Visibility of the Gask Ridge Road from Simulated Watchtowers: a Monte Carlo Testing Approach

Abstract

The Gask Ridge system is a series of forts, fortlets, and timber watchtowers situated along a Roman road in northern Scotland. The high intervisibility of the watchtowers in the Gask Ridge system has resulted in the proposal of two main functions: one that the watchtowers were a signalling system and two that the watchtowers provided visibility of the Gask Ridge road for surveillance and monitoring. Despite this, only the former function has been assessed. This paper explores the function of the watchtowers along the Gask Ridge road using computational methods, including Monte Carlo hypothesis testing. The analytical approach, which is documented and reproducible with accompanying code, rejects that the watchtowers were randomly located along the Gask Ridge road, instead favouring the alternative hypothesis that the watchtowers were located to maximise the visibility of the road. Furthermore, it is possible to claim that the need to monitor the road shows a causal relationship with the location of the watchtowers, rather than associative. The findings support the interpretation that main function of the watchtowers was for the surveillance and monitoring of the Gask Ridge road, providing an early warning system of an attack from the Highlands (Woolliscroft, 1993).

1. Introduction

The Gask Ridge system is a series of forts, fortlets, and timber watchtowers situated along a Roman road in northern Scotland (Breeze, 2000, pp. 55–61; Woolliscroft, 1993; Woolliscroft and Hoffmann, 2006). Despite gaps in knowledge on the dating of the line (Breeze, 2000; Hanson and Friell, 1995; Woolliscroft, 1993), debate has shifted to understanding its function (Donaldson, 1988; Woolliscroft, 1993). As watchtowers along the road are highly inter-visible (Woolliscroft, 1993), two main functions (although not mutually exclusive) have been proposed: one, that the watchtowers were a signalling system (Donaldson, 1988; Woolliscroft, 1993, 2001; Woolliscroft and Hoffmann, 2006, p. 230); and two, that the watchtowers provided visibility of the Gask Ridge road and would have
allowed for surveillance and monitoring (Breeze, 2000, p. 59; Donaldson, 1988; Hanson and Maxwell, 1983; Woolliscroft, 1993; Woolliscroft and Hoffmann, 2006, p. 230). Whilst the function of the watchtowers as a signalling system has been challenged by Woolliscroft (1993 and references therein), the latter function remains largely unexplored, particularly through the use of computational methods.

2. Background

2.1 Gask Ridge system in Northern Scotland

The Roman Gask Ridge system is a series of forts, fortlets, and watchtowers along a Roman road from Glenbeck to Bertha (Breeze, 2000, p. 59; Woolliscroft and Hoffmann, 2006, p. 34) (Fig. 1). Although poorly dated due to the lack of dating evidence, the fortifications are thought to be Flavian in date (Woolliscroft, 1993), with the road and watchtowers along the Gask Ridge playing an integral role in the first-century defence of northern Scotland (Woolliscroft and Hoffmann, 2006, p. 73).

![Fig. 1. Northern Scotland in the late first century. Based on Woolliscroft and Hoffmann (2006, p. 34)](image_url)
The function of the Gask Ridge system however has been debated, with multiple purposes suggested (Donaldson, 1988; Hanson and Maxwell, 1983; Robertson, 1974; Woolliscroft, 1993). Donaldson (1988) argued that the close spacing of the watchtowers along the Gask Ridge road suggested that the watchtowers acted as a signalling system. This has been challenged by Woolliscroft (1993 and references therein), who noted that signals being relayed from watchtower to watchtower would be unnecessary and inefficient due to the overlapping watchtower field of views. Instead, Woolliscroft (1993, 2002) has suggested that the watchtowers may have acted as observation posts, allowing for tight surveillance of the Gask Ridge road. Furthermore, the Gask Ridge system would have blocked access to the fife peninsula from the Highlands and provided an early warning system of an attack (Woolliscroft, 1993).

The auxiliary Roman forts of Ardoch, Strageath and Bertha are of turf- and timber construction and range from 4.4 to 9.6 ha in size (Sheldon, 2005, p. 216; Woolliscroft and Hoffmann, 2006). Eighteen timber watchtowers are interspersed between these forts (Woolliscroft and Hoffmann, 2006, p. 86), with the fortlets of Kaims Castle and Midgate positioned on hilltops offering a wide field of view (Woolliscroft and Hoffmann, 2006, pp. 104, 134). The watchtowers differ in construction type, with the southern section between Ardoch and Strageath being double ditched, whilst the northern section between Strageath and Bertha are single ditched (Woolliscroft and Hoffmann, 2006, Appendix). Similarly, the spacing of the watchtowers between the two sections are different, with the southern section showing a regular spacing of 3/5 of a Roman mile (887m), compared to the more random spacing of the watchtowers further north (Woolliscroft, 1993, p. 293). The difference in construction type and watchtower spacing between the two sections has been thought to suggest that the two regions represent different construction teams working simultaneously, rather than different time periods (Hanson and Friell, 1995, p. 513; Woolliscroft and Hoffmann, 2006, Appendix).

The northern section of the Gask Ridge system represents the ridge of land known as the ‘Gask Ridge proper’ (Robertson, 1974; Southern, 2016). Located along the valley of Strathearn, Perthshire (Robertson, 1974), the Gask Ridge proper is the northern limits of permanent occupation in
Scotland (Hanson and Maxwell, 1983). The ridge contains 10 watchtowers and has been noted to be
the best preserved examples of watchtowers within the whole Gask Ridge system (Hanson and Friell,
1995). The spacing between the watchtowers ranges from 800m to 1,520m (Woolliscroft, 1993), and
are connected via the road that runs alongside. As all the entrances of the watchtowers are orientated
towards the road, it has been suggested that the road either predates the watchtowers, or were built (or
at least planned) together (Woolliscroft and Hoffmann, 2006, Appendix). The location of the road has
been identified between the fort of Strageath and Westmuir watchtower (Robertson, 1974;
Woolliscroft and Hoffmann, 2006) (Fig. 2), however its location becomes more difficult to trace as it
continues towards the fort of Bertha on the River Tay (Woolliscroft and Hoffmann, 2006, p. 138).

![Fig. 2. Gask Ridge system fortifications along the Gask Ridge proper](image)

2.2 Research problem

This paper will attempt to address some of the questions related to the visibility of the Gask Ridge road from the watchtowers between the Roman fort of Strageath and the Westmuir watchtower. This investigation will focus on the simulation of spatial patterns that explain the spatial interaction structure of the watchtowers along the Gask Ridge road. Using Monte Carlo hypothesis testing, this paper statistically analyses whether the locations of watchtowers were randomly situated whilst abiding to the spatial interaction structure of the watchtowers, or whether they were selected in order to maximise visibility of the Gask Ridge road.
The testable hypothesis is formally stated as:

(1a) $H_1$: The locations of the watchtowers between Strageath and Westmuir are situated to maximise cumulative visibility of the Gask Ridge road.

(1b) $H_0$ (null): The locations of the watchtowers between Strageath and Westmuir are randomly situated (whilst abiding to the spatial interaction structure of the watchtowers) within 190m either side of the Gask Ridge road and are not situated to maximise cumulative visibility of the Gask Ridge road.

2.3 Simulating the null hypothesis in visibility studies

When assessing whether sites in the landscape were constructed in order to enhance visibility, multiple studies have stressed the importance of comparing the site sample against hypothetical ‘background’ samples that are generated within geographically similar areas (Bourgeois, 2013, p. 131; Fisher et al., 1997; Kvaamme, 1990; Lake et al., 1998; Lake and Woodman, 2003; Smith and Cochrane, 2011; Wheatley, 1995). From this, visibility measurements can be compared to identify if there are significant differences between the site sample and the geographically similar background samples (Smith and Cochrane, 2011). The background samples within geographically similar areas have often been generated through random sampling or stratified random sampling (i.e. complete spatial randomness) (e.g. Bourgeois, 2013, p. 131; Carrero-Pazos, 2018; Fisher et al., 1997; Lagerås, 2002; Lake and Woodman, 2003; Smith and Cochrane, 2011). However, the null hypothesis of complete spatial randomness ignores the spatial interaction between sample points (i.e. second-order effects) which result in the distribution of sample points not reflecting the true conditions of site selection (e.g. Illian, 2008, p. 83; Knitter and Nakoinz, 2018). Although the potential to include distance preferences and constraints when simulating sample points has been noted (e.g. Nakoinz and Knitter, 2016, p. 240; O'Sullivan and Unwin, 2010, p. 165), its application in statistical visibility studies is uncommon (but see Wright et al., 2014).
2.4 Testing the null hypothesis in visibility studies

The need to statistically analyse whether sites were constructed in order to enhance visibility has been advocated since the 1990s (Fisher et al., 1997; Kvamme, 1990; Wheatley, 1995). A popular statistical method to explore this question is the Kolmogorov-Smirnov (K-S) test (e.g. Déderix, 2015; Lake et al., 1998; Smith and Cochrane, 2011; Wheatley, 1995). By comparing the relative frequencies of cells that are visible from the site sample against the frequencies of cells that are visible from the background sample, the statistical significance of the site sample results can be assessed (Smith and Cochrane, 2011; Wheatley, 1995). The accuracy of the K-S test is dependent on whether the distribution of the background population of viewsheds is ‘exactly’ determined through the calculation of a total viewshed (Llobera, 2003; Llobera et al., 2010) or estimated through extrapolating between known points of the cumulative distribution (Kvamme, 1990). However, the calculation of the exact distribution of the background population of viewsheds is often prohibited by the computing time required (Fisher et al., 1997; Llobera et al., 2010), whilst estimating the distribution impacts the statistical validity of the K-S test (Fisher et al., 1997; Kvamme, 1990).

An alternative method to test the null hypothesis in visibility studies is Monte Carlo hypothesis testing (e.g. Fisher et al., 1997; Lagerås, 2002; Lake and Ortega, 2013; Marsh and Schreiber, 2015; Trick, 2008). Monte Carlo Hypothesis testing works by ranking a summary statistic describing the observed data against summary statistics from random samples generated in accordance with the hypothesis being tested (i.e. the null hypothesis). From this, the exact probability of the rank of the observed data occurring can be calculated (Besag and Diggle, 1977; Fisher et al., 1997; Hope, 1968). The benefits of Monte Carlo hypothesis testing in visibility analysis include being able to test the null hypothesis of spatial patterns where the underlying distribution is unknown or difficult to calculate (Baddeley et al., 2016, p. 384; Besag and Diggle, 1977; Fisher et al., 1997; Hope, 1968; Myllymäki et al., 2017), requiring a relatively small number of simulations (with 99 simulations being common) to compare against the observed data (Baddeley et al., 2016, p. 384; Besag and Diggle, 1977; Fisher et al., 1997; Gentle, 2002, p. 56; Hope, 1968), as well as removing any possible subjectivity in the analysis (Wright et al., 2014).
2.5 Visibility studies in archaeology

The application of GIS-based visibility methods have become commonplace in archaeology (Lake and Woodman, 2003; Verhagen, 2018; Wheatley and Gillings, 2002). Viewshed analysis has been used to better understand why sites were in a particular place (e.g. Fisher et al., 1997), to assess the intervisibility of sites and features in the landscape (e.g. Supernant, 2014; Wright et al., 2014), and to assess the defensibility of sites (e.g. Martindale and Supernant, 2009; Sakaguchi et al., 2010).

A common visibility method is cumulative viewshed analysis, which calculates how many times a raster cell is seen from one or more viewpoints by adding binary viewsheds together (Ruggles et al., 1993; Wheatley, 1995). Although cumulative viewshed has been criticised for not incorporating the decay in visibility as distance increases (Fisher, 1994; Ogburn, 2006), the issue can be overcome by limiting the maximum distance of visibility to 1km, which is the maximum distance at which clarity of visibility can be considered perfect (Fisher, 1994) or through the application of individual distance viewshed, whereby the viewshed distances represent potential visual control over individuals (Fábrega-Álvarez and Parcero-Oubiña, 2019).

3. Methods

3.1 Data acquisition

All location data for the known Roman sites (watchtowers and forts) were extracted from the Historic Environment Scotland (HES) Canmore database. The National Grid References of the Roman sites were reported to 8 numbers, resulting in an accuracy of within 1m. The section of the Gask Ridge Roman road between the Roman Forts Strageath and Bertha, also known as Margary 9b (Margary, 1973), was downloaded from Bishop (2014). The digital elevation model (DEM) is sourced from the Ordnance Survey Terrain 5 DTM elevation, which has a cell size of 5m and vertical error of ±2.5m (Ordnance Survey, 2017). When assessing the impact of DEM errors on viewshed results, Rueses Bitrià (2008) found that the vertical error of ±1.39m resulted in viewsheds that were very similar, with the reasoning being the low DEM error. Therefore, this study has assumed that the vertical error of ±2.5m should not have a consequential impact on the results. Nonetheless, it should be noted that
the use of Monte Carlo simulation for incorporating error into the viewshed results is a potential
option for further exploration (e.g. Fisher, 1992, 1991), however computational limitations prohibit
this approach in the current study. The data and code are available at 10.5281/zenodo.3953468.

3.2 Simulating Watchtowers along the Gask Ridge road

The simulated background samples were limited to the region between the Roman fort of Strageath
and the Midgate watchtower. A buffer of 1750m around Strageath was removed from the Roman
road. 1750m is the distance between the Roman fort of Strageath and the closest watchtower to the
east (Woolliscroft and Hoffmann, 2006, p. 120) and ensures that the simulated sample points cannot
be placed too close to Strageath. Similarly, a buffer of 800m around the Westmuir watchtower was
removed from the Roman road. Lastly, the simulated background samples were limited to 190m either
side of the Roman road, reflecting the high likelihood that the road either predates the watchtowers or
were planned together (Woolliscroft and Hoffmann, 2006, Appendix). The distance of 190m
represents the maximum calculated distance between the watchtowers and the road, and ensures that
the background samples accurately reflect the conditions of site selection.

The more random spacing of the watchtowers in northern section between Strageath and
Bertha is a noted characteristic (Woolliscroft, 1993, p. 293). In particular, the spacing of the 10
watchtowers along the Gask Ridge Proper ranges from 800m to 1,520m, with a mean of 1,165m and a
standard deviation of 280m. Therefore, it is important to include this information when simulating
background sample points. In order to simulate background samples that reflect the spatial interaction
structure of the watchtowers, each randomly simulated sample point is at least 800m from all other
sample points and less than 1,520m from the nearest sample point. The distances of 800m and 1,520m
reflect the minimum and maximum distances between watchtowers along the Gask Ridge Roman road
in the Gask Ridge proper (Breeze, 2000, p. 59; Donaldson, 1988; Woolliscroft, 1993). The initial
sample point was set to the location of the western-most watchtower (i.e. Parkneuk). This was done as
it is assumed that the first watchtower would not be randomly placed within the landscape, and
instead reflects the suggestion that the watchtowers along the Gask Ridge may have been laid out west-to-east (Woolliscroft, 1993, p. 294).

3.3 Cumulative viewshed analysis

Viewsheds were calculated from all of the ten watchtower locations along the Gask Ridge Roman road using the r.viewshed module in GRASS (GRASS Development Team, 2012). The heights used for the watchtowers were 7m and 10m (Woolliscroft, 2001). These represent the postulated minimum and maximum heights of the watchtowers based on remains of postholes (Woolliscroft, 2002). The standard height of an observer used in this analysis is 1.65m, resulting in the final observer heights of 8.65m and 11.65m. The maximum distance visible from the watchtowers when assessing the visibility of the Gask Ridge road was 600m. 600m reflects the threshold at which it is possible to begin recognising the identity and behaviour of an individual (Fábrega-Álvarez and Parcero-Oubiña, 2019).

The ten viewsheds at each observer height were added together to create two cumulative viewsheds showing the total number of cells that are visible from the watchtowers, as well as how many times each cell is visible (Ruggles et al., 1993; Wheatley, 1995). This process was repeated for the simulated sample points representing the background samples for both heights.

3.4 Monte Carlo Hypothesis Testing

In order to assess the statistical significance of the visibility of the Gask Ridge road from the watchtowers, this research uses Monte Carlo hypothesis testing. The Gask Ridge road line was converted to a total of 5,289 points at 5m intervals, reflecting the cell size of the Ordnance Survey Terrain 5 DTM elevation data (Ordnance Survey, 2017). The summary statistic used in this research is the sum of the cumulative number of cells that coincide with the points along the Gask Ridge road. The resultant statistic represents the maximum visibility of the Gask Ridge road from the watchtowers, taking into account that a single location along the road may be visible from more than one watchtower. As the summary statistics are discrete values, with the same summary statistic value possible for multiple random samples, the upper bound for the significance level was chosen (Besag and Diggle, 1977). More specifically, 99 random samples were
generated, thus the probability of the summary statistic of the observed data being at least as extreme
as the summary statistic of the random samples is $p(\text{observed data} \; \text{summary statistic}) = \frac{1}{99 + 1} = 0.01$. The results will be deemed statistically significant if the probability of seeing the observed data
$= 0.01$ and, therefore, the null hypothesis (H0) will be rejected in favour of the alternative hypothesis
(H1).

4. Results and Discussion

4.1 Visibility of the Gask Ridge Roman road from the watchtowers

The cumulative viewsheds identified how many times each cell is seen from the watchtowers (Fig. 3).

Fig. 3. Cumulative viewshed of the Gask Ridge Roman road from the watchtowers.

A: 8.65m observer height. B: 11.65m observer height
Table 1 shows the number of visible cells that coincide with the Gask Ridge road for both observer heights. The observer height of 11.65m resulted in an increase of 190 (4.8%) more visible cells than when compared to the sum of the cumulative number of visible cells from an observer height of 8.65m. The increase of visible cells from an observer height of 11.65m reflects the increase in height and subsequent higher chance of seeing more than when at the lower height of 8.65m.

Table 1. Number of visible cells that coincide with the Gask Ridge road from both watchtower observer heights

<table>
<thead>
<tr>
<th>Sum of cumulative number of visible cells</th>
<th>Observer height of 8.65m</th>
<th>Observer height of 11.65m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3,929</td>
<td>4,119</td>
</tr>
</tbody>
</table>

4.2 Statistical analysis of Gask Ridge road visibility

The background samples that were generated based on the spatial interaction structure of the watchtowers resulted in 99 simulated cumulative viewsheds for each observer height (Fig. 4).

Fig 4. Examples of Monte Carlo simulation cumulative viewsheds from simulated watchtowers along the Gask Ridge Roman road. A and C: 8.65m observer height. B and D: 11.65m observer height
Table 2 shows statistical summaries of the visibility of the Gask Ridge road from the true locations of the watchtowers and the 99 simulations. The sum of the cumulative number of visible cells that coincide with the Gask Ridge road from the true locations of the watchtowers with an observer height of 8.65m results in an increase of 892 (29.4%), 497 (14.5%), and 206 (5.5%) visible cells when compared to the minimum, mean, and maximum, respectively, of the 99 simulated results representing the null hypothesis. Similarly, the number of visible cells from watchtowers with an observer height of 11.65m results in an increase of 707 (20.1%), 685 (14.3%), and 87 (2.2%) visible cells when compared to the simulated results.

Table 2. Statistical summaries of the sum of the cumulative number of visible cells that coincide with the Gask Ridge road from the 99 simulations of the watchtower locations and the true locations of the watchtowers

<table>
<thead>
<tr>
<th>Observer Height</th>
<th>Median of the sum of the cumulative number of visible cells (simulated)</th>
<th>Min of the sum of the cumulative number of visible cells (simulated)</th>
<th>Max of the sum of the cumulative number of visible cells (simulated)</th>
<th>Sum of the cumulative number of visible cells from true locations</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.65m</td>
<td>3,432</td>
<td>3,037</td>
<td>3,723</td>
<td>3,929</td>
</tr>
<tr>
<td>11.65m</td>
<td>3,804</td>
<td>3,412</td>
<td>4,032</td>
<td>4,119</td>
</tr>
</tbody>
</table>

For both observer heights of 8.65m and 11.65m, it is evident that the sum of the cumulative number of visible cells from the true locations of the watchtowers that coincides with the Gask Ridge Roman road is greater than the maximum of the sum of the cumulative number of visible cells from the watchtower locations of the 99 simulations. Therefore, the null hypothesis *The locations of the watchtowers are randomly situated (whilst abiding to the spatial interaction structure of the watchtowers) within 190m either side of the Gask Ridge road and are not situated to maximise visibility of the Gask Ridge road* can be rejected. The results are statistically significant (*p* = 0.01) and suggest that the watchtowers with heights of 8.65m and 11.65m were located to maximise the sum of the cumulative visibility of the Roman road along the Gask Ridge proper. Nonetheless, as noted by Lake and Ortega (2013) and Wheatley (1995), it is important to remember that hypothesis testing
cannot definitively disprove in this case that the watchtowers were not situated to maximise visibility of the Gask Ridge road, but rather to increase confidence in the alternative hypothesis through the rejection of the null hypothesis. However, in this circumstance, it is possible to claim that high visibility was an important parameter in site choice, with the need to monitor the road showing a causal relationship with the location of the watchtowers, rather than associative. This suggests that the main function of the watchtowers along the Gask Ridge proper were for the surveillance and monitoring of the Gask Ridge road, providing an early warning system of an attack from the Highlands (Woolliscroft, 1993).

5. Conclusion

This paper assessed the cumulative visibility of the Gask Ridge road from watchtowers situated along it. Using Monte Carlo hypothesis testing, this research has rejected the null hypothesis in favour of the alternative hypothesis that the watchtowers were situated to maximise the sum of the cumulative number of cells along the Gask Ridge road in the Gask Ridge proper (p = 0.01). In particular, the location of the watchtowers with observer heights of 8.65m and 11.65m resulted in 206 (5.5%) and 87 (2.2%) more visible cells, respectively, than when compared to the maximum number of cumulative visible cells generated by the 99 simulations. This study suggests that the need to monitor the road shows a causal relationship with the location of the watchtower, rather than associative. Lastly, when assessing the statistical significance of visibility measurements, this paper argues against hypothetical background samples generated through random sampling. Instead, background samples should incorporate the spatial interaction between the known site samples, resulting in spatial points that better capture the underlying pattern.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
Acknowledgements

I am indebted to Sian Gilbert for commenting on early drafts of the text, though of course, all mistakes are my own. The analyses have been conducted in R (R Core Team, 2018) and GRASS (GRASS Development Team, 2012). Two reviewers provided welcome critical feedback on the manuscript.


