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Key Points:

- AuroraWatch UK is an automated, magnetometer-based, aurora alert system for the UK and Ireland
- It has been issuing free alerts of potential auroral visibility since September 2000 to over 100,000 subscribers
- We present over 150,000 h of AuroraWatch UK activity status, including nearly 9,000 h of elevated geomagnetic activity.

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AuroraWatch UK: An Automated Aurora Alert System

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Abstract The AuroraWatch UK aurora alert service uses a network of magnetometers from across the United Kingdom to measure the disturbance in the Earth's magnetic field caused by the aurora borealis (northern lights). The service has been measuring disturbances in the Earth's magnetic field from the UK and issuing auroral visibility alerts to its subscribers, since September 2000. These alerts have four levels, corresponding to the magnitude of disturbance measured, which indicate from where in the UK an auroral display might be seen. In the following, we describe the AuroraWatch UK system in detail and reprocess the historical magnetometer data using the current alert algorithm to compile an activity database. This data set is composed of over 150,000 h (99.94% data availability) of magnetic disturbance measurements, including nearly 9,000 h of enhanced geomagnetic activity.

Plain Language Summary Witnessing the aurora borealis, more commonly known as the northern lights, is a much desired event, often featuring in people's "bucket lists." Although rarer than in more arctic regions, such as Scandinavia, Iceland, and Canada, the northern lights are seen from the UK too. To help with this aurora-hunting endeavor, the AuroraWatch UK service sends alerts to its followers when UK aurora sightings may be possible. The service has been running for 17 years and has over 100,000 subscribers. We have recorded over 150,000 h of magnetic field measurements including nearly 9,000 h where geomagnetic activity was large enough for an aurora to potentially be seen from at least some parts of the UK.

1. Introduction

The aurora (more commonly known as the northern/southern lights) are a particularly engaging manifestation of the effects of space weather on the Earth. Witnessing an aurora firsthand is an extremely popular desire among the general public, particularly for those at subauroral latitudes, where auroral visibility is possible but less common, such as in the UK (Wild, 2006). As such, a wide variety of services exist which attempt to alert their users to when an aurora might be visible near them. These alerts are usually based on predicted geomagnetic indices, such as the *K_p* index (Bartels et al., 1939; Wing et al., 2005), and/or user sightings (e.g., Case et al., 2016).

These aurora alert services are often run informally through popular social media platforms, such as Facebook and Twitter, though some are stand-alone services run by the scientific community, for example, the space weather scale forecast of the U.S. National Oceanic and Atmospheric Administration (NOAA) (Poppe, 2000) and the Aurorasaurus citizen science alerts (MacDonald et al., 2015).

The aurora generally form in an oval around the northern and southern geomagnetic poles. During periods of intense aurora, that is, as the result of substorm activity, the oval expands and can be seen from latitudes further equatorward than usual (Elphinstone et al., 1996). At their simplest, the aurora are the result of a flow of electrically charged particles into and out of the upper atmosphere which collide with and subsequently excite the resident atmospheric gases. Some time later the excited gases relax energy states and emit photons, thus producing the lights of the aurora.

The colors of the aurora are dependent upon the particular atmospheric gases that are excited. For example, the most familiar color associated with the aurora is the green 557.7 nm emission which is the result of excited oxygen atoms in the 100–200 km altitude range. However, other colors are produced at different altitudes (i.e., red 630.0 nm at altitudes above 200 km) and by other atmospheric gases (e.g., blue 427.8 nm from singly ionized molecular nitrogen).

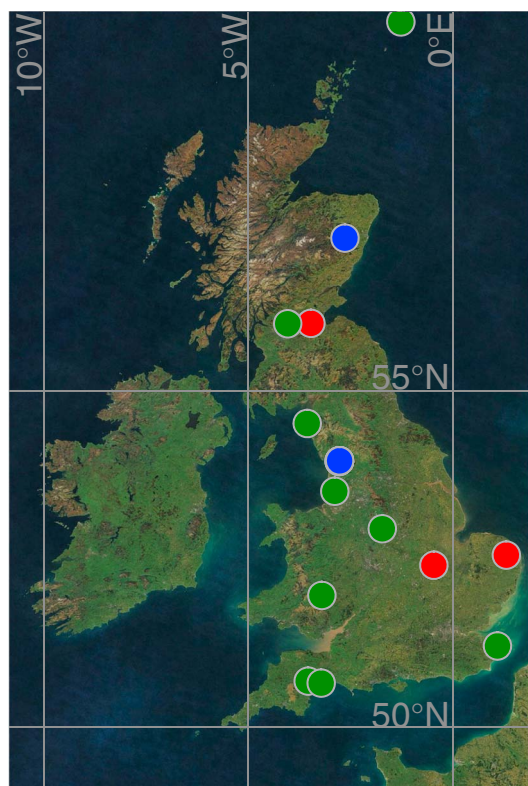


Figure 1. A composite NASA satellite image of the British Isles (including the UK and Republic of Ireland). Shown in blue are the locations of the magnetometers that form SAMNET, in green are the AuroraWatchNet magnetometers (including the Met Office magnetometer in Exeter, England), and in red are the magnetometers from the BGS School Magnetometer Network.

Variations in the location and intensity of the near-Earth current systems that drive the aurora result in disturbances to the local terrestrial magnetic field. These disturbances can be measured on the ground using magnetometer networks (Love, 2008) and can be used to create indices of geomagnetic activity (e.g., Davis & Sugiura, 1966; Sugiura, 1964). The geomagnetic indices act as proxies for the strength of the aurora and near-Earth current systems which enables the location and extent of these systems to be estimated (e.g., Carbary, 2005; Cramoysan et al., 1995).

AuroraWatch UK (AWUK) is an automated aurora alert service run with the specific aim of alerting residents of the British Isles (including the UK, Republic of Ireland, and the Crown Dependencies) of when an auroral display might be visible to them. The service is incredibly popular, with over 100,000 subscribers, and has a loyal user base from a wide range of backgrounds (Massey, 2012).

As described in section 2, AWUK uses a suite of ground-based magnetometers to issue alerts of auroral visibility based on disturbances in the magnetic field measured from the UK. These alerts, as described in section 3, have various levels which indicate from where in the British Isles one might be able to see the aurora.

AWUK has been operational since September 2000 and was created by the University of York, UK, as an offshoot to their Sub-Auroral Magnetometer Network (SAMNET) project (Yeoman et al., 1989). Since April 2003, however, AWUK has been run by Lancaster University, UK, which took over management of the SAMNET project (Wild, 2006). Throughout this operational period several magnetometers have served as the primary magnetometer for AWUK and several methods of calculating the alert level have been employed. In section 4, we present details of the frequency of the alerts over the past 16 years.

In section 5, we summarize the AWUK system and the historical data presented here. Furthermore, we discuss the future scientific studies that AWUK could facilitate, as well as the applicability of AWUK to other aurora alert systems across the globe.

2. Instrumentation

The number and location of the magnetometers that form SAMNET, now operated by the Space and Planetary Physics group in the Department of Physics at Lancaster University, has changed over time. In its current form, only two magnetometers are directly under SAMNET control. These two magnetometers, shown in blue in Figure 1, are located at Crooktree (near Aberdeen), Scotland, and Lancaster, England.

The SAMNET magnetometers are now supplemented with AWUK's own magnetometer network "AuroraWatchNet" (AWN), which includes a magnetometer owned by the UK's Meteorological Office (Met Office), and the British Geological Survey's (BGS) School Magnetometer Network (Beggan & Marple, 2016). The locations of these sites are also shown in Figure 1 (in green and red, respectively).

The primary magnetometer used by the AWUK system to generate alerts is the Crooktree SAMNET magnetometer. This is a science-grade triaxial fluxgate magnetometer and is capable of measuring variations in the magnetic field strength in the three orthogonal directions at a resolution of 0.05 nT (in the ± 1600 nT range). The fluxgate sensors are accompanied by compensation coils wound on quartz tubes, which allow for an operating temperature range of -10° to 40° C and a temperature coefficient of <0.25 nT/ $^{\circ}$ C. This temperature stability permits installation outside away from sources of magnetic interference.

In case of failure at the Crooktree magnetometer, for example, complete failure of the instrument or just a delay in reporting data, the AWUK system will automatically switch to using data from another site. A fallback list is maintained to determine the order of preference of the magnetometers to allow for multiple failures.

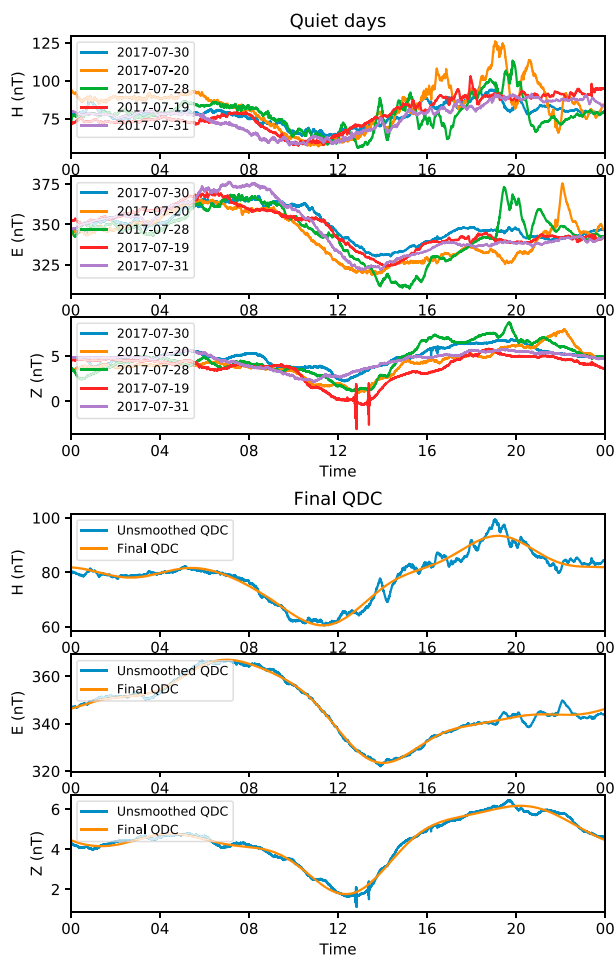


Figure 2. (top) The magnetic field data, recorded by the SAMNET Crooktree magnetometer, for the five geomagnetically quietest days in July 2017 are plotted. (bottom) In blue is plotted the mean of these quietest days, after baseline shifting, for each of the magnetic field components. These mean curves are then smoothed to produce the final quiet day curve, shown in orange.

This fallback mechanism can also be triggered manually, and the list modified in real time, if inspection of the data reveals them to be spurious.

3. Generating Alerts

The AWUK system reports the current magnetic field measurements in near real time, but the geomagnetic activity index, and thus the alert level, is determined every 3 min to account for any delays in data availability.

In the present implementation of the system, only the primary magnetometer is used to determine the “official” alert level (i.e., the alert level shown on the website and apps); however, an individual alert level is also calculated for each magnetometer in the network. Future iterations of AWUK may allow a user to chose which magnetometer they wish to receive alerts from (e.g., their most local site); however, we note that the differences between the measured magnetic field across mainland UK are often of the order of a few nanoteslas and would result in little difference to the number or type of alerts issued.

The majority of the AWUK magnetometers measure the local magnetic field in three orthogonal components: H (north-south), E (east-west), and Z (down-up). Since the ionospheric currents related to the aurora flow primarily in the east-west direction, strong auroral activity primarily drives disturbances in the H component of the magnetic field. However, auroral activity is sometimes more accurately reflected by disturbances in the E component when measured from the UK. The AWUK activity index is therefore determined using both the H and E components.

To compute the AWUK geomagnetic activity index, the daily solar quiet variation (e.g., Yamazaki & Maute, 2017) is first removed from the data by subtracting a “quiet day curve” (QDC). A custom method is used to create a set of quiet day curves for each calendar month. The method involves identifying the five “quietest” days in the calendar month, that is, those days with the least variation in geomagnetic activity from the monthly mean. The mean “quiet day” is then determined by averaging these five quiet days. The mean curve for each component is then smoothed using a truncated Fourier series expansion to remove higher-order components and to ensure the ends of the curve osculate. The truncated Fourier series approach has been used successfully in the MIA data processing software

(Marple & Honary, 2004) for many years for both magnetometer and riometer quiet day curves and has also been used with IMAGE magnetometer data (van de Kamp, 2013). Each component uses the same five quiet days, but different magnetometers may use different quiet days due to local variations, man-made disturbances or data availability.

An example of this QDC method is shown in Figure 2. In the top three panels, the magnetic field data recorded by the Crooktree SAMNET magnetometer are plotted for each of the five geomagnetically quietest days in July 2017. The mean average curves of these five quietest days is plotted in the bottom three panels in blue. These curves are then smoothed to produce the final QDCs and are plotted in orange.

Before the QDCs are used they are adjusted to compensate for any baseline changes that may have occurred. This problem is more common with the citizen science AWN magnetometers which can exhibit a slight temperature dependence. For each day a predicted “real-time baseline” is computed, which is the expected daily mean field strength value for each component. Tomorrow’s real-time baseline is computed as the mean value for each component from yesterday and the 9 days preceding it. Thus, the baseline value can be computed in readiness for the real-time data. As the current month’s quiet day curve is not available in real time, the previous month’s quiet day curve is used, first shifted to have zero mean for each component, and then the daily baseline values are added algebraically. For the first 3 days of the calendar month it is assumed that the quiet day curve is not ready and so the QDC from the month prior to the previous month is used instead.

Table 1
AuroraWatch UK Activity States

| Color | Activity range (nT) | Description | Meaning |
|--------|---------------------|------------------------------|---|
| Green | $A < 50$ | No significant activity | Aurora is unlikely to be visible by eye or camera from anywhere in the UK. |
| Yellow | $50 \leq A < 100$ | Minor geomagnetic activity | Aurora may be visible by eye from Scotland and may be visible by camera from Scotland, northern England, and Northern Ireland. |
| Amber | $100 \leq A < 200$ | Amber alert: possible aurora | Aurora is likely to be visible by eye from Scotland, northern England, and Northern Ireland; possibly visible from elsewhere in the UK. Photographs of aurora are likely from anywhere in the UK. |
| Red | $A \geq 200$ | Red alert: aurora likely | It is likely that aurora will be visible by eye and camera from anywhere in the UK. |

This approach enables the QDC to track any temperature-related baseline shifts without being significantly affected by geomagnetic storms.

Since deviations from the QDC can swap between being positive or negative, we also compute the maximum hourly range (in both the *H* and *E* components) in the disturbance values. Whichever of the disturbance level or the hourly range is greater, in either *H* or *E*, is used as the activity index. We note that the rate of change of the magnetic field (i.e., dB/dt) can also prove as a useful auroral indicator (Kauristie et al., 2016); however, this not currently used in the latest implementation of the AWUK system. Though the activity index is calculated in near real time, this real-time value is only ever stored if it is larger than the current hour's activity value. If the real-time activity registered drops during the hour, the AWUK activity index (and alert level) will remain at its elevated value until the next hour commences.

There are four AWUK activity levels (green, yellow, amber, and red) which each relate to the value of the activity index. As is shown in Table 1, the alert levels have their own descriptions and meanings, including an estimate of where in the UK an aurora might be seen from. A larger activity index, and thus more elevated alert level, indicates that the auroral oval is brighter and has expanded equatorward, suggesting that the aurora might be seen from further south in the UK. We note that the aurora is often "seen" through a camera lens rather than by eye, since a camera sensor is more sensitive than the human eye and is capable of long exposures. As such, we include both "by eye" and "by camera" estimates in the alert level meanings.

The thresholds and descriptions for each activity level have been determined based on extensive past experience of where in the UK the aurora is seen at certain levels of geomagnetic activity. However, we note that these levels are not based on some fixed physical parameter and so may change over time to improve our alert accuracy. For example, in the original implementation of AWUK there was no yellow alert; this level was added later to improve aurora nowcasting for those in the north of the UK. Future analyses, perhaps with the aid of citizen science observations, may result in small changes to the activity levels and their thresholds.

Presented in Figure 3 are the AuroraWatch UK magnetic field and geomagnetic activity plots for an example geomagnetic storm that occurred on 25 October 2016. In Figure 3 (top) are the magnetic field measurements for each of the three orthogonal components (*H*, *E*, and *Z*). The blue lines are the magnetic field measurements, and the gray lines are the QDCs. Plotted in Figure 3 (bottom) is a bar chart of the AWUK activity index for the same period. The color of the bar indicates the alert level, with the threshold value for each alert level shown by the colored horizontal lines.

If enhanced activity is measured (i.e., yellow or above) an alert is posted on AWUK's social media outlets (currently Twitter, Facebook, and Telegram) and through AWUK's mobile applications (iOS and Android). Additionally, alerts are sent via email to two mailing lists (amber and red, and red only) if activity reaches sufficient levels. All alerts are automated and are issued as soon as an activity threshold is met. Alerts are issued during daylight hours but the text is modified to suggest that the aurora may only be visible if enhanced activity continues when dark.

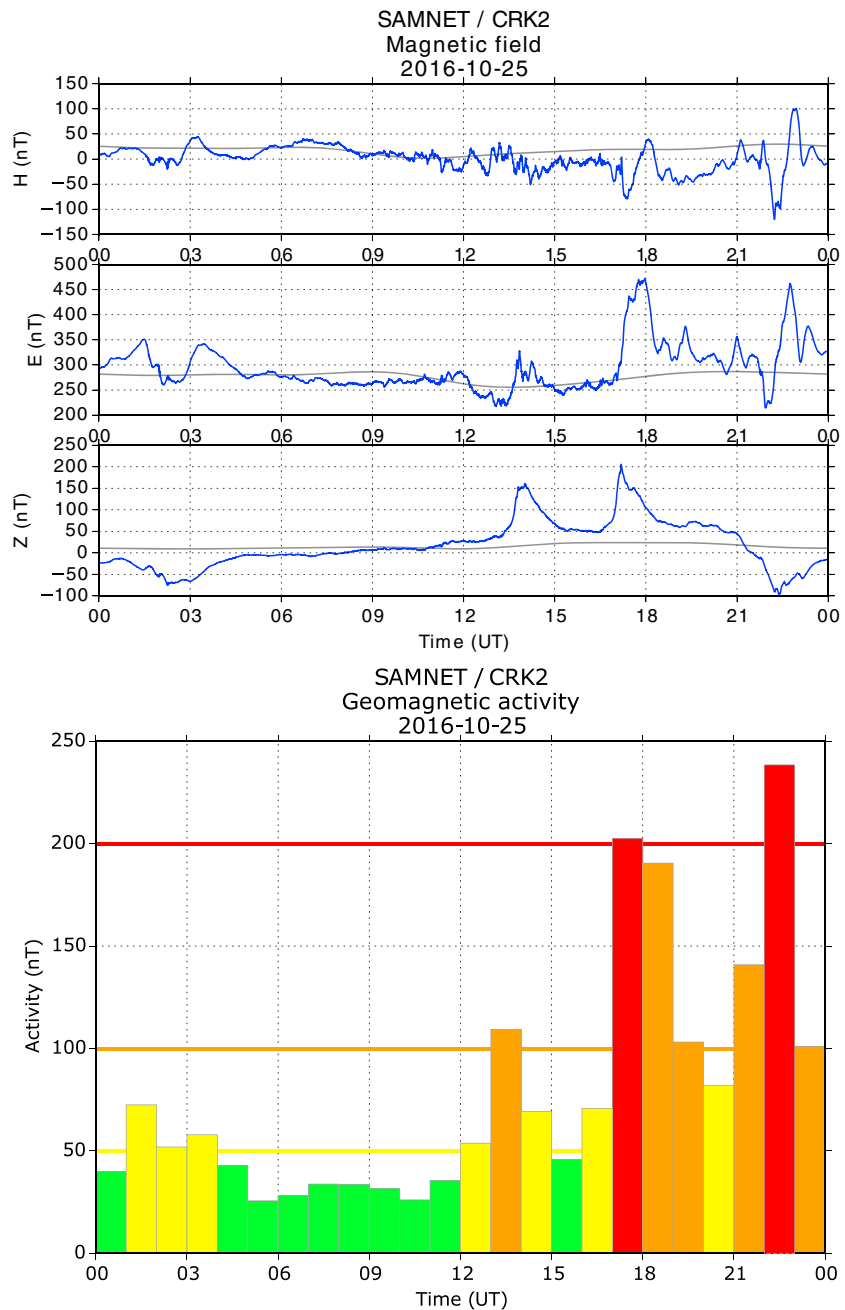


Figure 3. (top) In blue are the three orthogonal magnetic field components, as measured by the Crooktree SAMNET magnetometer on 25 October 2016. In gray are the quiet day curves for each component. (bottom) The corresponding hourly activity indices for this interval are shown. The bars are colored depending upon the value of the activity index. The threshold values for each level are shown by the horizontal colored lines.

The frequency of alerts is limited to prevent “spamming” users. Social media alerts are limited to once per 6 h, unless the activity level increases beyond the highest previous level. A return to a higher alert level, after a drop in activity (e.g., amber to yellow to amber), will not result in another alert, however. Email alerts are limited to once per 24 h for each activity level (i.e., two email alerts will be issued to the amber and red mailing list if activity rises from amber to red).

3.1. Merging Historical Data

In the following section, data from some of the various magnetometers employed during the past 15 years have been merged into a single historical data set (see Table 2 for the name, location, and operational lifetimes

Table 2
Magnetometers Used for AuroraWatch UK Historical Data Set

| Name | Location | Geomagnetic coordinates | |
|------|---------------------------|-------------------------|----------------------------------|
| | | (IGRF 2017) | Operational |
| CRK1 | Crooktree (Scotland) | 58.98°N, 85.22°E | June 2006 to February 2013 |
| CRK2 | Crooktree (Scotland) | 58.98°N, 85.22°E | August 2015 to present |
| ESK1 | Eskdalemuir (Scotland) | 57.32°N, 83.65°E | February 2001 to present |
| GML1 | Glenmore Lodge (Scotland) | 59.22°N, 84.21°E | pre-September 2000 to May 2002 |
| LAN1 | Lancaster (England) | 56.14°N, 83.35°E | March 2005 to July 2012 |
| LAN2 | Lancaster (England) | 56.14°N, 83.35°E | March 2016 to present |
| LER1 | Lerwick (Scotland) | 61.65°N, 88.70°E | February 2001 to present |
| YOR1 | York (England) | 55.70°N, 85.11°E | pre-September 2000 to March 2006 |

of the magnetometers used). When data from more than one magnetometer exist for the same time period, a preference list is used to decide which data to select. This preference list is based upon the general quality of the magnetometer itself and its location in the UK (with a latitude similar to Crooktree being most preferable). Additionally, if the activity index from the most preferred site is greater than 1.2 times the next highest index value from the other sites, for example, due to artificial influences, the data from the next magnetometer in the preference list is chosen instead.

If no data from any AWUK magnetometer is available, or if the data available has integrity issues, for example, spikes in the data that are characteristic of nonaurora influences, we utilize data from one of the BGS observatory stations (ESK1 and LER1 in Table 2). Data from these magnetometers are not available to AWUK in real time and so they cannot form part of the AWUK alert system; however, they can be used for historical analyses such as this.

Furthermore, the most recent alert generation method (i.e., the one previously described) has been retrospectively applied to all of the historical data. This allows for direct comparisons between years but does mean the results presented here may not match exactly with the historical archives found on the AWUK website.

4. Results

In the following we present a historical overview of the newly curated AWUK data. By merging data from several historical magnetometer sites, we find that the triaxial magnetometer data availability is 99.94% for the period spanning 00:00 (UTC) on 1 September 2000 to 00:00 (UTC) on 24 October 2017 (150,192 out of 150,288 h). We note that the actual “up-time” of the AWUK system would be marginally less than this; however, this is not something that we have recorded in the past.

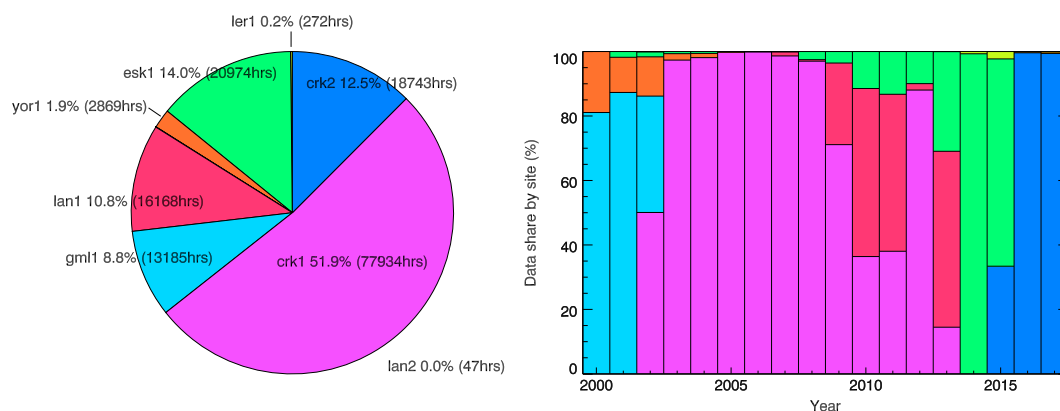


Figure 4. (left) Overall data share by site for all years. (right) Data share by site per year. Site colors match with those in the pie chart.

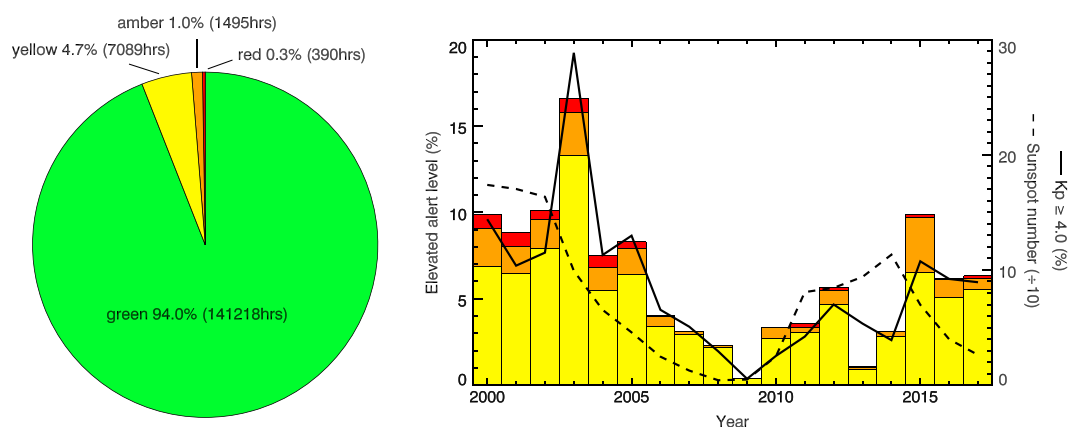


Figure 5. (left) A pie chart illustrating the number of hours spent at each AWUK activity level, as a percentage of the total number of hours. (right) A histogram of the percentage of hours spent at an elevated alert level (i.e., yellow or above) per year. Also plotted are (solid line) the percentage of time per year where $K_p \geq 4$ and (dashed line) the mean daily sunspot number per year (as a proxy for solar activity). The sunspot number is divided by 10 for scale.

As shown in Figure 4 (left), 85.8% of these data are provided by the AWUK real-time magnetometers and 14.2% by the BGS magnetometers at Eskdalemuir (ESK1) and Lerwick (LER1). The majority of the AWUK real-time data are provided by the SAMNET CRK1 magnetometer (51.9% of all data) and, more recently, by its replacement CRK2 (12.5%).

As shown in the pie chart of Figure 5, during this interval the activity level in this merged data set reached the yellow threshold for 7,089 h (4.7%), amber for 1,495 h (1.0%), and red for 390 h (0.3%). This corresponds to approximately 412 h of yellow, 88 h of amber, and 23 h of red alert level per year.

Plotted in the stacked bar chart of Figure 5 are the varying percentages of each elevated alert level (i.e., yellow or higher) by year. The solid black line also plotted is the percentage time, per year, for which K_p was elevated (≥ 4) indicating increased global geomagnetic activity. The dashed line is the mean daily sunspot number for each year, divided by 10 for scaling purposes, and is shown as a proxy for solar activity and position in the solar cycle. We note that the year 2017 is not complete, and the different data sources have slightly different end dates, so this year should be treated as provisional and subject to change.

5. Discussion and Summary

The AuroraWatch UK alert system is based upon disturbances in the magnetic field measured at its magnetometers located across the UK. Using the algorithm described herein, the magnetic field measurements are turned into an activity value, and alerts are issued at varying levels according to this activity value. We note that the AWUK activity value is calculated in real time, unlike the K_p index which is determined every 3 h, and so can be used to issue alerts of measured geomagnetic disturbance.

The AWUK system is robust and can utilize data from any of several magnetometers in the system. However, this real-time alerting mechanism is not infallible and has resulted in the rare “false alert.” In one widely reported case (e.g., Quanta, 2016), the main Crooktree magnetometer was suffering from a network-related issue and so the system fell back to using data from the Lancaster magnetometer. Unfortunately, the Lancaster site is not guaranteed to be magnetically quiet and, on that day, the ground’s team responsible for the site mowed the lawn creating significant magnetic disturbances. These disturbances resulted in the issuing of a “false” red alert.

To prevent such false alerts in the future, it is envisaged that the service will instigate the fallback mechanism automatically if data being returned from the main site are significantly different from the other sites in the network. Alternatively, some average activity value from across the whole network of magnetometers could be used either to issue alerts or as a quality control check. In the highlighted case, these improvements may have resulted in the system falling back to the next magnetometer in the preferred list instead of issuing the red alert.

In this report we have merged data from various magnetometers and used the latest alert algorithm to generate a historical AWUK record of geomagnetic activity. Although the historical record presented here starts in September 2001, to coincide with the launch of the AWUK system, there is no reason why the algorithm could not be applied to other UK-based triaxial magnetic field measurements that predate this time. Additionally, the same algorithm could be applied to non-UK-based magnetometers, although the thresholds for the alert levels may need adapting if their geomagnetic latitude is significantly different.

In this historical record, we have predominantly used magnetometers from the AWUK network to provide the activity level. As shown in Figure 4, however, we have relied on two BGS magnetometers to provide data, particularly during the period of August 2014 to August 2016. As previously noted, the BGS magnetometers cannot be used by AWUK for aurora alerts as we do not have real-time access to the data. Instead, during this interval, AWUK utilized one of its own single-axis magnetometers. While the single-axis magnetometer data cannot be used with the latest alert algorithm, we were able to use them for the version of the algorithm in operation at that time.

In the historical data set we find that the alert status was yellow for 4.7%, amber for 1.0%, and red for 0.3% of the time which corresponds to approximately 412 h of yellow, 88 h of amber, and 23 h of red alert level per year. We note, however, that the actual number of alerts issued would be lower than this due to the alert frequency criteria we apply (discussed earlier).

As shown in Figure 5, the percentage of hours for which an elevated status level is recorded is not consistent throughout the years. This result does not suggest an issue with the data, rather it is indicative of the varying levels of geomagnetic activity spanning two solar cycles. This is clearly demonstrated by the fact that the elevated status percentages closely match the percentage of time that $Kp \geq 4$ (i.e., geomagnetically active). The one exception to this trend is 2013 which may be due to our reliance on a lower latitude magnetometer for much of the year (see Figure 4). Additionally, we note that the level of elevated geomagnetic activity does not match the solar activity (as measured through sunspot numbers) exactly, with the large levels of geomagnetic activity recorded during the declining phase of the solar cycle. This is consistent with previous observations (e.g., Venkatesan et al., 1991).

The AWUK system is not only a useful tool for aurora hunters. With its long history of recording localized geomagnetic disturbances, it can also be used for scientific study and for global real-time geomagnetic monitoring (Love & Finn, 2017). For example, future studies will be undertaken to compare the AWUK data with citizen science observations of the aurora to determine the accuracy of our alerts levels (e.g., Harrison, 2005; Lockwood & Barnard, 2015; MacDonald et al., 2015; McBeath, 2006).

Additionally, since the AWUK alert level is not affected by local conditions such as cloud cover or light pollution, the historical data presented here could be used to determine the frequency of potential aurora sightings from the UK if local conditions had permitted. Perhaps more interestingly, the data could be used to investigate the dependency of such viewing opportunities on variables such as position in the solar cycle or time of year.

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Acknowledgments

The real-time AuroraWatch UK alert data are freely available, under license, through the AuroraWatch UK API (<http://aurorawatch.lancs.ac.uk/api-info/>). The historical activity values used in this study may be obtained from <https://doi.org/10.17635/lancaster/researchdata/184>. The SAMNET, AuroraWatchNet, and BGS magnetometer data are also available, under varying licenses, and may be obtained from the AuroraWatch UK (<http://aurorawatch.lancs.ac.uk/>) and BGS (http://www.geomag.bgs.ac.uk/data_service/data/home.html) websites. Real-time and historical quick look plots are freely available on the AuroraWatch UK website. We acknowledge use of NASA/GSFC's Space Physics Data Facility's OMNIWeb service for providing the Kp index data and the WDC-SILSO (Royal Observatory of Belgium, Brussels) for the sunspot number data. We gratefully acknowledge the work of Ian Mann (University of Alberta) and his team in their development of the original AuroraWatch UK system. N. A. C., A. G., and J. A. W. were supported during this study by STFC grant ST/M001059/1.

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