A real-time hybrid aurora alert system: combining citizen science reports with an auroral oval model

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Key Points.

- Citizen science reports are combined with the OVATION Prime aurora model to predict auroral visibility
- Using the model and reports, a real-time adaptable aurora view-line is created and alerts are issued
- Over 100,000 aurora alerts have been issued thus far to over 2,000 users from across the globe

Abstract. Accurately predicting when, and from where, an aurora will be visible is particularly difficult, yet it is a service much desired by the general public. Several aurora alert services exist that attempt to provide such predictions but are, generally, based upon fairly coarse estimates of auroral activity (e.g. Kp or Dst). Additionally, these services are not able to account for a potential observer's local conditions (such as cloud cover or level of darkness). Aurorasaurus, however, combines data from the well-used, solar wind driven, OVATION Prime auroral oval model with real-time observational data provided by a global network of citizen scientists. This system is designed to provide more accurate and localized alerts for auroral visibility than currently available. Early results are promising and show that over 100,000 auroral visibility alerts have been issued, including nearly 200 highly localized alerts, to over 2,000 users located right across the globe.

1. Introduction

The Aurorasaurus citizen science project [*MacDonald et al.*, 2015] is designed primarily to collect reports of the aurora (both the northern and southern lights) to improve auroral modelling, to foster understanding of the aurora by the public, and to generate aurora visibility alerts. The broader aims and scopes of the project are discussed in detail in *MacDonald et al.* [2015] but, in the following, we focus only upon the particular aspect of generating alerts of auroral visibility.

A multitude of aurora visibility alert services already exist, some run by academic or research institutions and some by the interested public. Most of these services rely solely upon measures or, more often, estimates of the disturbance in the Earth's magnetic field. These disturbances, which are the result of events such as geomagnetic storms, are driven by particular solar wind structures (e.g. coronal mass ejections or high speed streams) with a favorable southward magnetic field orientation. A stronger disturbance in the terrestrial field, most commonly specified using a real-time estimate of the Kp index [*Bartels et al.*, 1939; *Wing et al.*, 2005] or the Dst index [*Sugiura*, 1964], correlates with stronger auroral activity. Whilst these estimates provide a general picture of the potential overall strength and location of an aurora (e.g. *Carbary* [2005] who compared images from the Polar Ultraviolet Imager with the Kp index), they are purely empirically based and provide relatively poor spatial resolution.

Providing the interested public with alerts of when, and from where, an aurora might be visible requires accurate specification of the drivers behind the aurora and accurate modeling of auroral dynamics (both geo-spatially and temporally). Whilst auroral precipitation models are under constant development and improvement (e.g. *Newell et al.* [2002, 2010, 2014]), the current generation are still only able to provide an averaged, somewhat coarse, estimate of where an aurora might be visible [*Machol et al.*, 2012]. Additionally, these estimates are only for the area in which a visible aurora might be contained, not necessarily the exact area of auroral visibility.

Furthermore, neither the geomagnetic disturbance based estimates or the empirically derived statistical models are able to take into account the potential observer's local conditions (e.g. cloud cover, level of darkness, or physical obstructions). These localized conditions further complicate the ability to predict, on a local scale, where an aurora might be visible. Yet accurate and personalized alerts of auroral visibility is the single most desired feature of Aurorasaurus users and is the primary reason for users signing up to the service (N. Lalone, personal communication, 2015).

To attempt to overcome these shortcomings, and to provide more accurate alerts of auroral visibility to Aurorasaurus users, we have developed a hybrid alert system that combines data from the well-used OVATION Prime auroral oval model (OP10) [*Newell et al.*, 2010] with real-time auroral reports provided by a community of citizen scientists [*MacDonald et al.*, 2015]. Whilst combining models and real observations to provide more accurate predictions has been attempted in other fields, e.g. the SKYWARN program run by the US National Weather Service (NWS) [*Waxberg*, 2013], this is the first time it has been used to predict (or "nowcast") auroral visibility in real-time.

In the following sections the technical system behind the Aurorasaurus alerts, including how the system assimilates citizen science reports with OP10 and how alerts are created and issued, is described. Some early results are then presented and further work that could be undertaken to improve the system is discussed.

2. Data Sources

The Aurorasaurus website provides an indication of both the location and strength of an aurora through its main aurora map (see Figure 1). Plotted as a layer on this Google map is the current short-term prediction of the probability of visible aurora, both in the northern and southern hemispheres. This auroral oval forecast, provided by NOAA's Space Weather Prediction Center (SWPC), is based upon the OP10 model output.

OP10 is driven by the rate of delivery of interplanetary magnetic flux to Earth's magnetopause, as parameterized by the $d\Phi_{MP}/dt$ magnetospheric coupling function [*Newell et al.*, 2007]. Solar wind data is provided by NASA's ACE mission (soon to be replaced by NOAA's DSCOVR mission) which, owing to its location at Lagrangian point 1, provides approximately 30 minutes advance prediction during active times.

The SWPC forecast is provided through a public HTTP-access ASCII file which contains an estimate of the "probability of visible aurora" for each of the $0.35° \times 0.35°$ segments of the Earth's surface (i.e. 1024 columns of geographic longitude and 512 rows of geographic latitude). Details of how the OP10 energy flux output is converted into a probability of visible aurora can be found in *Case et al.* [2016].

A Python routine is run every 15 minutes on the Aurorasaurus Amazon server to determine a series of contours of constant probability from the SWPC forecast data. The contours are smoothed, drawn on the map, and filled using the custom color scale shown in Figure 1. By default, Google maps will stack the contour polygons on top of each other, causing the colors to blend together and the opacity to increase. To maintain the correct opacity and coloring, the set-theoretic difference is taken for each polygon and its next smallest neighbor (i.e. the area matching the smaller contour is cut out from the larger contour). The end result is a collection of non-overlapping polygon rings that have both interior and exterior coordinates, with the smallest contour having only an exterior set of coordinates.

The presentation of the SWPC forecast on the Aurorasaurus website is consistent with SWPC's own 30 minute aurora forecast product. This similarity, including using the same color scale and terminology, was intentional, so that users who are already familiar with the SWPC forecast product would naturally be familiar with the Aurorasaurus product. The major difference between the two outputs is the use of the Google Web Mercator projection of the globe on Aurorasaurus rather than the polar projection used by SWPC. The Mercator projection, which is common for online maps, is useful for panning the globe and zooming in to local areas, however, it does cause some distortion of the oval at high latitudes where areas are greatly exaggerated in apparent size.

2.1. Aurora view-line

An aurora can often be viewed several hundred kilometres equatorward (i.e. southward in the northern hemisphere; northward in the southern hemisphere) of the auroral oval boundary owing to its altitude. Thus Aurorasaurus also plots a "view-line" (shown in red in Figure 1) to estimate the most equatorward latitude from which an aurora might be seen. Equation 1 demonstrates how this view-line is determined (for both-hemispheres).

$$\phi_{\mathrm{VL}} = \phi_{\mathrm{EB}} \pm 8 \tag{1}$$

where ϕ_{VL} is the view-line latitude and ϕ_{EB} is the equatorial boundary of the visible auroral oval. The equatorial boundary is determined every 15 mins and is defined as the lowest latitude at which the probability of visible aurora is at least 18%. The view-line presented in Equation 1 was determined to most accurately reflect citizen science aurora reports during a case-study into auroral visibility [*Case et al.*, 2016]. Since an aurora can only be seen during darkness, the view-line is clipped at the day/night terminators.

2.2. Citizen Science Reports

Also plotted on the Aurorasaurus map are any citizen science reports of auroral visibility. These reports can be either positive (i.e. an aurora was visible) or negative (i.e. an aurora was not visible). Included in all reports is the time and geographic location from which the observation was recorded. For positive reports, further details about the auroral characteristics (e.g. color, activity, and height in the sky) may also be provided, sometimes along with a photograph of the aurora. For negative reports, further details about the local sky conditions may also be provided (e.g. cloud cover and light pollution).

Positive reports (an example of which is shown in Figure 2) include sightings submitted directly to the project, either through its website or mobile apps, and sightings found on Twitter [*Case et al.*, 2015a] which have then been verified by Aurorasaurus users as true real-time sightings of the aurora (known as "verified tweets" [*MacDonald et al.*, 2015]).

Whilst negative reports, at first glance, might seem less important than the positive reports, they can, in fact, also be useful for aurora hunters. Negative reports located where an aurora is predicted to be visible are particularly useful since they provide evidence that either local conditions are not conducive to auroral visibility (e.g. there is too much cloud cover) or that OP10, or the view-line based upon it, are inaccurate at that time.

During low auroral activity, positive reports are quite rare and sparse, being predominantly located near the polar regions. During intense auroral activity, however, hundreds of positive reports can be recorded in one evening [*Case et al.*, 2015b].

3. Assimilation Method

The unique aspect of the Aurorasaurus aurora map is that it assimilates citizen science reports with the SWPC forecast to produce a more accurate representation of where an aurora might be visible from. The view-line, which is first determined using the current forecast (see Equation 1), is then adapted to account for real observational data based on clusters of positive reports (either direct reports or verified tweets).

To determine which positive reports should be grouped together to form clusters, a technique called "density-based spatial clustering of applications with noise" (DBSCAN) [*Ester et al.*, 1996] is applied to all positive reports that have an observation start time and submission time occurring within the last 90 minutes. DBSCAN is a type of clustering algorithm widely used in the computer science discipline to cluster geo-spatial data sets. Along with the positive reports, the parameter of 160 km is given to DBSCAN to define what is considered "near" and allows the process to be tuned. The convex hull, i.e. the smallest region in which each report is contained and within which a straight line segment joining each report to every other in that cluster can be drawn, is determined and defines the boundary of each "positive cluster" (see Figure 3). We note that a minimum of three positive reports, located "near" to each other are needed to form a cluster.

This technique has often been used in spatial data mining and has been used in the study of other natural phenomena (such as earthquakes [*Georgoulas et al.*, 2012]), but this is the first time, to our knowledge, that such a technique has been used to help nowcast auroral visibility.

3.1. Adapting the view-line

As shown in Figure 3, the view-line is adapted to encompass any positive clusters that may lie equatorward of the original estimate. In principle, several different clusters may appear on the map at any one time, particularly during strong auroral activity, and the view-line will adapt to each.

The adaptation is fairly simple: the lowest latitude (i.e. most equatorward) vertex of the cluster is determined and the distance between this vertex and the original view-line estimate, at the middle longitude of the cluster, is calculated. An additional 100 km (corresponding to approximately 1° latitude) is added to this distance creating the adaptation height, h.

As shown in Figure 4, a third order polynomial function is determined to fit three specific points located around the cluster (labeled A, B, and C in the figure). The longitude of point A is the central longitude of the cluster and its latitude is the latitude of the original view-line minus the adaptation height (h). Points B and C lie at the coordinates $\pm h$ from the cluster's central longitude and at latitude h poleward of A. If the polynomial fit intersects the original view-line, that segment of the original view-line is kept (e.g. the dashed upward line near point B); else, the polynomial fit replaces the original view-line segment (shown as the dashed line between points B and C).

The addition of 100 km to the distance between the vertex and view-line, and the locations of points B and C, are based purely on empirical observations made whilst developing the system. Further investigation may result in changes to the offset and locations in future iterations of the system.

4. Generating Alerts

The adaptable view-line itself is a novel product for aurora hunters. Rather than just relying on estimates of geomagnetic activity or statistical models, which have been smoothed and averaged over fairly large spatial and temporal scales, it demonstrates where people are actually observing the aurora at that moment. However, it is unrealistic to assume that users of Aurorasaurus will always be able to check on this view-line using the aurora map. Instead, issuing personalized (i.e. localized) alerts of auroral visibility is much more useful.

The Aurorasaurus service offers two types of alerts: Level 1 and Level 2. Level 1 alerts are issued to any registered user whose profile location is contained within a positive cluster. This alert is designed to emphasize that it is extremely likely that an aurora is visible from this location at the time of the alert. The text of the Level 1 alert is: **{#} aurora sightings reported near {location} on {date} at {time}**, where {#} is the number of observations contained in the cluster, {location} is a field containing the user's profile location, and {date} and {time} are the date and time of the alert. The Level 2 alerts are issued to all users whose profile location is poleward of the view-line, including any adaptations made to it owing to the presence of positive clusters, and contained within the night-time terminator. This alert is designed to raise awareness of the possibility of a visible aurora and the text is: **Aurora sightings are possible near {location} on {date} at {time}**.

This type of alert system, with two or more "severity" levels, is common for other natural phenomena and includes examples such as the NWS's Watch/Warning alert system for severe weather (e.g. tornadoes, thunderstorms, and oppressive heat) [*Belville*, 1987].

The alerts are issued based upon the location in the user's profile, which is an optional field in the sign-up process that can be updated at any time, rather than the user's current location (i.e. GPS tracking on smartphones). The option to instead use GPS location is an often requested feature by Aurorasaurus users (N. Lalone, personal communications, 2015), however, and may be implemented in the project's smartphone applications (which are available for iOS and Android) in the future.

Aurorasaurus alerts are optional and can be issued via email, Twitter, and through in-app notifications (both in the smartphone applications and on the website). Native push notifications (where the application does not need to be running in the foreground to receive a notification) are not, at this time, supported owing to the cross-platform nature of the application. The clustering algorithm runs frequently, approximately every 15 minutes, however, a maximum of one alert (of each type) per 24 hour period is sent to each user.

We note that, ideally, users who receive a Level 2 alert should head outside, attempt to view the aurora, and report back on their success. By doing so, they would then be able to generate Level 1 alerts for other users in their vicinity. An alert-response-alert feedback system, such as this, is an area of significant research for early warning system communities [*Lalone et al.*, 2015].

5. Early Results

The OP10 based view-line has been operational on the Aurorasaurus website since November 2015. In the period spanning 1 November 2015 to 1 April 2016, 1,194 citizen science reports (630 positive and 564 negative) were submitted directly to Aurorasaurus and 1,580 tweets were verified as auroral sightings by its users. The combined 2,210 positive reports and verified tweets resulted in the formation of 33 positive clusters over seven separate geomagnetic storm events. We note that, although reports were received from the southern hemisphere, all clusters formed in the northern hemisphere.

Approximately 15% of the positive reports and verified tweets were recorded equatorward of the view-line. This lead to the formation of five positive clusters which were also, at least in part, equatorward of the view-line - an example of which is shown in Figure 3.

As a result of the positive clusters, 186 localized Level 1 alerts were issued to 139 unique users. These alerts were the result of the unique combination of citizen science observations and clustering algorithms employed by Aurorasaurus and would not have been issued based on the SWPC forecast alone. Additionally, 112,203 Level 2 alerts, sent to all users poleward of the view-line, were issued to 2,006 unique users.

We note that as the number of Aurorasaurus users increases and/or a large auroral event occurs, the number of positive reports should also increase. As such, it is likely that increasing numbers of positive observations and clusters will appear equatoward of the view-line which may lead to further improvements of our initial forecasting of the extent of auroral visibility.

6. Discussion

The OP10 based view-line has, thus far, been a good indicator of auroral visibility with the majority (85%) of positive reports and verified tweets occurring poleward of the view-line. There have, however, been many positive reports or verified tweets that have been located equatorward of the view-line and this has lead to the formation of five equatorward clusters.

Both verified tweets and direct reports are treated equally when generating the positive clusters and alerts. Verifying tweets is not always a simple task however, and approximately 60% of "verified" tweets do not relate to real-time aurora sightings (Case et al., manuscript submitted for publication, 2016). Further work will, therefore, need to be undertaken to determine what impact the use of verified tweets has on the accuracy of the alerts and how the effect of falsely-verified tweets can be mitigated. We note that, for this paper, the reports and verified tweets have not been manually inspected and so some of the reports may have data integrity issues (e.g. the citizen scientist may have selected the wrong start/end times, or the Aurorasaurus users may have incorrectly verified a tweet as a real-time auroral sighting).

Further investigation into the accuracy of the view-line, by comparing it with the latest citizen science reports, and investigation into the validity of the parameters used in determining both when a cluster is formed and its effect of on the view-line is planned.

Additionally, several improvements to the method used to adapt the view-line based on the presence of positive clusters are already being considered. These improvements, and possibilities for incorporation into the system, are discussed below.

The current implementation of adapting the view-line to clusters of positive reports is to use a third order polynomial fit to create the curve around the cluster. Whilst this is a good first approximation and is easy to compute, in reality, other fits might perform better. Once this system has been running for some time, and more positive clusters have formed equatorward of the view-line estimate, an analysis of the performance of the view-line adaptation method can be undertaken.

The view-line will, in principle, adapt to an unlimited number of clusters; however, it currently does so in a singular way. Specifically, the view-line will adapt to each cluster (i.e. computing the polynomial fit) individually, rather than grouping clusters located close together and making one larger modification to the view-line that fits the group of clusters better (see Figure 5 for example). Future work will be undertaken with the aim of adapting to multiple clusters in a more cohesive manner without creating an overly broad notification area.

As previously discussed, the view-line adapts only to clusters of positive reports (including those reports submitted directly to Aurorasaurus and verified tweets). Aurorasaurus users, however, are also able to submit "negative reports" (i.e. they were not able to see an aurora). If a cluster of such negative reports were to occur poleward of the view-line (i.e. the model predicted an aurora would be visible, yet it was not), then the view-line should perhaps also adapt to this cluster.

We note that there are several types of negative reports. Firstly, there are those negative reports that agree with the model, in that the aurora was not predicted to be visible from where the observer was located (i.e. the observer was equatorward of the view-line). Such reports can be termed "true negatives".

Secondly, there are those reports that indicate an aurora was not visible even though the model, or view-line, suggested it ought to be (i.e. the observer was poleward of the view-line). These reports can be further decomposed. For example, if an aurora is not visible when it was predicted that it should be, it might be that local conditions, such as cloud cover or light pollution (which OP10 cannot take into account), are obscuring visibility, or, the model was inaccurate at that time.

Whilst only the latter (which can be thought of as "false positives") are useful for scientific investigation, i.e. determining the accuracy of OP10 and the view-line based upon it (e.g. *Case et al.* [2016]), both could be considered important for issuing accurate visibility alerts.

7. Conclusion

The Aurorasaurus project collects scientifically useful data about the visibility of auroras from citizen scientists. This information is used both to improve our understanding of the aurora and, as described herein, to create a hybrid auroral visibility alert system. The citizen science reports are combined with a traditional space-weather based auroral oval model to provide more localized estimates of where an aurora can be viewed from.

These estimates are provided in real-time both in the form of a interactive map, with an auroral oval and view-line plotted, as well as optional alerts. By using, "ground-truth" observations, in addition to the large-scale model output, Aurorasaurus is able to provide greater spatial resolution of auroral visibility and provide localized alerts to the Aurorasaurus users - a highly requested feature. So far, the system has shown promising results, having issued over 100,000 alerts of auroral visibility, including nearly 200 highly localized alerts, to over 2,000 registered users.

This is a novel approach for auroral nowcasting and future analyses will be conducted to test the accuracy of the system and to investigate ways to incrementally improve upon it. As a test-bed for early warning systems, the Aurorasaurus alert system presents a useful tool to study how people respond to localized alerts and future work will investigate what actions Aurorasaurus users took (such as heading out to view the aurora) after receiving such an alert.

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The Aurorasaurus citizen science data used in this study can be obtained by contacting the corresponding author.

The OVATION Prime output was kindly provided by the Space Weather Prediction Center (Boulder, CO) of the National Oceanic and Atmospheric Administration (NOAA), US Dept. of Commerce. The output can be freely downloaded from the NOAA SWPC product pages (http://www.swpc.noaa.gov/products/aurora-30-minute-forecast).

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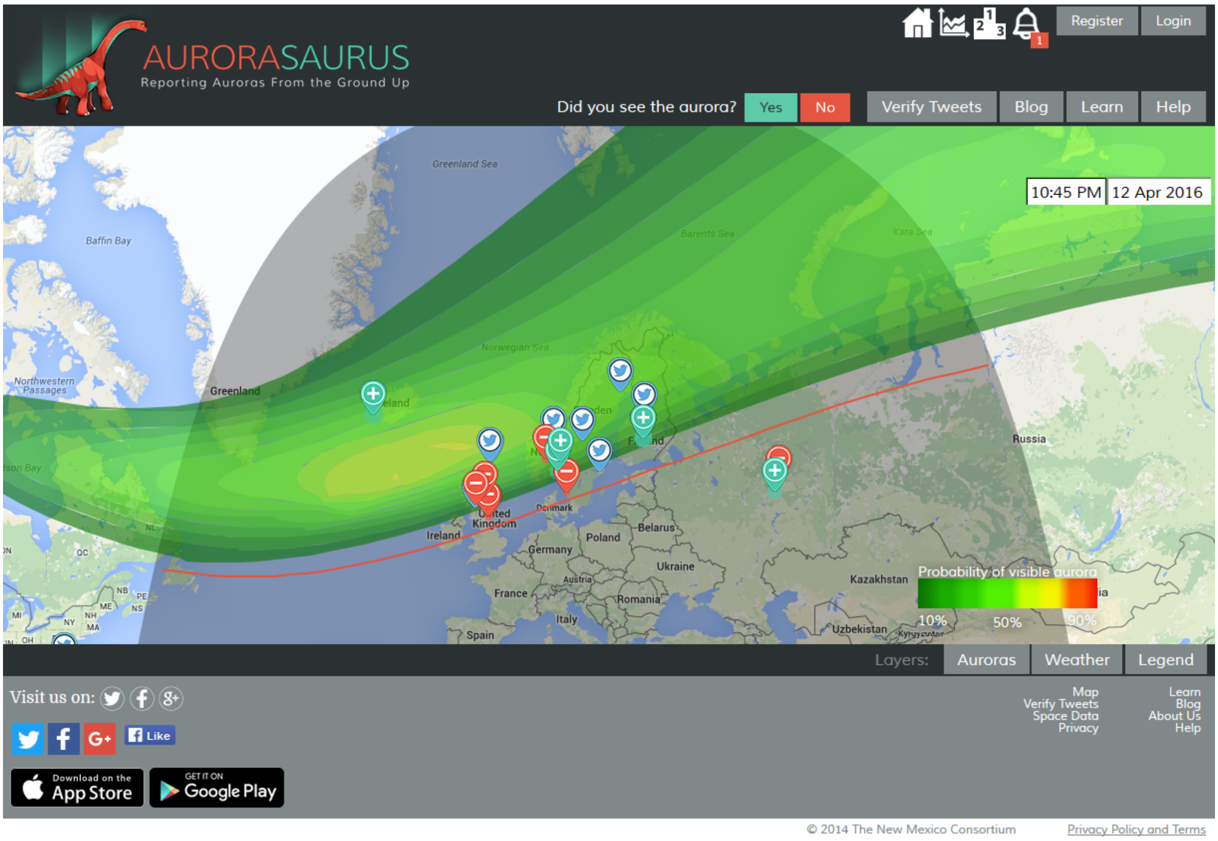

Figure 1. An example of the Aurorasaurus "aurora map" (screenshot of 12 April 2016 at 2245UT). Shown on the map are: the SWPC auroral forecast (filled semi-transparent polygons), an estimated view-line (red), and citizen science reports (green, red, and blue pins). Reports submitted directly to Aurorasaurus (either through its apps or website) are depicted by the green (positive reports) and red (negative reports) pins and tweets that have been verified by Aurorasaurus users as recent aurora sightings (i.e. within the last 30 mins or so) are depicted by the blue pins. The day/night regions are illustrated using light/dark shading.

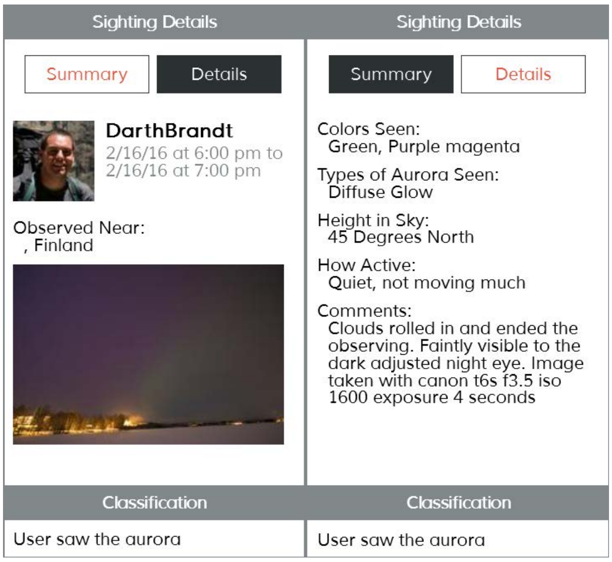

Figure 2. An example positive report submitted directly to Aurorasaurus, either through its website or mobile app. The report includes details about where the sighting took place (the exact geographic latitude and longitude is not shown but is stored by Aurorasaurus) and information about the aurora itself. Also included in this report is a photo of the aurora taken by the citizen scientist.

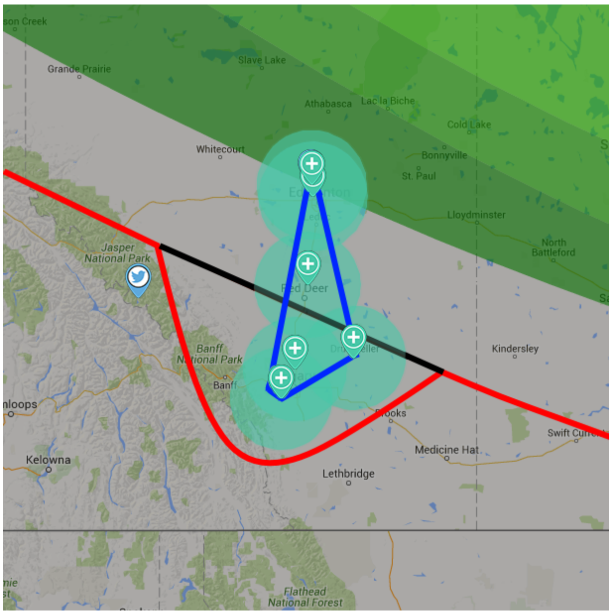

Figure 3. A close-up example of the Aurorasaurus map as it appeared on 3 February 2016 at 0515 (UT). A cluster of positive reports has formed with several vertices lying equatorward of the view-line (note: the verified tweet visible was not verified until several hours later and so did not form part of the cluster). The view-line (solid red line) automatically adapted to incorporate the cluster (outlined in blue). The black line segment indicates where the view-line would have been drawn had there been no cluster.

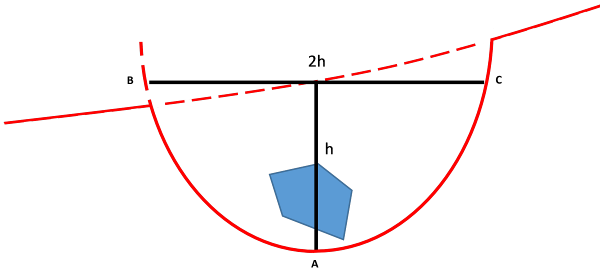

Figure 4. A schematic diagram depicting how the view-line (red) would adapt to a cluster of positive citizen science reports (blue polygon). A third order polynomial fit is applied to points A, B and C, which are determined by the distance between the cluster and the original view-line estimate. Note: this example is illustrative and not an actual cluster.

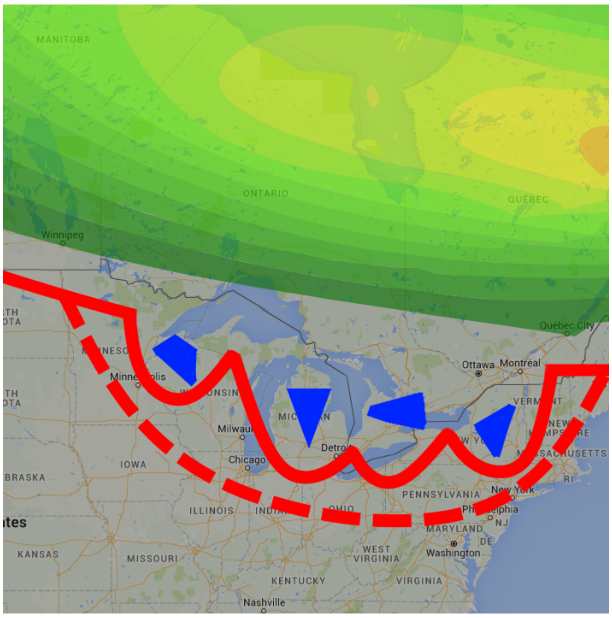

Figure 5. A schematic example depicting how the view-line (solid red line) would adapt to multiple clusters of positive citizen science observations (blue polygons). The view-line would adapt to each cluster individually but treating the clusters as a single group might produce a more desired result (i.e. dashed red line). Note: this is an illustrative example and is not based on actual clusters.