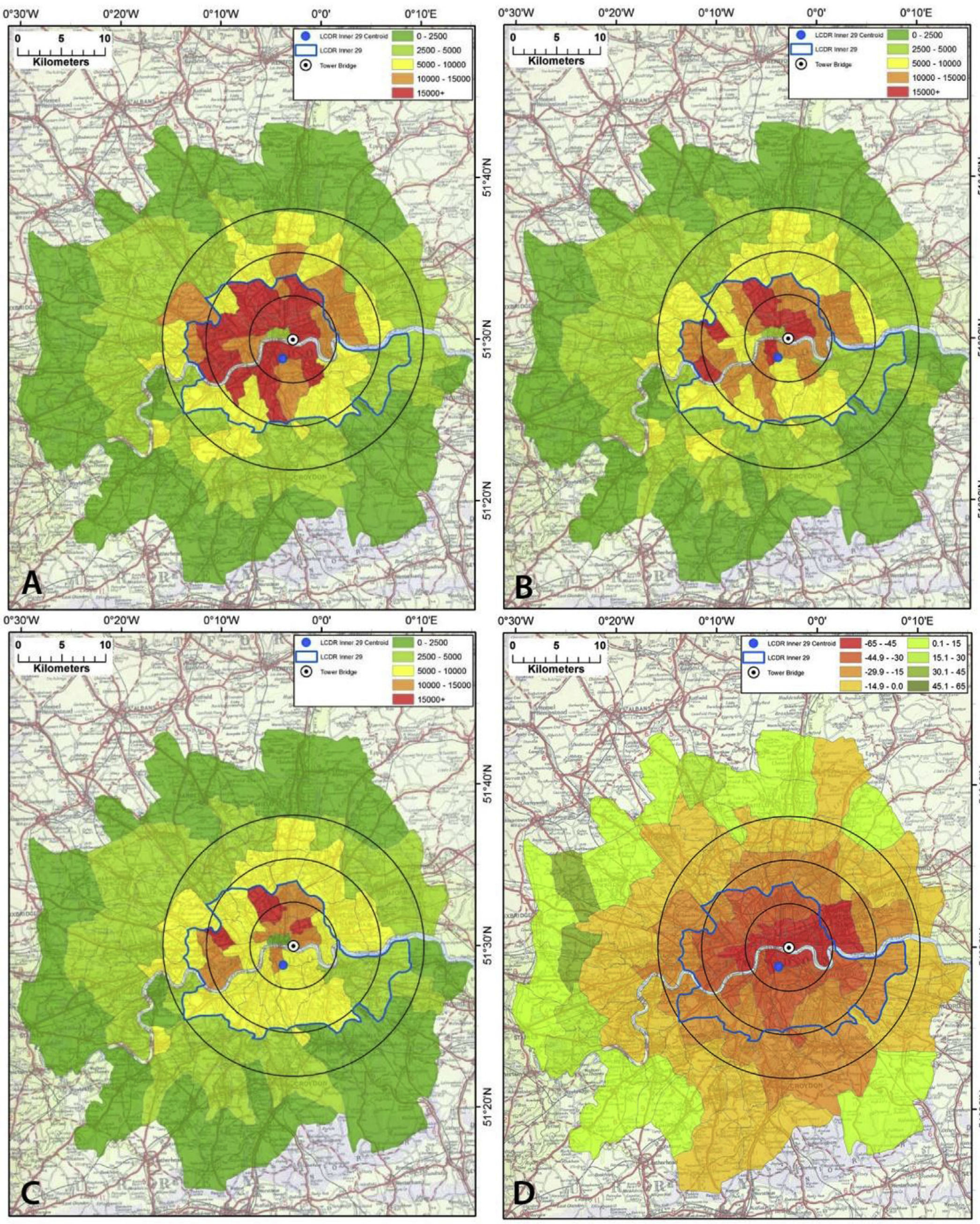


**Fig. 2.** Population density (persons/km$^2$) of LCDR in 1938, 1939, and 1944, and population density change 1938–1944. A: density based on Registrar General's estimate of population in mid-1938 (Table I in HMSO, 1944). B: density based on enumeration in *The National Register* on September 29, 1939 (HMSO, 1944). C: density based on Registrar General's estimate of population in mid-1944 (data from TNA HO 198/245). D: Percentage change (positive and negative) in population density between 1938 and 1944. Note effect of evacuation and resettlement within LCDR in August and early September 1939 and subsequent thinning out by further evacuation up to 1944. Concentric circles are 5, 10, 15 km radius from Tower Bridge, the primary aiming point (black dot) assumed for the V1 missile attacks. The County of London forming the inner core of LCDR is outlined by bold blue line; blue dot is centroid of the County of London. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

LCDR target. This can also be seen in the statistical relation between population density (PD) and distance from the aiming point. In Fig. 3, the mid-1938 population density (PD1938) of administrative units in the LCDR shows an exponential decline with distance of the centroid of the administrative unit from the nominal aiming point (X) in Central London ($PD1938 = e^{-0.14327X}34477.68$. $r^2 = 0.759$; cf. Clarke, 1951). The post-thinning-out 1939 population density data (PD1939) shows a similar distance decay relation ($PD1939 = e^{0.123058X}22598.41$. r2 = 0.712) as does the 1944 data ($PD1944 = e^{-0.109232X}17102.025$; $r^2 = -0.6556$); although the fit is less precise the broad Clarke-type negative exponential relationship ($PD = e^{-aX}b$) is maintained. Thus any missile falling within the centre of LCDR would still fall on its densest population (Fig. 3).

## 4. V1 impact geography

The LCDR suffered a total of 2420 recorded V1 impacts at an average impact density of 1.3/km$^2$. The County of London (area = 303 km$^2$), the densely populated core of LCDR (Fig. 4), suffered the greatest density of cruise missile impact during the offensive (Fig. 4)

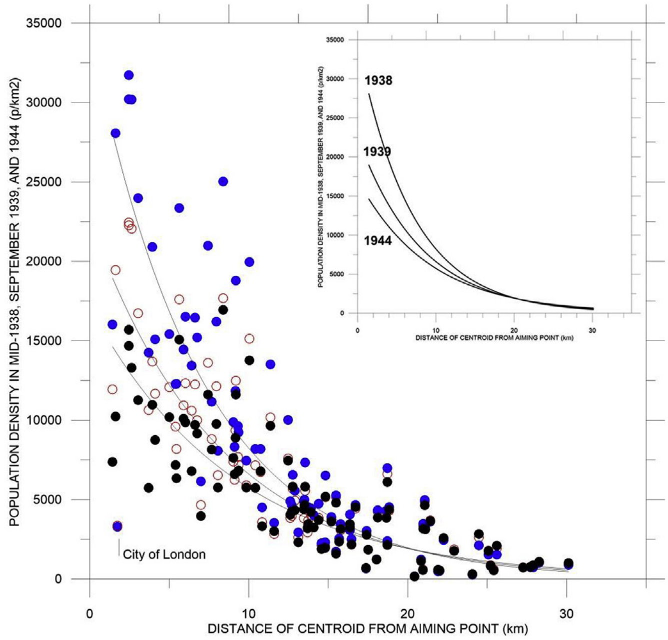


**Fig. 3.** Relation between population density of the 95 administrative units of LCDR in mid-1938 (blue dots), September 1939 (open red circles), and 1944 (black dots) and distance of centroid of unit from the Tower Bridge aiming point in Central London. City of London outlier excluded from fit. 1938 and 1939 population density calculated from Table I in HMSO (1944); 1944 population density calculated from population estimates in TNA HO 198/245. Inset shows calculated fits only for 1938, 1939, and 1944; note "thinning out" of population density in central core area of LCDR. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and experienced 966 incidents (40% of the total V1 missiles striking the LCDR) equal to an average impact density of 3.2 incidents/km$^2$. V1 strike densities in the inner core reached a maximum of 6.6/km$^2$ for the City of London, immediately adjacent to the nominal aiming point (Fig. 4). 7 boroughs in the County of London experienced V1 impact densities greater than 4/km$^2$; Bermondsey (4.9), Greenwich (4.7) Deptford (4.7), Camberwell (4.5), Stepney (4.2), Lambeth (4.2), and Lewisham (4.1) (Fig. 4). As seen in Fig. 1, all these boroughs are located south of the River Thames, with the exception of Stepney. Outside the Inner London core impact densities exceeded 4/km$^2$ only in the tiny borough of Penge (5.8), located on the southern boundary of the inner core in Kent (Fig. 4).

Higher resolution V1 impact density data extracted from a hand drawn map in TNA HO 193/54 is plotted in Fig. 5 on the British Cassini grid consisting of 1 km squares. A total of 1038 Cassini grid squares were impacted by V1 missiles. Of these 111 (10.7%) squares experienced 5 or more hits and two grid squares had 10 impacts (Fig. 5).

The extent to which the impact geography, dominated by a bias to the south-southeast (Figs. 4 and 5), resulted from deception measures by British Intelligence has long been the subject of historical discussion (e.g., Howard, 1990; Jones, 1978; Woolven, 2002); we note that extensive discussions in official War Cabinet documents are ambiguous (e.g., TNA CAB 80/85; TNA CAB 80/86). Our interpretation of this discussion (see summary in Supplementary S3) is that any passive deception undertaken by British Intelligence did not significantly alter the primary V1 impact geography in London which we assume to be the exclusive product of the extant V1 missile technology applied to an aiming point in Central London. This view is supported by the fact that German missile officers have stated that they did not change aiming points during the V1 offensive (e.g., Howard, 1990; Hölsken, 1994, p. 177).

## 5. Impact distribution in relation to target geography

These general numbers indicate that the V1 missiles fell with greater density in the core of the LCDR. Further, the geography of all missile impact densities shows a rough concentric pattern of concentration around the aiming point in Central London (Figs. 4 and 5) manifested in a decay of impact density with distance from Tower Bridge. A secondary feature of the impact pattern is a bias in the impact density distribution in the south and east quadrants of the LCDR in the direction of the ground ramp launch sites in northern France and air-launch areas off the east coast of England.

In more detail, Fig. 6 shows a clear negative exponential relationship between missile impact density (MID) and distance from the aiming point (X) similar to that obtained for population density in Fig. 3 where MID = $e^{0.11563X}5.4843$ ($r^2 = 0.591$; n = 95). This is further illustrated in Fig. 7 where cumulative percentage plots of total population of LCDR in 1938, 1939, and 1944 and V1 missile impacts in LCDR v. distance of the centroid from the aiming point show a very similar form. V1 impact density was thus highest in boroughs and districts of highest population density and both density variables decay exponentially with distance from the aiming point.

With reference to Fig. 7, we completed a Chi Square Test on the distribution of: i) V1 missile impacts and the distance from the central aiming point, and; ii) V1 missile impacts and 1939 population in the LCDR. This test was completed to determine if there was evidence that the German missiles were targeting locations of high population densities close to the main aiming point. Our null hypothesis stated that there is no relationship between the distribution of missile impacts and i) the distance from the aiming point, and; ii) 1944 LCDR population densities (Fig. 7). The null hypothesis was rejected with p-value = $9.3 \times 10^{-11}$ for distance from the aiming point and p-value = $1.8 \times 10^{-11}$ for population density. We conclude that there is a strong relationship between V1 missile impacts and location (i.e., distance from the aiming point) and V1 missile impacts and 1944 population distribution confirming the visual impression in Fig. 7.

An additional component of the V1 impact distribution within the County of London is the difference between the boroughs to the north and south of the River Thames (Figs. 2, 4 and 5). This difference has implications for evaluating casualties resulting from V1 impact and was the main driver of the proposed British deception plan outlined in Supplement S3. The 19 boroughs north of the Thames had a 1944 population of 1,329,200 (population density = 10,373 p/km$^2$) and the 10 boroughs south of the Thames 1,132,910 (population density = 6842 p/km$^2$); this population density is 66% of that north of the Thames. In terms of missile impact density, the 10 boroughs south of the Thames sustained 3.8 V1 impacts/km$^2$ whereas the 19 boroughs to the north had an impact density of 2.4/km$^2$, 64% of that of the south. Thus the London boroughs to the north of the Thames had 1.5 times the population density of boroughs to the south that received V1 impact densities 1.6 greater than those of the north.

## 6. Accuracy of the V1 missile system

### *6.1. The geography of missile accuracy; Mean Point of impact, Circular Error Probable, precision and bias*

The basic assessment of the accuracy of a number of missiles involves the determination of the Mean Point of Impact (MPI), the Circle Error Probable (CEP) and offset in relation to the MPI (also known as the systematic error or bias) (Mackenzie, 1990). The Mean Point of Impact is defined as the co-ordinate pair (*x, y*) corresponding to the mean distances of *n* impacts from a point of origin of an arbitrary *x,y* grid covering the impact zone. The precision of a missile attack is commonly expressed in terms of the Circle Error Probable (CEP) (e.g., Dullum, Fulmer, Jenzen-Jones, Lincoln-Jones, & Palacio, 2017; Mackenzie, 1990; Tsipis, 1975). Two Circle Error Probable (CEP) can be

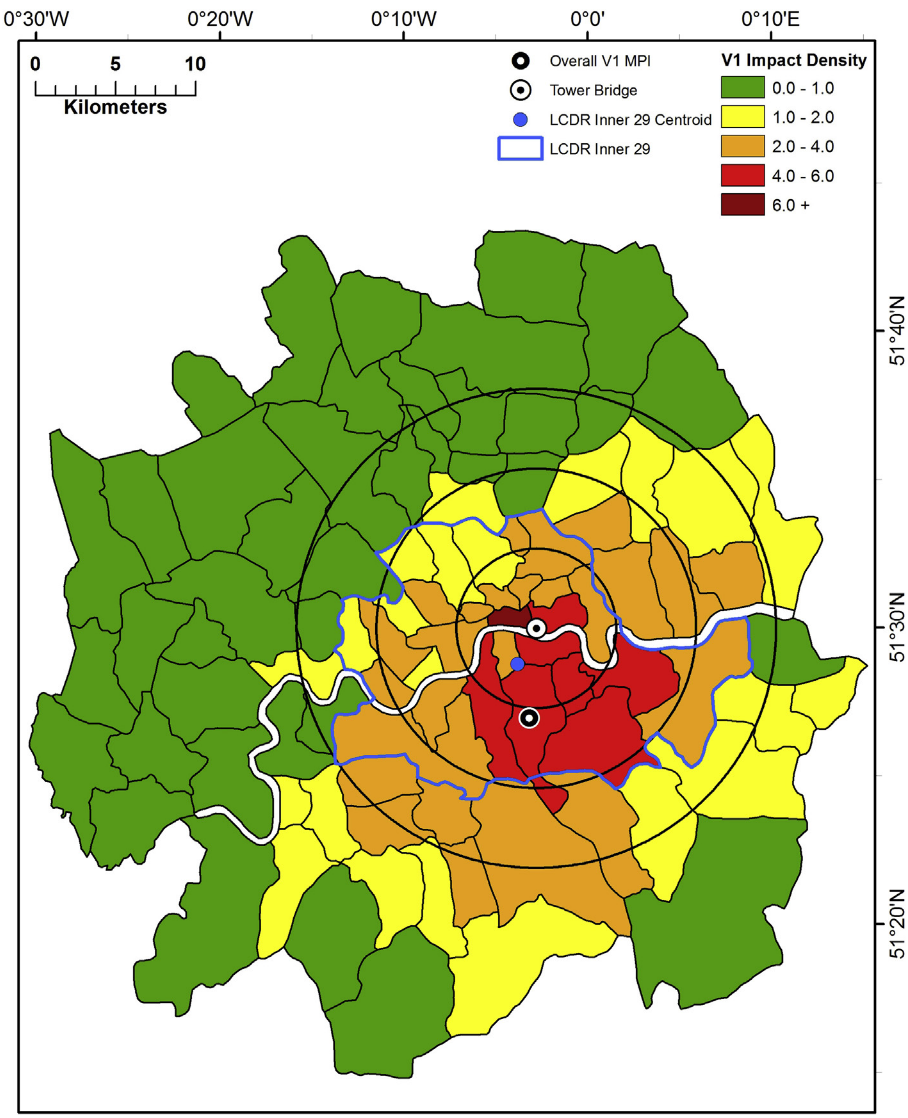


**Fig. 4.** Density of V1 missile impacts (impacts/km$^2$) for 95 boroughs and districts of LCDR June 1944 to March 1945 (n = 2420). These include impacts of missiles launched from ramps in France and Holland as well as missiles air-launched from over the North Sea. Note bias in density distribution marking the southerly and southeasterly entry corridor. Data collated in GIS from TNA sources. Black dot (with white centre) is overall MPI of 2111 V1 impacts from June 22 to August 31, 1944 (data collated from TNA AIR 20/4262). The County of London forming the inner core of LCDR is outlined by thick blue line; blue dot is the centroid of the County of London. Concentric circles are 5, 10, 15 km radius from Tower Bridge, the nominal aiming point in Central London. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

defined. The CEP is first defined as the radius of the circle around the target (CEP-T), in which 50% of the missiles (that enter the target area) fall over a given range (Mackenzie, 1990, p. 348). Unless all the missiles fall around the aiming point such that the MPI corresponds to the aiming point, the MPI is offset from the aiming point by distance x, termed the bias (Mackenzie, 1990. p. 355) or systematic error; this is a measure of accuracy. In this case we can also define the CEP as the radius of the circle around the MPI (CEP-MPI), in which 50% of the missiles (that enter the target area) fall over a given range (Fig. 7.1 in Mackenzie, 1990). However, area targets, such as large cities, are not points; this aspect of city targets requires a different approach to accuracy and involves a consideration of the geospatial properties of the target itself.

Consider Fig. 8. Fig. 8 is roughly scaled to the geometry of LCDR and Inner London in which CEP-T is taken to be equal to CEP-MPI. The CEP Ratio is defined as the ratio of the CEP to the equivalent radius of the city target.

The larger circle represents the target city with an equivalent radius (R) of 24 km. An inner circle represents the densely-populated target urban core with an equivalent radius (C) of 10 km. We take the aiming point for the missile batteries as the centre of the circle (A in Fig. 8). Fig. 8 shows that in attacks on city targets the MPI could be offset from the aiming point by some distance yet still do considerable damage to the urban area target (Fig. 8). For example, with a CEP $\leq 1/2$R (in this case CEP = 12 km), the bias can be $\leq 1/2$R for the CEP to be contained within the urban area target (MPI-2 in Fig. 8), i.e., 50% of the missiles will fall within the city target. With greater CEPs or greater offset ($> 1/2$R) (i.e., more inaccurate) a significant number of hits would still occur in the target (MPI-3 in Fig. 8) until, with greater offset (and/or greater CEP) $\geq 1.5$R then 50% of the missiles will fall outside the city target area (MPI-4 in Fig. 8). Thus missiles aimed at a large area target do not require a restrictively small CEP and a small offset associated with high accuracy to be effective in destroying significant sections of an urban area target. Fig. 8 also shows that the accuracy requirements are more restrictive (lower CEP and lower offset) for missiles launched to specifically damage the core of a city since it presents a smaller target radius (C < CEP in Fig. 8). Building damage and life loss results from the interaction between density of population (a distance-decay relationship linked to offset) and density of impacts (linked to CEP); with increasing offset, despite maintaining a limited CEP, the density of the target population will decrease (cf. Clarke, 1951; also see Fig. 3) thus damage will be reduced for the same attack parameters. Further, a reduction in precision (i.e., higher CEP and lower CEP ratio for a given target) will result in a lower density of missile impacts within the urban area and thus less cumulative damage for a given attack.

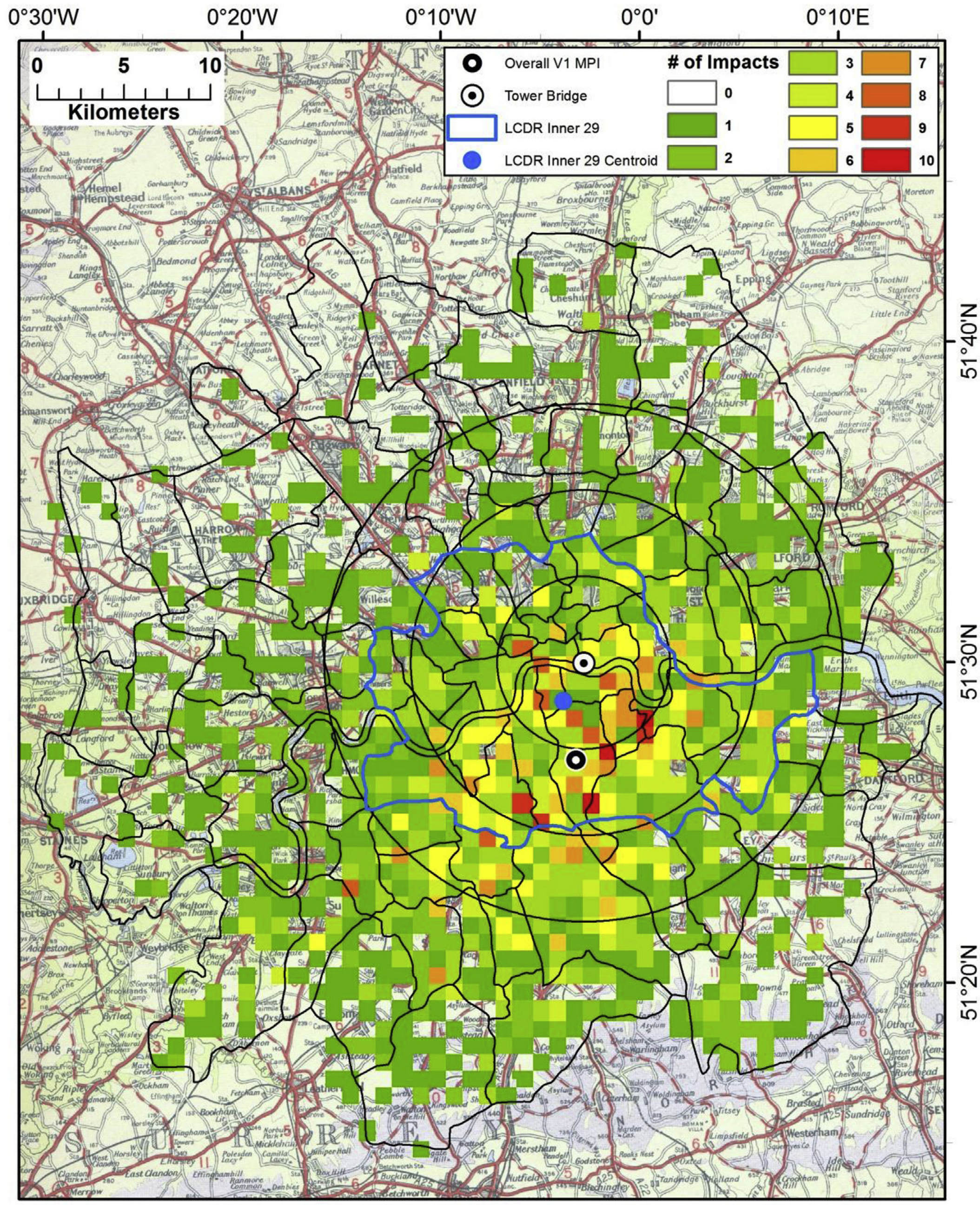


**Fig. 5.** High-resolution impact density map of V1 cruise missile impacts in the LCDR from June 15, 1944 to September 20, 1944 (n = 2345) dates corresponding to the main V1 offensive. Grid squares are square km within British Cassini Grid. See Fig. 1 and Supplementary S1 for key to the 95 administrative units of LCDR (outlined in black). County of London forming the inner core of LCDR outlined in thick blue line; blue dot is centroid of the County of London. Concentric circles are 5, 10, 15 km radius from Tower Bridge, the nominal aiming point in Central London. Data abstracted from LCDR map in TNA HO 193/54 and plotted in ArcGIS. Black dot (with white centre) is overall MPI of 2111 V1 impacts from June 22 to August 31, 1944 (data extracted from TNA AIR 20/4262). Background map is from *Bartholomew's Road Atlas of Great Britain* (London, 1943, 96 p.). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

### *6.2. The London V1 impact data and operational accuracy*

Extensive discussion took place on the accuracy of the Flying Bomb (V1) missile system at the time of the attacks and much concern (involving Churchill himself) surrounded keeping the actual fall of Flying Bombs a secret thus denying German missile batteries calibration data on the fall of shot (e.g., TNA CAB 80/85; also see discussion in Supplementary S3). This discussion has continued in subsequent years (see Werrell (1985. p. 47–62) and Ordway and Sharpe (1979), for example). Despite claims that the V1 was "inaccurate" (e.g., Ordway and Sharpe, 1979; Kartha, 1998), the German cruise missile system clearly had operational accuracy in that 2420 missiles struck the LCDR target (area = 1869 $km^2$) causing substantial loss of life and massive damage to London's housing stock (Collier, 1957; Titmuss, 1951). 966 of these missiles (40%) struck the densely-populated boroughs of the County of London (area = 303 $km^2$, 16% of the area of LCDR) forming the inner core of LCDR that housed 38% of its 1944 population.

We attempted a rough estimate of the CEP-T around the nominal aiming point of the V1 missile through an analysis of impact data for the LCDR. We assumed that i) the aiming point for the V1 attack was Tower Bridge (see discussion above and in Supplementary S2), and ii) missiles that did not reach LCDR were subject to gross errors and thus

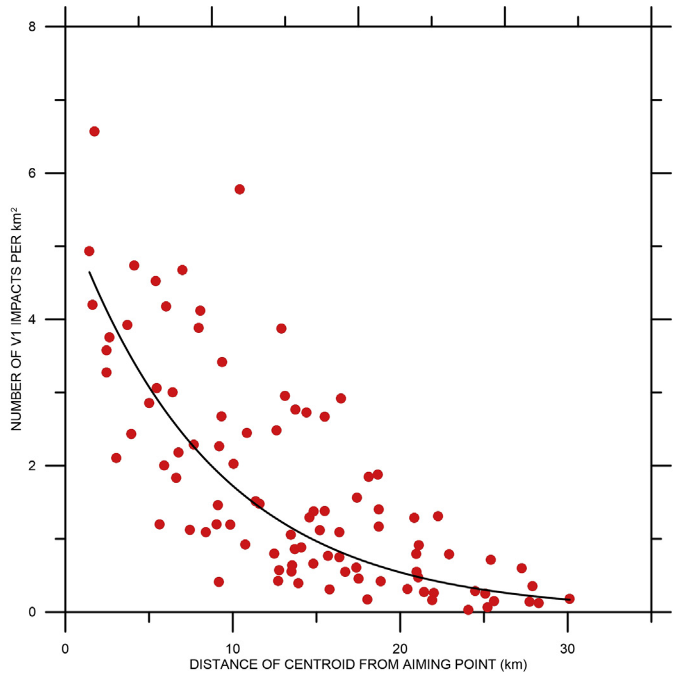


**Fig. 6.** Relationship between density of V1 missile impacts (impacts/km$^2$) in 95 administrative units within LCDR and distance of centroid of administrative unit from nominal aiming point (Tower Bridge). Plot shows exponential decay in impact density with distance from aiming point (X). Data collated in GIS from TNA sources.

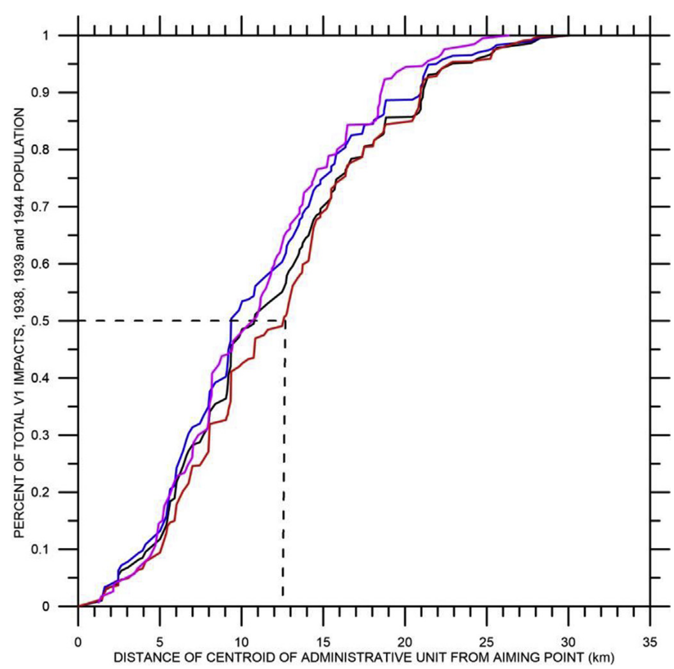


**Fig. 7.** Cumulative percentage of population (1938 - blue line, 1939 - black line. and 1944 - magenta line) and V1 cruise missile impacts (red line; n = 2420) in 95 administrative units within LCDR as a function of distance of centroid of administrative unit from the aiming point. The radius of the circle within which 50% of missiles fell is estimated at 12.5 km, which approximates the operational Circular Error Probable (CEP) of the V1 missile system (dashed line). Impact data collated in GIS from TNA sources; 1938 and 1939 population data extracted from *The National Register* (HMSO, 1944). 1944 population data is Registrar General's estimate for the LCDR administrative unit concerned extracted from TNA HO 198/245. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

could be excluded from the analysis. The accuracy plot in Fig. 7 indicates that the V1 has an estimated CEP-T of 12.5 km, i.e., that 50% of the cruise missiles launched at London fell within a circle with radius 12.5 km (area = 491 km$^2$) centred on Tower Bridge. This value corresponds well with estimates from other sources (e.g., Kartha, 1998; Zaloga, 2005).); thus the CEP-T (12.5 km) is intermediate between the equivalent radius of LCDR (24.4 km) and the County of London (9.8 km) (Figs. 8 and 9).

British defence analysts determined the MPI for all phases of the V1 attack on a daily basis for night and day missile impacts and reported the locations in Cassini Grid co-ordinates (TNA AIR 20/4125, TNA AIR 20/4262, TNA AVIA 11/55, and TNA AVIA 11/60). We extracted the Cassini Grid co-ordinates of the MPIs and converted them to Lat/Long for plotting in GIS using a co-ordinate translator at http://www.echodelta.net/mbs/eng-translator.php#. This impact data does not include air-launched Flying Bombs from the east and also excludes V1 missiles brought down by defensive measures and missiles subject to gross errors (landing more than 48 km from Central London). The MPIs are plotted on Fig. 9; we also note that TNA documents show that the distribution of impacts around the overall MPI has a robust circular normal distribution.

From this data British analysts calculated the CEP-MPI. These estimates of CEP-MPI varied from 11.3 km calculated for 1076 V1 impacts between June 22 and July 14, 1944 (TNA AVIA 11/60) to 12.1 km (TNA AIR 20/4125) and 12.9 km reported in TNA CAB 121/215. Thus we conclude that in the V1 attacks CEP-T is roughly equal to CEP-MPI.

The overall MPI calculated by British analysts for the main V1 attack (Fig. 9), consisting exclusively of missiles launched from France, did not, however, correspond to the nominal aiming point. Instead it was displaced 5.6 km south of Tower Bridge, but still within the inner core (Fig. 9), and located in Dulwich at 51.45739°N/0.07778°W. This offset represents the bias (or systematic error) in the V1 impact geography. Since we have no primary knowledge of the actual aiming point (s) used by German missile batteries (see discussion in Supplementary S2), three alternatives present themselves 1) that the Dulwich MPI was the actual aiming point used and that bias is absent, 2) that another aiming point was used (e.g., the centroid of the County of London located 3.5 km N of the MPI and that the bias is less), 3) that the aiming point was Tower Bridge and that the V1 had a systematic error in its guidance technology which led to the actual bias. With reference to alternative 3, the bias in the Dulwich MPI represents an error of < 4% of the range flown from launch ramps in France (~200 km) which is within the specifications of the V1 guidance system (Temme, 1957). An element of this bias is the intrinsic error in the V1 guidance system estimated by British engineers to be in the order of 3.5 km over a range of 240 km (TNA AVIA 11/60). Yet despite this bias, the V1 missiles fell with greatest density in the densely populated core of London; the density of impacts decayed exponentially from the aiming point in central London, a density-distance relation that mirrored (by apparent design) the exponential decay in population density from the same aiming point. However, as a consequence of this bias, V1 impact density was less in the densest populated boroughs north of the Thames (Fig. 9 A & B) than would have been the case with a smaller bias; we note, however, that these boroughs were still within the CEP-MPI (Fig. 9 A & B and see discussion in Supplementary S3).

## 7. Discussion and conclusions

The V1 missile attack on London in a 291 day period between June 12, 1944 and March 29, 1945 is significant in that i) it constituted the major component of the first large-scale missile attacks in war, ii) it targeted densely populated urban areas within a massive urban complex, and iii) massive urban damage and significant civilian casualties resulted. We have analysed a substantial body of data from The National Archives on the V1 attack and map the fall of 2420 missiles on the 1869 km$^2$ London Civil Defence Region (LCDR). Despite suggestions

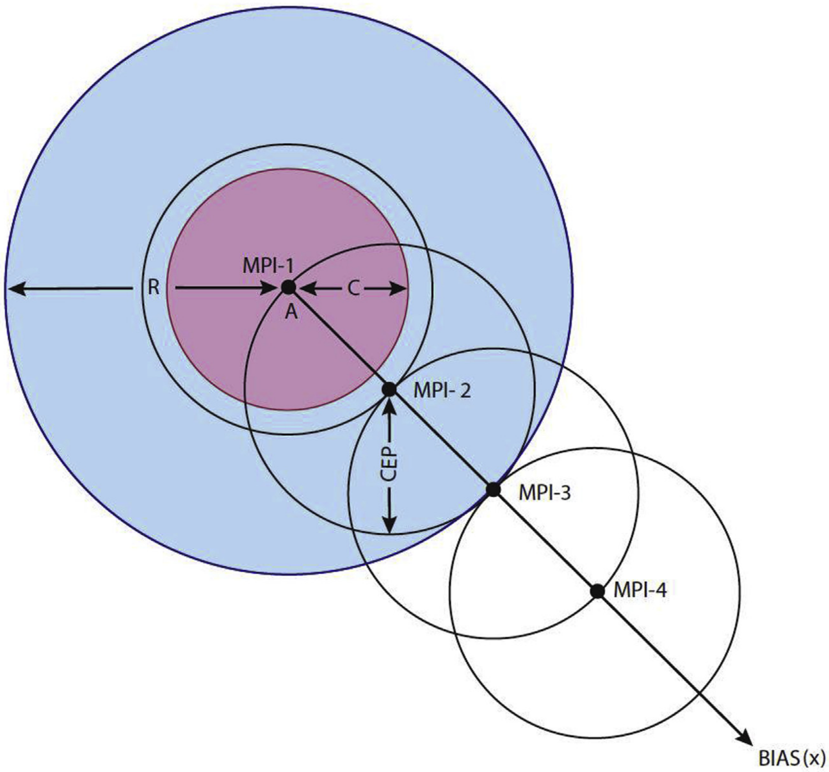


**Fig. 8.** Schematic diagram, scaled roughly to the geometry of LCDR, showing trace of city area target (blue circle) with equivalent radius (R), inner urban core (red circle) with radius (C; C/R = 0.41). The centre of the city target is taken as the aiming point (A). Four equal CEPs (CEP Ratio = 2) associated with Mean Points of Impact MPI-1, MPI-2, MPI-3 and MPI-4 are shown. MPI-1 corresponds to aiming point (A) and bias is zero (CEP-T is coincident with CEP-MPI). MPI-2 to MPI-4 are located along an arbitrary bias vector; bias is the offset (x) of the MPI from the aiming point, A. Further explanation in text. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

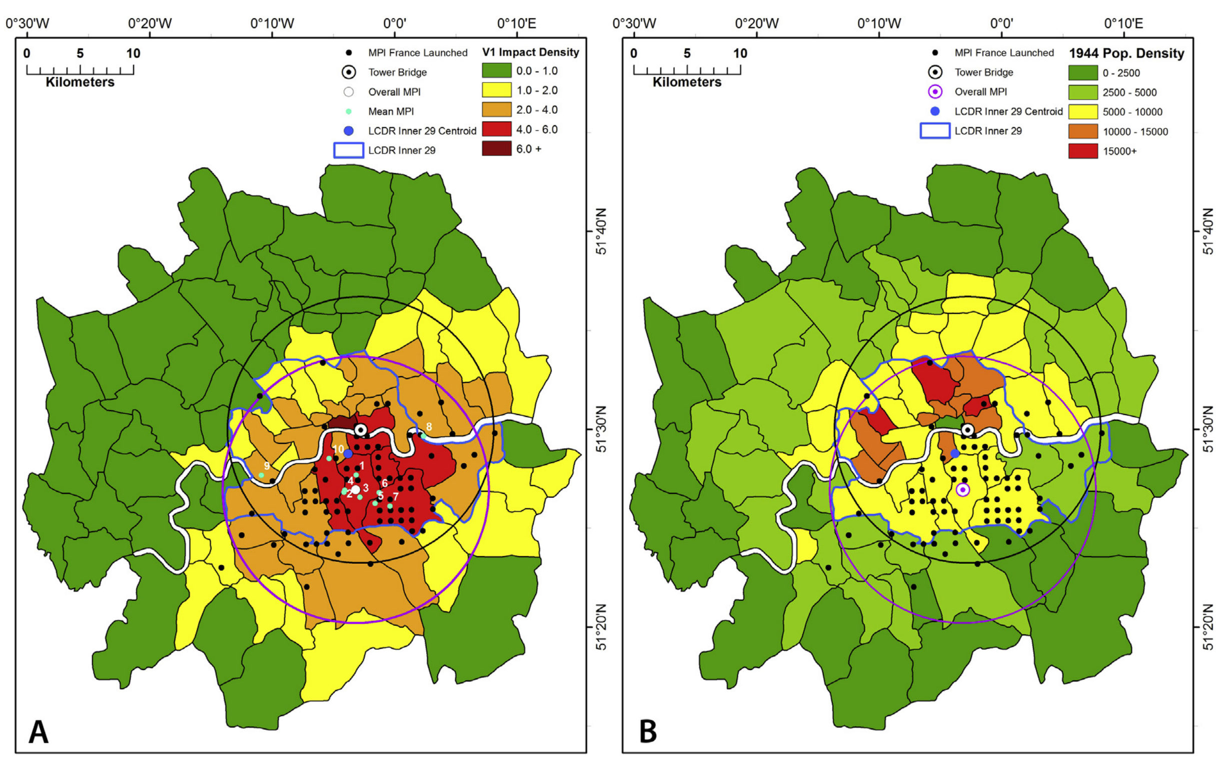


**Fig. 9.** Accuracy of V1 missile strikes on LCDR (with boundaries of 95 administrative units shown). Black circle in A and B is CEP-T estimated as 12.5 km from Fig. 7 (centred on the nominal aiming point) of V1 cruise missile impacts. Black dots in A and B are 88 Mean Points of Impact (MPI) for the period June 22 to September 1, 1944 calculated by British defence analysts for 2111 impacts of V1 missiles launched from France. Blue dot is centroid of County of London forming the inner core of LCDR (heavy blue line). A: background map is density of V1 missile impacts in LCDR June 1944 to March 1945 (n = 2,420, from Fig. 4). Purple circle is 12.5 km CEP-MPI centred on overall MPI (white dot) of 2111 V1 impacts from June 22 to August 31, 1944. Also shown are 10 MPIs (numbered 1–10) calculated for 10 weekly periods from June 23 to September 1, 1944 (n = 2.045; Supplementary S3). B: background map is 1944 population density (data calculated from TNA HO 198/245; see also Fig. 2C). Purple circle is 12.5 km CEP-MPI centred on overall MPI (purple dot) of 2111 V1 impacts from June 22 to August 31, 1944. Overall MPI is offset 5.6 km from Tower Bridge aiming point. For further discussion see Supplementary S3. Data for A and B collated in ArcGIS from TNA AIR 20/4125, TNA AIR 20/4262, TNA AVIA 11/55, and TNA AVIA 11/60. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

that the V1 was "inaccurate" (manifested in large line and range mean deviations and a large CEP) we find that the missiles fell with highest impact density near the centre of the LCDR; 40% of the impacts fell on the County of London which makes up only 16% of the area of LCDR forming the region's inner core. This is consistent with an aiming point near the centre of London which, we take as Tower Bridge. V1 impact density shows a negative exponential relationship with distance from this nominal aiming point. Despite efforts to "thin out" the population density in the inner core through mass evacuation, population density data also shows a negative exponential relationship with distance from the aiming point similar to the Clarke relation. As a consequence of this distance-decay behaviour, the missiles fell on areas with high population density. The MPI calculated by British analysts for the main V1 attack (for France launched missiles) did not, however, correspond to the nominal aiming point. Instead it was displaced 5.6 km south of Tower Bridge, but still within the inner core, located in Dulwich; this bias is less than 4% of the range form launch ramps in France.

We suggest that this impact geography arose out of an operational accuracy in the nascent German cruise missile technology despite the fact that, in relation to modern missile systems it was unreliable, imprecise. and inaccurate. Our data shows that the CEP-T roughly equalled the CEP-MPI. The interaction of the V1 target and impact geographies verify the assertion that high-resolution accuracy is moot in missile attacks on large cities when i) missiles with large CEP are launched against large city area targets that have spatial geometries (equivalent radii)) that are equal to or exceed that of the missile CEP, and ii) that bias in the MPI is $\leq$ CEP. These conditions satisfy the inequality BIAS $\leq 0.5R \leq$ CEP, where R is the equivalent radius of the target. Clearly, only a crude operational accuracy is required in these circumstances to cause significant casualties among the city's inhabitants and to destroy substantial elements of its built environment by missile attack. In the V1 case, its impact geography suggests BIAS $\leq$ C $<$ 0.5R $\leq$ CEP which suggests high accuracy in relation to the geometry of the LCDR target (Fig. 8) and to the strategic objectives of the bombardment. As stated in a British document (TNA AIR 19/417) "*The enemy have had what is probably a unique opportunity to make effective use of their simple flying bomb against London because the target is so large and so near to their launching bases that a reasonable number of hits within the target area could be expected in spite of the weapon's high factor of inaccuracy*." These conclusions have important implications in modern conventional missile warfare. Further, it supports several more general observations that when terror attacks on urban civilians is the objective of conventional missile attack (e.g., Stein & Postol, 1992) high-resolution accuracy is not required since the warhead will impact on one neighbourhood or another within large area targets.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.apgeog.2018.07.019.

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