The Ionospheric response over the UK to major bombing raids during World War II

Christopher. J. Scott[1], Patrick. Major[2]

[1] Department of Meteorology, University of Reading, Berkshire, UK
5 [2] Department of History, University of Reading, Berkshire, UK

Correspondence to: C. J. Scott (chris.scott@reading.ac.uk)

Abstract. The Earth's ionosphere is subject to disturbance from above (via solar variability and space weather effects) and from below (such as tectonic activity, thunderstorms and sudden stratospheric warmings). Identifying the relative contribution of these effects remains challenging, despite recent advances in spacecraft monitoring near-Earth space. Man-
10 made explosions provide a quantifiable proxy for natural terrestrial sources, enabling their impact on ionospheric variability to be studied. In this paper, the contribution of ground-based disturbances to ionospheric variability is investigated by considering the response of the ionospheric F2-layer over Slough, UK, to 152 major bombing raids over Europe during World War II, using a superposed epoch analysis. The median response of the F2 layer is a significant decrease in peak electron concentration (~0.3 MHz decrease in foF2). This response is consistent with wave energy heating the thermosphere,
15 enhancing the (temperature dependant) loss rate of O^+ ions. The analysis was repeated for a range of thresholds in both time of bombing before the (noon) ionospheric measurement and tonnage of bombs dropped per raid. It was found that significant (~2-3σ) deviations from the mean occurred for events occurring between approximately 3 and 7 hours ahead of the noon ionospheric measurements and for raids using a minimum of between 100 and 800 tonnes of high explosives. The most significant ionospheric response (2.99σ) occurred for 21 raids up to 5 hours before the ionospheric measurement, each with a
20 minimum of 300 tonnes of explosives. To ensure that the observed ionospheric response cannot be attributable to space weather sources, the analysis was restricted to those events for which the geomagnetic Ap index was less than 48 (Kp < 5). Digitisation of the early ionospheric data would enable the investigation into the response of additional ionospheric parameters (sporadic E, E and F1 layer heights and peak concentrations). One metric ton of TNT has an explosive energy of 4.184 10^9 joules, which is of the same order of energy as a cloud to ground lightning stroke. Since the occurrence of
25 lightning has distinctive diurnal and seasonal cycles, it is feasible that a similar mechanism could contribute to the observed seasonal anomaly in ionospheric F-region electron concentrations. Further investigation, using less extreme examples, is required to determine the minimum explosive energy required to generate a detectable ionospheric response.

1 Introduction

The source of much of the observed variability within the Earth's ionosphere remains poorly understood. In this study we examine unique ionospheric measurements made above Slough, UK for the duration of the Second World War (WWII) in order to determine whether any of the observed variability could be attributed to the major bombing campaigns across

5   Europe.

Production of ionisation in the Earth's upper atmosphere is predominantly through photo-ionisation by solar Extreme Ultra Violet (EUV) and x-ray radiation, while loss rates are very sensitive to the temperature and composition of the neutral thermosphere. As a result, the long term average behaviour of the ionosphere is closely tied to solar activity and is well understood. Transient space-weather phenomena such as coronal mass ejections, high-speed solar wind streams and

10   energetic particle events can temporarily perturb the ambient ionospheric conditions by enhancing ionospheric production through impulsive brightening of the solar atmosphere (solar flares), enhancing ionospheric loss rates (through heating of the thermosphere, affecting neutral composition and loss rates) and through direct enhancement of ionisation by precipitation of energetic particles. While the details of such processes are still the subject of on-going research, once again, the underlying physics is broadly understood. Despite this, there are further sources of ionospheric variability that remain unaccounted for

15   and it has been suggested (e.g. Rishbeth and Muller-Wodarg, 2006) that the source of this variability is from the lower atmosphere. Sources such as earthquakes (e.g. Astafyeva et al, 2013 and references therein), thunderstorms (Davis and Johnston, 2005; Yu et al, 2017) and explosions (e.g. Rishbeth, 1996) have been cited as potential causes of ionospheric variability, with a variety of proposed mechanisms including pressure waves, gravity waves, infrasound and modulation of the Global Electric Circuit.

20   There have been a number of case-studies into the impact of terrestrial explosions on the upper atmosphere (e.g. Rishbeth 1996), most notably the events surrounding the explosion at the Flixborough chemical plant in 1974 (Jones and Spracklen, 1974; Krasnova et al, 2003). In this paper we make use of historical records to identify large bombing raids over mainland Europe during the Second World War (WWII) and, using a superposed epoch, or composite analysis (Chree, 1913), look for any consistent response in ionospheric measurements made at the Radio Research Station at Slough in the UK.

25   **Early ionospheric measurements**

The Radio Research Station (latterly the Radio and Space Research Station and ultimately the Appleton Laboratory) located at Ditton Park near Slough (Gardiner et al, 1982) conducted routine measurements of the Earth's ionosphere from 1933 to 1996. These measurements continue today at the Rutherford Appleton Laboratory near Chilton, UK. This sequence represents the longest continuous set of ionospheric measurements in the world. The technique used exploits the fact that a

30   transmitted radio pulse is returned from an ionised atmospheric layer when the radio frequency of the pulse, f, matches the local plasma frequency. From this, the local electron concentration, N, can be determined via the relation $f \approx 9\sqrt{N}$. By transmitting a sequence of radio pulses over a range of radio frequencies, it is therefore possible to construct a height profile

of ionospheric electron concentration. Such measurements are most often presented in the form of an ionogram; a plot of 'virtual height' (estimated from the time of flight of the signal assuming a vacuum) against radio frequency. From such records the virtual height and the peak frequency (and therefore electron concentration) returned from each ionospheric layer can be determined and tabulated. While modern digital soundings automatically identify a comprehensive set of such

5   parameters, this was a time consuming task for the earliest analogue measurements and so only the peak frequency of the ionospheric F layer (denoted foF2) was initially routinely scaled. While other parameters were scaled intermittently, foF2 represents the most comprehensive parameter scaled from these data that exists in a digital form. The original photographic prints of these early ionograms are held by the UK Solar System Data Centre from which additional information can potentially be gleaned (Davis et al, 2013).

10   Bombing raids during World War II

Looking for a signature in the UK ionospheric records from allied bombing campaigns over Europe between 1943 and 1945 may not seem like the most obvious of studies but there are several reasons as to why a signature from such raids may be detectable over others. While the bombing of London by the Luftwaffe between September 1940 and May 1941 (popularly known as 'The London Blitz') would have generated explosions at a closer proximity to the ionospheric measurements being

15   made above Slough, this bombing was more or less continuous, making it difficult to separate the impact of wartime raids from those of natural seasonal variability. In addition, it is well documented that the Luftwaffe did not possess any four-engine long-range bombers (e.g. Bekker, 1969). The mainstay of the Luftwaffe was the Heinkel 111, a twin-engined bomber capable of carrying 4,400 lb (1667 kg) of bombs. Using external racks, the aircraft could carry 7,900 lbs (3,600 kg) of bombs but the external racks blocked the internal bomb bay and significantly impaired the aircraft's performance (Regnat, 2004).

20   In contrast, the allied airforces' use of four-engined bombers enabled them to carry much larger bombing loads, including individual High Explosive (HE) bombs of increasing capacity. A regular Avro Lancaster load designed for bombing of heavily industrialised cities (Mason, 1990) consisted of; 1 x 4,000 lb (1,667 kg) Amatol-filled ('Cookie'), 3x 1000 lb (455 kg) Minol or Tritonal filled, impact-fused High Capacity (HC) bomb short-finned, short-delay, tail-armed HE bombs, and up to six additional compartments filled with 4 lb or 30 lb incendiary bombs. An alternative configuration, used for the bombing

25   of factories, railyards and dockyards consisted of 14 x 1,000 lb (1,667 kg) Medium Case (MC), General Purpose (GP) short-finned HE bombs. The other mainstay of the RAF during this period was the Handley Page Halifax bomber which had a maximum bomb load of 13,000 lbs. (5,897 kg.). Typical loads consisted of; six 500 lb, six 1000 lb and two 2000 lb HE bombs or six 500 lb and four 2000 lb HE bombs. Unlike the Lancaster, the Halifax was not able to carry the 4000 lb or larger bombs. A third aircraft used by the RAF in combined or individual raids, was the De Havilland Mosquito, which was

30   capable of carrying a single 4000 lb bomb. The USAAF B-17 'Flying Fortress' bomber was able to carry a bomb load between 4,500 lb (2,000 kg) and 8,000 lb (3,600 kg) depending on the range of the mission. This aircraft too was capable of

carrying the larger 4000 lb bombs. The use of additional aircraft, such as the Wellington (4,500 lb bomb load) and Short Stirling bombers (8,000-14,000 lb bomb load) were gradually phased out during this period of the war.

Amatol, Minol and Tritonal represent various mixtures of tri-nitro-toluene (TNT) with aluminium or ammonium nitrate. Originally formulated to extend limited supplies of TNT, these mixtures provided similar or even enhanced explosive energy compared with TNT alone (Maienschein, 2002). Torpex was 50% more powerful than TNT. One metric ton of TNT has an explosive energy of $4.184 \ 10^9$ joules.

The 'Cookie', used by the RAF, was the first 'blockbuster' bomb. The minimum height at which an aircraft could safely drop the 4,000 lb 'cookie' without being damaged by the resulting shockwave was considered to be 6,000 feet (1,800 m). Even so, there are anecdotal accounts of aircraft being damaged despite following this instruction (Nelmes and Jenkins, 2002). Later versions, designed to penetrate and destroy reinforced underground bunkers, were even bigger. These so-called 'earthquake' bombs included the 12,000 lb (5,450 kg) 'Tall Boy' and the 22,000 lb (10,900 kg) 'Grand Slam'.

While the bombing of London continued during 1943-1945, it was mostly via V1 and V2 rockets which, while individually devastating, did not compare with the explosive energy associated with that of a heavy bombing raid.

Method

While there was much military activity throughout Europe and beyond during the Second World War, some of the largest bombing raids over Berlin and other European targets took place between 1943 and 1945. The dates of these heavy raids are listed in Table 1, along with an estimate of the combined weight of high explosives used. Where no reference to the total mass of HE bombs could be found for a particular raid, an estimate was made from the recorded number of aircraft, weighted by the mean ratio of HE to total bomb load from raids for which this information was known (0.667). These dates were selected to coincide with the latter part of the war, during which intensive bombing of London was less prevalent and the raids over mainland Europe were more intense (in terms of tonnage of high explosives dropped); the length of time spent bombing was usually much shorter; and more raids were occurring during the day (Middlebrook and Everitt, 1985). The times listed in this table mostly came from Berlin air-raid records (Demps, 2004). These were augmented with timings gleaned from various eye-witness accounts (see appendix A) in particular from the archives of 550 and 410 RAF squadrons whose records have been made available online. For aircraft records, the times of the first and last recorded bombing were used. For times taken from the times of air-raid alarms, the start and end of these warnings was used. Where no detail about the length of each raid was given, the start and end times are identical. The Berlin air-raid records were recorded in local time, while military records are most likely recorded in GMT. Where known, this time difference has been taken into account but for some this may introduce an uncertainty of one hour into the analysis. The start times from these raids were used as 'trigger' times in a superposed epoch or Chree analysis (Chree, 1913). This type of analysis is useful in geophysics for detecting a faint signal in a noisy data sequence (e.g. Davis et al, 1997). By calculating the median response of a dataset around these trigger times, any small but repeatable signal is reinforced while any signal not associated with the trigger

events is expected to occur at random and therefore cancel out when averaged. Medians were used in order to minimise the influence of outliers in the analysis.

The ionospheric data used in this study contain a strong seasonal variation introduced by annual and solar cycle variations in ion production and loss. In order that the seasonal distribution did not dominate the signal in any superposed epoch analysis,

5 a thirty day running median was subtracted from these data. Data from the resulting parameter, δfoF2 were then aligned according to the trigger times and combined in the superposed epoch study. Since it is not possible for the ionosphere to be influenced by a given raid prior to its occurrence, the study was further constrained to ensure that each trigger event was aligned with the first subsequent ionospheric data point within a given time window. The length of time between a raid and the subsequent ionospheric measurement, along with the minimum tonnage considered for a 'large' raid are subjective

10 variables in this analysis. In order to address this, the analysis was repeated for a range of time windows, from 0 to ≤23 hours and the size of a bombing raid was defined by the minimum estimated total tonnage of HE used, from ≥100 tonnes to ≥ 1000 tonnes in steps of 100 tonnes.

Results

The results of a typical superposed epoch analysis using the estimated start time of each bombing raid are shown in figure 1.

15 This analysis uses thresholds of ≤ 10 hours of the ionospheric observation for raids using ≥ 700 tonnes of HE for which there are 14 events. The median ionospheric response is shown as the black line in the top panel. Here the standard error in the median is shown as a grey shaded area around the line while the dashed and dotted lines represent the 95th and 99th percentiles obtained by repeating the analysis 10,000 times using a similar number of random trigger times drawn from the same epoch for which no major bombing raid has been identified. It can be seen that the ionosphere is significantly weaker

20 (1.9 standard deviations from the mean and around the 99th percentile level when compared with the range calculated from random trigger events) at time = 0 (the day of the bombing raids). In order to ensure that geomagnetic disturbances did not contribute to the ionospheric response, all events for which Ap exceeded 48 (Kp>5) were not considered. This is reflected in the low median values in Ap presented in the lower panel.

In order to investigate the sensitivity of this analysis to the arbitrary thresholds applied to the data, the analysis was repeated

25 for a range of thresholds in both the length of time between the raid and the ionospheric measurement (from 0 to 23 hours) and the size of raid as defined by the minimum amount of explosives used (from 100 to 1000 tonnes). The significance of each of these analyses was estimated by calculating the mean and standard deviation of all response times other than at time=0 and calculating the number of standard deviations the time=0 measurement was from this mean. The result of these analyses is shown in figure 2. The results are plotted on grid with maximum time between raid and measurement along the y

30 axis and minimum tonnage of the raid along the x-axis. The significance of the response at time=0 for each analysis is shown as a colour contour. As the thresholds used are varied, the number of raids included in each analysis will vary. This is reproduced in a similar grid also presented in figure 2, with the colour axis representing the number of events used in each

analysis. Two results are clear from this analysis. Firstly a significant (>2σ) ionospheric response is obtained for a broad range of trigger thresholds (4 ≤ time window ≤ 7 hours & 100 ≤ minimum tonnage ≤800 tonnes). Secondly, the most significant result (2.99σ) is seen for a time window of ≤ 5 hours and a minimum tonnage per raid of 300 tonnes. The results of this analysis are presented in figure 3, for which there are 20 events. Consideration of the number of events contributing to

5   each study suggests that 14 or more events are required before the random noise is reduced to a level where a significant signal can be detected. The ionospheric response for the analyses that contain the most events (with thresholds exceeding 15 hours) are not significant, indicating that these events do not contribute to the response observed within 5 hours of the ionospheric observations.

Discussion

10   From the analysis undertaken in this study, no minimum threshold in HE tonnage is resolved. In order to investigate this, data for smaller raids needs to be included. In addition to the major raids considered here, there are many more smaller-scale raids involving fewer or smaller aircraft. For example Mosquito aircraft were used in many hundreds of bombing raids throughout this period (MiddleBrook and Everitt, 1985). Given the fact that the current list of major bombing raids used in this study is by no means comprehensive, it is likely that information about many hundreds of smaller raids would need to be

15   included in order to tease out the signal of such raids from the background ionospheric variability in which further large raids were occurring. As such we consider this beyond the scope of the current study.

For the ionosphere (at ~ 250-350 km) above the UK to respond to bombing raids conducted at distances up to 1000 km away, the bombing must have generated pressure waves that were capable of propagating to ionospheric altitudes. A sound wave travelling this distance in the lower atmosphere would arrive within an hour. The speed of sound is temperature

20   dependent and the temperature decreases with altitude in the troposphere and mesosphere before increasing in the thermosphere. Since the thermosphere represents the most significant fraction of the vertical profile, it is likely that a soundwave propagating vertically as well as horizontally would arrive even sooner. One potential mechanism therefore is of a pressure wave propagating upwards in all directions. At higher altitudes its amplitude increases until it breaks in the upper atmosphere, depositing its energy as heat. The dominant ion species in the mid-latitude ionospheric F-region is O^+ whose

25   recombination rate is temperature dependant (Rees, 1989). A rise in the background thermospheric temperature would therefore result in an enhanced loss rate, with the equilibrium between production and loss being established at a lower peak electron concentration, as observed. Such equilibrium would be reached within minutes of perturbation, well within the resolution of the ionospheric data.

If the bombing resulted in the generation of shock waves or atmospheric gravity waves, their horizontal propagation speed

30   would need to be of the order of 300 km/hour while the vertical velocity component would need to be around 100 km/hour in order to affect the atmosphere above Slough.

Infrasonic waves generated by explosions are launched preferentially in a vertical direction. Any impact on the upper atmosphere overhead would then require horizontal transport to move that region over Slough. For the scale sizes involved this would require winds of the order of 300 km/hour to blow consistently in a westward direction for the impact to be observed within three hours, as suggested by the data. For this to happen continuously throughout the epoch being studied is

5   unlikely.

Whatever the cause of the ionospheric depletion, the impact appears to last less than 24 hours, since only the subsequent noon value is affected.

One metric ton of TNT has an explosive energy of 4.184 10^9 joules, which is of the same order of energy as a cloud to ground lightning stroke. While a ground-based explosion and a lightning stroke are somewhat different in location and

10   duration, it is not unfeasible that wave energy generated by lightning could also influence the ionosphere in a similar way. Since the occurrence of lightning has distinctive diurnal and seasonal cycles, it is feasible that this mechanism could contribute to the observed seasonal anomaly in ionospheric F-region electron concentrations (Rishbeth and Muller-Wodarg, 2006).

Conclusions

15   We have shown that the influence of major bombing raids over Europe during the latter half of WWII caused a significant depletion of the ionosphere above Slough, UK. This depletion is consistent with an enhanced ionospheric loss rate resulting from thermospheric heating via the dissipation of wave energy in the upper atmosphere. While the list of bombing raids used in this analysis is by no means complete, it is nevertheless sufficient to reduce the background noise in a composite analysis to a level where the ionospheric response to bombing is statistically significant. No lower limit to the minimum mass of

20   explosives required to generate such a response was revealed in this study, though raids using $\geq 100 < 800$ tonnes of HE were observed to deplete the ionosphere above Slough if they took place between four and seven hours before the ionospheric measurement. It is possible that raids occurring outside of these thresholds could still produce an effect but the current study contains insufficient data to test this.

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25   ground lightning stroke. Since the occurrence of lightning has distinctive diurnal and seasonal cycles, it is feasible that a similar mechanism could contribute to the observed seasonal anomaly in ionospheric F-region electron concentrations (Rishbeth and Muller-Wodarg, 2006).

The duration of the ionospheric effect appears to be limited to within 24 hours. This is currently restricted by the resolution of the digitised data. While hourly foF2 data were digitised from the original analogue ionograms, these data could be re-

30   examined to increase the temporal resolution and investigate the behaviour of other parameters such as the D, E, F1 and sporadic-E layers. The ionospheric sporadic-E layer has already been shown to be enhanced by terrestrial lightning (Davis and Johnson, 2005, Johnson and Davis, 2006, Davis and Lo, 2008). Examining the response of this layer to terrestrial

explosions would also provide further information on mechanism(s) involved in this process. The digitisation of these records is therefore highly desirable for a range of different research topics.

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10   lost their lives as a result of the bombing during WWII.

References

Astafyeva, E., Shalimov, S., Olshanskaya, E., and Lognonné, P., Ionospheric response to earthquakes of different magnitudes: Larger quakes perturb the ionosphere stronger and longer, Geophys. Res. Let., 40, 1675–1681, doi:10.1002/grl.50398, 2013.

15   Beker, C.: 'The Luftwaffe war diaries', Transworld Publishers Ltd, London, 1969.

Chree, C.: Some Phenomena of Sunspots and of Terrestrial Magnetism at Kew Observatory, Phil. Trans. Roy. Soc. Series A, 212, 75-116, 1913.

Davis, C. J., James, S., Clements, K., Clarke, B.: A blast from the past, Astronomy & Geophysics, 54, 4, 4.24–4.27, https://doi.org/10.1093/astrogeo/att120, 2013.

20   Davis, C. J., and Johnson, C. G.: Lightning-induced intensification of the ionospheric sporadic-E layer, Nature, 435, doi:10.1038/nature03638, 2005.

Davis, C. J., and Lo, K.-H.: An enhancement of the ionospheric sporadic-E layer in response to negative polarity cloud-ti-ground lightning, Geophys. Res. Lett, 35, L05815, doi:10.1029/2007GL031909, 2008.

Davis, C. J., Wild, M. N., Lockwood, M., Tulunay, Y. K.: Ionospheric and geomagnetic responses to changes in IMF B_z: a
25   superposed epoch study, Ann. Geophys., 15, 217-230, 1997.

Demps, L.: Luftangriffe auf Berlin: Die Berichte der Hauptluftschutzstelle, Links Christoph Verlag, ISBN-10: 3861537060, 2014.

Gardiner, G.W., Lane, J.A., Rishbeth, H.: Radio and Space Research at Slough 1920-1981, The Radio and Electronic Engineer, 52, 3, 111-112, 1982.

Johnson, C. G., and Davis, C. J.: The location of lightning affecting the ionospheric sporadic-E layer as evidence for multiple enhancement mechanisms, Geophys. Res. Lett, 33, L07811, doi:10.1029/2005GL025294, 2006.

Jones, T. B., and Spracklen, C. T.: Nature, 250, 719, 1974.

Krasnov, V. M., Drobzheva, Y., V., Lastovic ka, Y.: Recent Advances and Difficulties of Infrasonic Wave Investigation in the Ionosphere, Surveys in Geophysics, 27:169–209, DOI 10.1007/s10712-005-6203-4, 2006.

Krasnova, V.M., Drobzheva, Ya.V., Venart, J.E.S., Lastovicka, J.: A re-analysis of the atmospheric and ionospheric effects of the Flixborough explosion, J. Atmos.Sol. Terr. Phys., 65, 1205–1212, 2003.

Maienschein, J. L.: Estimating Equivalency Of Explosives Through A Thermochemical Approach, Lawrence Livermore National Laboratory. UCRL- JC-147683 , 2002.

Mason, F. K.: 'The Avro Lancaster', 1990.

Middlebrook, M. and Everitt, C.: The Bomber Command War Diaries, an operational reference book, 1939-1945, Viking Penguin Inc, New York, ISBN: 0-670-80137-2, 1985.

Nelmes, M. and Jenkins, I.: G-for-George, Banner Books,Maryborough QLD, ISBN 1-875593-21-7, 2002.

Rees, M. H.: Physics and Chemistry of the Upper Atmosphere, Cambridge University Press, ISBN-10: 0521368480, 1989.

Regnat, K.-H.: Black Cross Volume 4: Heinkel He 111, Hersham, Surrey, UK: Midland Publishers, ISBN 978-1-85780-184-2, 2004.

Rishbeth, H.: Ionospheric science and geomagnetism, Q. J. Roy. Astro. Soc., 32, 409-421, 1991.

Rishbeth H., Muller-Wodarg I. C. F.: Why is there more ionosphere in January than in July? The annual asymmetry in the F2-layer, Ann. Geophys., 24, 3293-3311, 2006.

Yu, B., Xue, X., Lu, G., Ma, M., Dou, X., Qie, X., Ning, B., Hu, L., Wu, J., Chi, Y.: Evidence for lightning-associated enhancement of the ionospheric sporadic E layer dependent on lightning stroke energy, J. Geophys. Res., 120, 9202–9212, DOI: 10.1002/2015JA021575, 2015.

Date	Start Time (GMT+1)	End Time (GMT+1)	HE tonnage	Location
1943/01/16	19:33	21:48	150	Berlin
1943/01/17	19:32	22:21	133	Berlin
1943/03/01	21:39	23:50	343	Berlin
1943/03/27	22:08	00:13	429	Berlin
1943/03/30	01:20	03:22	315	Berlin
1943/08/23	23:41	02:35	2541*	Berlin
1943/11/18	20:11	22:23	798	Berlin
1943/11/22	19:30	21:12	1133	Berlin
1943/11/23	19:26	21:19	710	Berlin
1943/11/26	20:52	22:30	859	Berlin
1943/12/02	21:31	02:04	882	Berlin
1943/12/04	04:06	04:10	2156*	Leipzig
1943/12/16	19:24	21:04	947	Berlin
1943/12/20	19:39	19:54	2653*	Frankfurt
1943/12/24	03:29	05:09	710	Berlin
1943/12/29	19:23	20:23	1099	Berlin
1944/01/02	03:13	03:18	771	Berlin
1944/01/03	01:59	03:21	658	Berlin
1944/01/14	18:16	19:31	2092*	Brunswick
1944/01/20	18:56	20:25	1164	Berlin
1944/01/21	23:01	23:24	2653*	Magdeburg
1944/01/27	19:58	21:20	1067	Berlin
1944/01/29	02:50	04:20	10866	Berlin
1944/01/30	19:47	21:07	1069	Berlin
1944/02/15	20:23	22:15	1203	Berlin
1944/02/20	04:03	04:17	3367*	Leipzig
1944/02/21	04:00	04:12	2439*	Stuttgart
1944/02/24	23:10	01:15	3002*	Schweinfurt
1944/02/25	22:45	22:56	2000	Augsburg
1944/03/02	03:02	03:15	2262*	Stuttgart
1944/03/06	12:43	14:07	1196	Berlin
1944/03/09	12:45	14:34	554	Berlin
1944/03/15	23:18	23:28	3511*	Stuttgart
1944/03/18	22:01	22:14	3442*	Frankfurt
1944/03/22	12:43	13:54	515	Berlin
1944/03/22	21:50	22:05	3340*	Frankfurt
1944/03/24	21:48	23:12	1322	Berlin
1944/03/26	22:01	22:11	2833*	Essen
1944/03/30	01:16	01:26	3253*	Nuremberg

1944/04/09	23:55	23:55	899*	Villeneuve
1944/04/11	02:23	02:38	567*	Aulnoye
1944/04/11	22:42	22:45	1442*	Aachen
1944/04/19	02:20	02:31	1160*	Rouen
1944/04/21	02:09	02:15	1518*	Cologne
1944/04/23	01:15	01:27	2150	Düsseldorf
1944/04/24	23:45	01:05	2577*	Karlsruhe
1944/04/27	01:30	01:37	1975*	Essen
1944/04/28	02:06	02:14	1234	Friedrichshafen
1944/04/29	11:11	12:08	709	Berlin
1944/04/30	23:53	00:13	488*	Maintenon
1944/05/02	01:05	01:16	315*	Lyons
1944/05/04	00:25	00:32	1465*	Mailly
1944/05/07	10:34	11:44	1370	Berlin
1944/05/08	10:38	11:36	858	Berlin
1944/05/08	00:18	00:18	231*	Rennes
1944/05/10	00:11	00:12	1590*	Mardyck
1944/05/11	23:50	00:04	164*	Hasselt
1944/05/20	00:43	00:56	503*	Orleans
1944/05/24	10:30	11:34	430	Berlin
1944/05/25	02:23	02:30	1760*	Aachen
1944/05/28	02:25	02:31	687*	Aachen
1944/06/03	00:30	00:34	1053*	Calais
1944/06/05	01:14	01:18	1003*	coastal
1944/06/05	23:34	23:37	5000	Normandy
1944/06/07	01:22	02:30	3488	Acheres
1944/06/10	03:15	03:27	1571*	airfields
1944/06/11	01:09	01:18	1299*	railways
1944/06/13	00:59	01:09	1216*	Gelsenkirchen
1944/06/14	22:33	23:34	1230	Le Havre
1944/06/16	01:20	01:27	1265*	Sterkrade
1944/06/21	09:25	11:12	1220	Berlin
1944/06/22	15:44	15:52	912*	v-weapons
1944/06/24	02:00	02:15	856*	railways
1944/06/25	03:17	03:24	2929*	v-weapons
1944/06/27	03:31	03:39	2849*	v-weapons
1944/06/30	07:55	08:06	433*	Oisemont
1944/07/02	14:14	14:21	1580*	v-weapons
1944/07/05	01:21	01:44	1189*	railways
1944/07/06	01:50	02:01	647*	Dijon

1944/07/06	20:58	21:03	2139*	v-weapons
1944/07/07	21:50	22:02	2276	Caen
1944/07/13	01:52	02:02	1594*	railways
1944/07/18	05:45	05:55	6800	Caen
1944/07/19	01:30	01:40	672*	Scholven
1944/07/20	21:00	21:01	1405*	v-weapons
1944/07/23	01:06	01:34	2583*	Kiel
1944/07/25	01:46	01:53	2540*	Stuttgart
1944/07/26	01:57	02:11	2275*	Stuttgart
1944/07/29	01:47	02:10	2078*	Stuttgart
1944/07/30	08:31	08:38	2753*	Normandy
1944/08/01	19:59	20:03	1405*	Le Havre
1944/08/03	14:16	20:02	4479*	v-weapons
1944/08/04	18:01	18:08	1144*	v-weapons
1944/08/05	19:04	19:09	1286*	oil plants
1944/08/06	11:46	13:00	229	Berlin
1944/08/08	23:19	23:24	684*	oil plants
1944/08/10	12:00	12:06	416*	Dugny
1944/08/11	16:14	16:25	1816*	railways
1944/08/12	15:10	15:13	287*	u-boats
1944/08/13	02:15	02:19	541*	Falaise
1944/08/14	15:29	15:39	3146*	Normandy
1944/08/15	12:02	12:04	4048*	airfields
1944/08/26	01:01	01:12	1732*	Rüsselsheim
1944/08/26	23:10	23:14	1571*	Keil
1944/08/30	02:00	02:13	1690*	Stettin
1944/08/31	15:20	15:33	2364*	v-weapons
1944/09/03	17:28	17:33	2712*	airfields
1944/09/05	18:12	18:43	1339*	Le Havre
1944/09/06	09:20	09:38	1331*	Le Havre
1944/09/08	08:45	08:45	458*	Le Havre
1944/09/10	18:55	19:30	3902*	Le Havre
1944/09/12	22:54	23:13	1589*	Frankfurt
1944/09/16	23:45	23:47	859*	airfields
1944/09/17	11:35	12:05	3000	Boulogne
1944/09/17	18:15	18:18	487*	Flushing
1944/09/20	15:59	17:06	2534*	Calais
1944/09/23	21:19	21:30	2208*	Neuss
1944/09/26	12:21	12:27	2804*	Calais
1944/09/27	10:11	10:15	1292*	Calais

1944/09/28	01:04	01:04	909	Kaiserslautern
1944/10/03	14:37	14:45	1065*	Walcheren
1944/10/05	22:28	22:40	2248*	Saabrücken
1944/10/06	11:40	13:01	545	Berlin
1944/10/07	14:00	14:28	1437*	Emmerich
1944/10/11	16:40	16:56	1172*	Breskens-Flushing
1944/10/14	08:08	08:57	3574	Duisburg
1944/10/15	01:20	01:33	4040	Duisburg
1944/10/15	19:45	19:55	2031*	Wilhelmshaven
1944/10/19	20:30	20:37	2389*	Stuttgart
1944/10/23	19:30	19:53	4084	Essen
1944/10/25	15:29	15:46	4182	Essen
1944/10/28	15:46	16:04	2940*	Cologne
1944/10/30	21:02	21:21	3431	Cologne
1944/10/31	21:00	21:15	1972*	Cologne
1944/11/02	19:15	19:35	3957*	Düsseldorf
1944/11/04	19:39	19:52	2947*	Bochum
1944/11/09	10:42	10:47	1093*	Wanne-Eickel
1944/11/11	19:02	19:06	894*	Dortmund
1944/11/16	15:30	15:34	9400	Düren, Jülich, H
1944/11/18	19:03	19:03	1217*	Wanne-Eickel
1944/11/21	19:15	19:25	1159*	Aschaffenburg
1944/11/27	20:01	20:08	1900	Freiburg
1944/11/29	14:58	15:10	1249*	Dortmund
1944/12/04	19:34	19:47	2167*	Karlsruhe
1944/12/05	10:28	11:38	1060	Berlin
1944/12/06	20:40	20:53	2006*	Leuna
1944/12/12	19:37	19:43	2131*	Essen
1944/12/15	18:28	18:36	1386*	Ludwigshafen
1944/12/24	18:30	18:35	412*	Cologne/Nippes
1944/12/29	18:58	19:06	1379*	Scholven Buer
1944/12/31	18:46	19:00	640*	Osterfeld
1945/01/02	19:30	19:30	2166*	Nuremberg

Table 1: Dates, times, locations and estimated tonnage of major bombing raids conducted over Europe between 1943 and 1945. Times for Berlin raids were taken from the duration of air-raid warnings (Demps, 2014). Other times were taken from a variety of eye-witness accounts (see appendix A). Raids for which the total tonnage of HE bombs was estimated from the type and number of

5 **aircraft involved are marked with a *.**
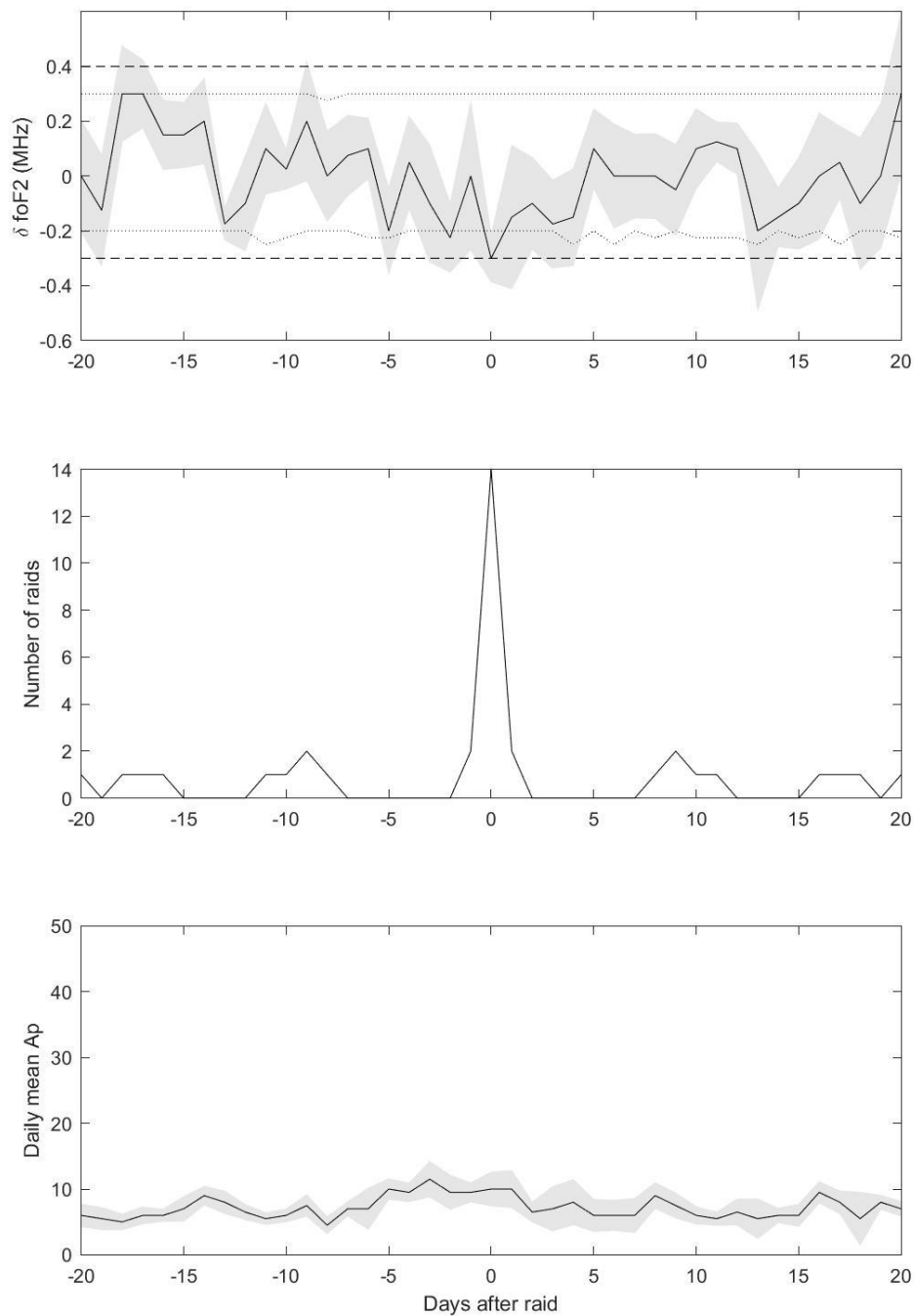
Figure 1: A superposed epoch analysis of the ionospheric response to major bombing raids over Europe. The black line in the top panel shows the median response in δfoF2 (foF2 with a 30 day median subtracted) to 60 bombing raids used as trigger event in the analysis. The grey shaded area represents the standard error in these median values while the dashed and dotted lines represent the 95th and 99th percentiles of 10,000 repeated analyses using random control days in which no bombing raids were identified. At time=0 (within 24 hour of the trigger events) δfoF2 is depleted (1.9 standard deviations from the mean). Arbitrary threshold values were used, corresponding to > 700 tonnes of high explosives per raids occurring within 10 hours before the noon ionospheric measurements.
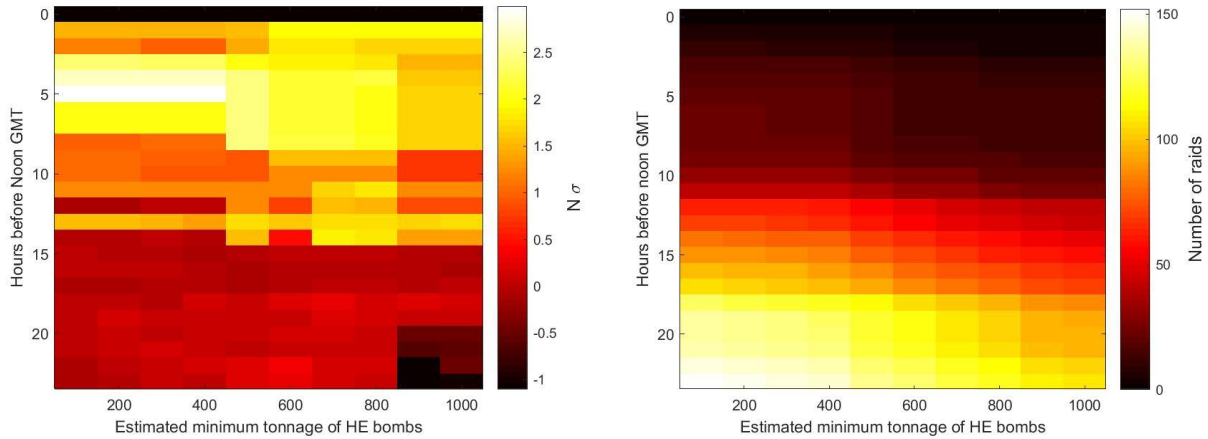
Figure 2: The left hand panel presents the relative significance of the ionospheric response at time zero (estimated standard deviations from the mean) for a range of thresholds. Events preceding the ionospheric measurements were considered for time windows from 0 to 23 hours ahead of the noon ionospheric measurement and the minimum tonnage of HE bombs used in each raid was also varied from 100 to 1000 tonnes. The most significant ionospheric response occurred for events occurring within five hours before noon, in which a minimum of 300 tonnes of HE bombs were dropped. The right hand panel presents the number of events contributing to each analysis. The significance of the response decreases if the threshold is extended beyond 5 hours ahead of the ionospheric measurement. This indicates that events occurring at larger time offsets are not contributing to the observed median response. The significance of the result 5 hours ahead decreases as the threshold on the minimum tonnage of HE bombs increases. This is likely due to the decreasing number of events contributing to each analysis.
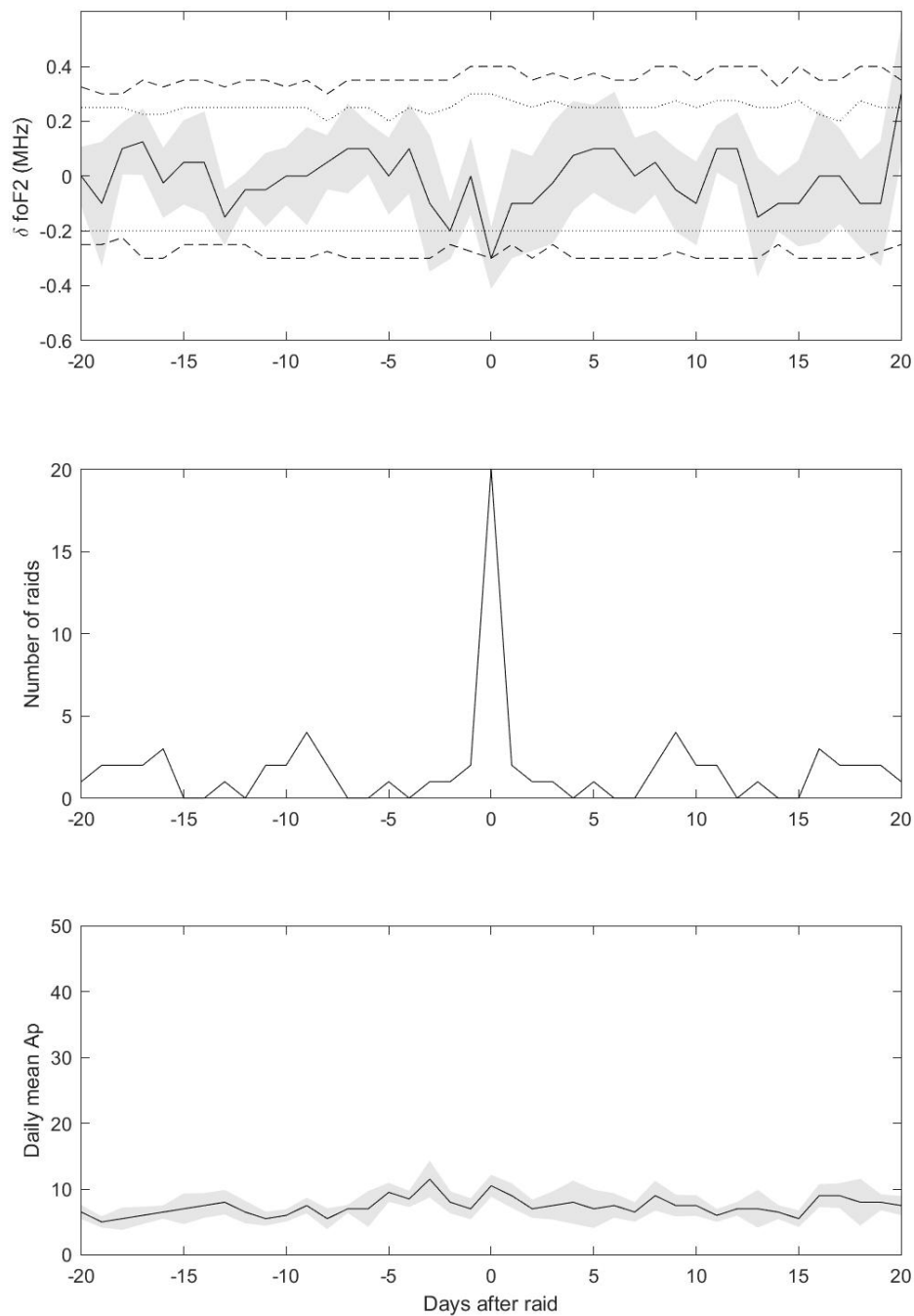
Figure 3: The same as figure 1, except for the most significant response using 20 bombing raids within threshold values corresponding to > 300 tonnes of high explosives per raids occurring within 5 hours before the noon ionospheric measurements. The ionospheric response at time=0 is around the 99th percentile of 10000 control studies using random dates on which no bombing raids are catalogued within the study.

5 **Appendix A**

The information used to determine the times of bombing raids came from a variety of sources. Berlin raids were determined from the information about air-raid alarms detailed in Demps (2014). The timings of most other raids were obtained from the online records of 550 Squadron RAF (www.550squadronassociation.org.uk/) or 420 Squadron RCAF (www.aquatax.ca/snowyowl.html) . Additional sources are listed below.

17 September 1944 – Boulogne

Source:http://www.rafcommands.com/forum/showthread.php?21928-Master-Bomber-required-Boulogne-17th-September-1944&p=128047&styleid=3

"AP 3 - Master Bomber was W/C DM Walbourn, 582 Squadron, H-Hour was 11.35."

15 *"AP 2 - Master Bomber was S/L NS Mingard, 582 Squadron, H-Hour was 12.05."*

20 September 1944 – Calais

Source: https://www.awm.gov.au/collection/C189567

"Units: No. 460 Squadron, RAF Bomber Command

20 *Accession Number: F02586*

Place made: France: Nord Pas de Calais, Pas de Calais, Calais

Date made: 20 September 1944

"RAF Bomber Command operational film No. 232. Time 15.59 - 16.20. Height: 4,300ft. Heavy attack by 646 (27 of 460 Sqn RAAF) Lancasters of Bomber Command on Calais."

25

27/28 September 1944 – Kaiserslautern

Source: http://www.vickersvaliant.com/619-squadron-ops-13---21.html

Extract from the 619 Squadron Operational Record Book (ORB) 27th September 1944: *"The primary target, KAISERSLAUTERN, was attacked and bombed from 4,500-ft at 0104 hours."* (on the 28th).

30

28 October 1944 - Cologne

Source: http://www.rafcommands.com/forum/showthread.php?7690-Bomber-Losses-28-October-1944

e.g. "LM182 Primary 20,000ft at 15.46 1/2hrs", "PB56 Primary 19,000ft at 16.04hrs"

6th November 1944 - Gelsenkirchen

Source: http://www.lokalkompass.de/gelsenkirchen/politik/6-november-1944-fliegeralarm-in-gelsenkirchen-d24273.html

"Um 13:47 wurde an diesem 6. November Fliegeralarm für Gelsenkirchen ausgelöst. 738 Bomber befanden sich im Anflug auf Gelsenkirchen. Vollalarm. Das Heulen der Sirenen trieb die Bewohner der Stadt in die Bunker und Schutzräume, gegen

5 *14:00 Uhr fielen die ersten Bomben." – "At 13:47 air raid alarm for Gelsenkirchen was triggered on this 6th of November. 738 bombers were approaching Gelsenkirchen. Full alarm. The howling of the sirens drove the inhabitants of the city into the bunkers and shelters, at 14:00 the first bombs fell."*

16th November 1944-Düren, Jülich, Heisburg

10 Source:http://www.heimatverein-

wassenberg.de/images/Wassenberg/archiv/publikationen/sonstige/FrenkenLancaster_PB_137.pdf

"Von immer lauter dröhnendem Motorenlärm alarmiert, befanden sich am 16. November 1944

um 15.30 Uhr alle Besatzungen an ihren Geschützen und gleich der erste Feuerschlag der Batterie Türk gipfelte in

15 *einem Volltreffer." – "Alarmed by the ever louder booming engine noise, all crews were at their guns on 16 November 1944 at 15:30 and the first fire of the battery Türk resulted in a direct hit"*

13th February 1945 – Dresden

Source: 'Dresden: Tuesday 13th February 1945' by Frederick Taylor, Bloomsbury, 2004.

20 *"At 9.51 p.m. in Dresden the air raid sirens sound, as they have so often during the last five years, and almost always a false alarm"*

"The first wave of destruction lasts between fifteen and twenty minutes, the second, two hours later and featuring even more aircraft, last slightly longer"

25 Source:http://www.550squadronassociation.org.uk/php-library/mysql-

utils/reports/rpt_squadron_operations.php?target=dresden

e.g. "NN715 Primary at 16,000ft at 01.30hrs", "RA503 Primary at 18,000ft at 01.43hrs"

14th February 1945 – Dresden

30 Source: http://news.bbc.co.uk/onthisday/hi/dates/stories/february/14/newsid_3549000/3549905.stm

"The Americans sent 450 B-17 Flying Fortress long-range bombers which arrived at 1230 local time."

27th February 1945 – Mainz

Source: http://self.gutenberg.org/article/WHEBN0041209387/Bombing%20of%20Mainz%20in%20World%20War%20II

"On 27 February 1945 the RAF flew 435 bombers to attack the city. Between 16:29 and 16:45 hours 1,500 tons of bombs were dropped, hit large parts of the Neustadt. St. Joseph and St. Boniface were destroyed."

1st March 1945 – Mannheim

Source:http://www.550squadronassociation.org.uk/php-library/mysql-
utils/reports/rpt_squadron_operations.php?target=Mannheim

e.g. *"26 aircraft with their crews took off at approximately 11.30hrs without incident to participate in a daylight attach on a large concentration of enemy troops reported to be in the vicinity of the Rhine bridgeheads near MANNHEIM"*

While no information on time over target is given for this date, from a previous raid over Mannheim on 1st February 1945, the flight time was approximately 4 hours and so the time over target is estimated to be around 15.30 GMT.

12 March 1945 – Dortmund

Source:http://www.550squadronassociation.org.uk/php-library/mysql-
utils/reports/rpt_squadron_operations.php?target=Dortmund

"23 aircraft took off without incident at approx. 12.50 hours on what was in almost every respect a repetition of the previous days effort. The only difference, the target was DORTMUND. The colour of the sky markers was changed and the time of the attack about tea time"

Source: https://75nzsquadron.wordpress.com/12345-attack-against-dortmund/

Bomb Load 1 x 4,000 H.C. 13 x 500 ANM.,

Primary Target – Dortmund

Tracking error of .02 large on GH H2S on at 16.50 on run up to target.

Flight

Up 13.01 12th March

Down 18.16 12th March

Total Flight Time 5 hours 15 minutes

25 April 1945 – Wangerooge

Source: http://www.go2war2.nl/artikel/4413/Air-raid-on-Wangerooge-25-April-1945.htm?page=4

"On 16:47 hours, finally an alarm was sounded at Wangerooge by the central communication post on the island that had received messages from transmitting posts on shore. This alarm was directed to the civilian population, that immediately ran for the air raid shelters. A number of them, however, was too late to find refuge. At 16:59 hours, the pathfinding Mosquitoes

dropped their coloured markers for the incoming bombers. Less than a minute later the planes came under anti aircraft fire...”

25 April 1945 – Berchtesgaden

5   Source: https://www.awm.gov.au/wartime/61/berchtesgaden

"The bombers arrived in two waves at 9 am and 10.30 am."

"Once the target was found, over 1,400 tons of bombs were dropped, including four 12,000 pound Tallboy bombs."