REAL TIME AURORA OVAL FORECASTING – SVALTRACK II

F. Sigernes [1], M. Dyrland [1], P. Brekke [2], E. K. Gjengedal [3], S. Chernouss [4], D.A. Lorentzen [1], K. Oksavik [1] and C. S. Deehr [5]

[1] The University Centre in Svalbard (UNIS), N-9171 Longyearbyen, Norway
[2] Norwegian Space Centre, Oslo, Norway
[3] Storm Weather Center, Bergen, Norway
[4] Polar Geophysical Institute, Murmansk Region, Apatity, Russia
[5] Geophysical Institute, University of Alaska, Fairbanks, USA

Abstract – A method to forecast, up to one hour in the future, the size and location of the aurora oval is described. The work is based on a mathematical description of the aurora oval coupled to predicted values of the planetary K_p index. As a result, a real time animation of the oval mapped onto the Earth's surface is created. The night- and dayside are visualized together with the location of the twilight zone as Earth rotates under the aurora oval.

1. INTRODUCTION

The impact areas on the Earth of energetic particles from the Sun causing circular belts of auroral emissions around each geomagnetic magnetic pole are known as the aurora ovals. The location and size of these ovals have been studied extensively during the last decades [cf. 1, 2, 3, 4, 5].

The size and location of the auroral oval was found to be directly related to the planetary index of geomagnetic activity, K_p. This index is produced by the Helmholtz Centre in Potsdam [6]. Because the production of this index involves worldwide data collection and interpretation in order to continue a record begun in 1936, it is not useful for forecasting, and an intermediate method of scaling K_p from one or a small number of mid-latitude stations has evolved. The K_p index derived in this way must be referred to as the estimated K_p index, and it is this index we use in the present work.

The advent of stationary spacecraft approximately one hour upstream in the solar wind between the Sun and the Earth has led to studies of the relationship between the structure of the solar wind and the resulting auroral and geomagnetic disturbances [7, 8]. Because the input data come from a satellite approximately one hour upstream in the solar wind, the resultant forecast is a relatively short-term forecast. This can be a very useful quantity both for auroral observing and for the purpose of conducting experiments that are dependent on the location and intensity of the aurora.

During the International Geophysical Year (IGY 1957-1958), the boundaries of auroral occurrence were determined from all-sky camera studies for a wide variety of activity levels. The resulting figure was made up from a statistical study of auroral occurrence showing the poleward and equatorward boundaries of the 75% occurrence probability [2, 3]. The relationship between the morphology of the auroral oval and the level of geomagnetic activity allows us to develop a means of locating the aurora, independent of the vagaries of auroral observations. In addition, we may predict its location up to an hour in the future.

The goal of this paper is therefore to produce in real time, a forecast, up to one hour in the future, of the location and size of the aurora oval mapped on to the Earth's surface that includes observing conditions from a selected geographical site. The solar elevation and the cloud cover are the main obstacles for an aurora watcher at ground level. To the authors' knowledge, no such display of information exists.

Below is a mathematical presentation of the aurora oval and the geographical mapping used to visualize the result.

2. A MATEMATICAL REPRESENTATION OF THE AURORAL OVALS

The model used to calculate the boundaries of the aurora oval is from work done by Starkov [9]. He compiled simple formulas of the poleward, the equatorward and the diffuse aurora boundaries as a function of magnetic activity.

The magnetic input parameter is the AL index. This index describes the polar or planetary magnetic disturbances that occur during auroras. The range of the index is in the order of ± 800 nT. In terms of K_p index it is given as [10]

$$AL = c_0 + c_1 \cdot K_p + c_2 \cdot K_p^2 + c_3 \cdot K_p^3. \qquad (1)$$

The coefficients c_i for $i \in [0...3]$ are given in Table 1.

c_0	c_1	c_2	c_3
18	-12.3	27.2	-2.0

Table 1. Coefficients for converting K_p to AL indices in equation (1) by Starkov [10].

	A_0	A_1	A_2	A_3	α_1	α_2	α_3
			Poleward boundary of the auroral oval				
b_0	-0.07	-10.06	-4-44	-3.77	-6.61	6.37	-4.48
b_1	24.54	19.83	7.47	7.90	10.17	-1.10	10.16
b_2	-12.53	-9.33	-3.01	-4.73	-5.80	0.34	-5.87
b_3	2.15	1.24	0.25	0.91	1.19	-0.38	0.98
			Equatorward boundary of the auroral oval				
b_0	1.61	-9.59	-12.07	-6.56	-2.22	-23.98	-20.07
b_1	23.21	17.78	17.49	11.44	1.50	42.79	36.67
b_2	-10.97	-7.20	-7.96	-6.73	-0.58	-26.96	-24.20
b_3	2.03	0.96	1.15	1.31	0.08	5.56	5.11
			Equatorward boundary of the diffuse aurora				
b_0	3.44	-2.41	-0.74	-2.12	-1.68	8.69	8.61
b_1	29.77	7.89	3.94	3.24	-2.48	-20.73	-5.34
b_2	-16.38	-4.32	-3.09	-1.67	1.58	13.03	-1.36
b_3	3.35	0.87	0.72	0.31	-0.28	-2.14	0.76

Table 2. Expansion coefficients for auroral boundaries by Starkov [9] used in Eq. (3).

The value of the K_p index varies from 0 to 9 with 0 being very quiet and 5 or more indicating geomagnetic storm conditions. In detail, K_p represents a 3 hour weighted average from a global network of magnetometers measuring the maximum deviation in the horizontal component of the Earth's magnetic field.

In coordinates of corrected geomagnetic co-latitude, θ, the boundaries of the oval are expressed as

$$\begin{aligned}\theta = A_0 + A_1 \cos\left[15\left(t+\alpha_1\right)\right] + \\ + A_2 \cos\left[15\left(2t+\alpha_2\right)\right] + A_3 \cos\left[15\left(3t+\alpha_3\right)\right],\end{aligned} \quad (2)$$

where A_i for $i \in [0...3]$ are amplitudes in units of degrees of latitude, t is the local time in decimal hours, and α_i for $i \in [1...3]$ are phases also given in units of hours. Eq. (2) is valid for the poleward, the equatorward and the diffuse aurora boundaries. The challenge now is to find the coefficients of Eq. 2.

Starkov [9] does this using a new third order polynomial for both the A_i and α_i coefficients

$$\begin{aligned}A_i \ or \ \alpha_i = b_0 + b_1 \log_{10}\left|AL\right| + \\ + b_2 \log_{10}^2\left|AL\right| + b_3 \log_{10}^3\left|AL\right|.\end{aligned} \quad (3)$$

In other words, for each coefficient A_i or α_i there is a set of b_i for $i \in [0...3]$ values. Table 2 lists all the values.

Starting with the K_p index, Eq. (1) is used to obtain the AL index. Next, Table 2 is used to obtain the correct set of b_i values to calculate the A_i or α_i coefficients by Eq. (3). Finally, the auroral boundaries are obtained using Eq. (2).

Note that the above procedure works for K_p indices that are floating point numbers. The ovals are expanding smoothly as the K_p index increases.

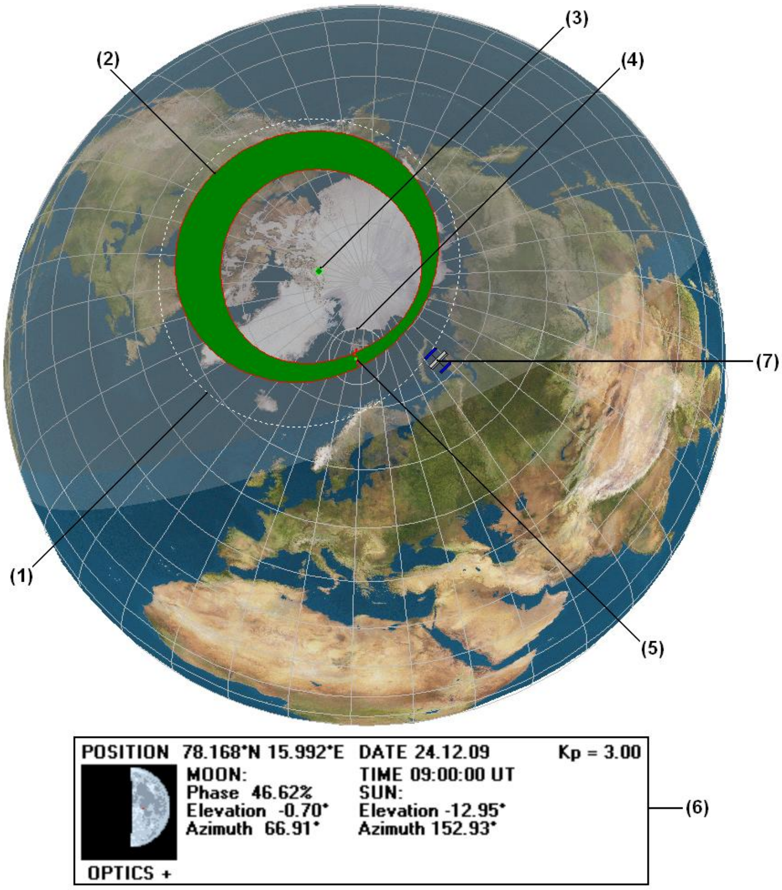

Fig. 1. SvalTrackII screen dump: (1) equatorward boundary of the diffuse aurora, (2) aurora oval K_p=3, (3) magnetic north pole, (4) field of view aurora observer, (5) observer location, (6) Moon and Sun information at local site, (7) position of the Rapideye 1 satellite. Time: 09:00 UT on 24th December 2009.

3. GEOGRAPHICAL TRANSFORM

The ovals calculated in the previous section are centred on the magnetic poles. The Cartesian components in the graph are related to the polar magnetic coordinates by

$$x_m = \sin\theta \cdot \cos\phi$$
$$y_m = \sin\theta \cdot \sin\phi \ , \qquad (4)$$
$$z_m = \cos\theta$$

where θ and ϕ are the magnetic latitude and longitude, respectively. In local magnetic time it becomes

$$\phi = 2\pi \cdot t/24 + \Delta\phi(t), \qquad (5)$$

where $\Delta\phi(t)$ is the longitudinal difference between the sub-solar point and the magnetic poles at time t (hours). It is important in order to make sure that the ovals are oriented correctly with magnetic noon pointing towards the Sun as Earth rotates around its own axis.

The transformation to geographic coordinates is then

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \widetilde{R} \cdot \begin{bmatrix} x_m \\ y_m \\ z_m \end{bmatrix}, \qquad (6)$$

where $\widetilde{R}$ is a rotational matrix. The invariant magnetic north pole is located in geographic coordinates at latitude $\theta_0' = 82.41^o\,N$ and longitude $\phi_0' = -82.86^o\,E$. The elements of the rotational matrix are then simply

$$\widetilde{R} = \begin{bmatrix} \cos\phi_0' \cos\lambda & -\sin\phi_0' & \cos\phi_0' \sin\lambda \\ \sin\phi_0' \cos\lambda & \cos\phi_0' & \sin\phi_0' \sin\lambda \\ -\sin\lambda & 0 & \cos\lambda \end{bmatrix}, \qquad (7)$$

where $\lambda = \pi/2 - \theta_0'$ is the latitudinal difference between the geographic and the north magnetic pole.

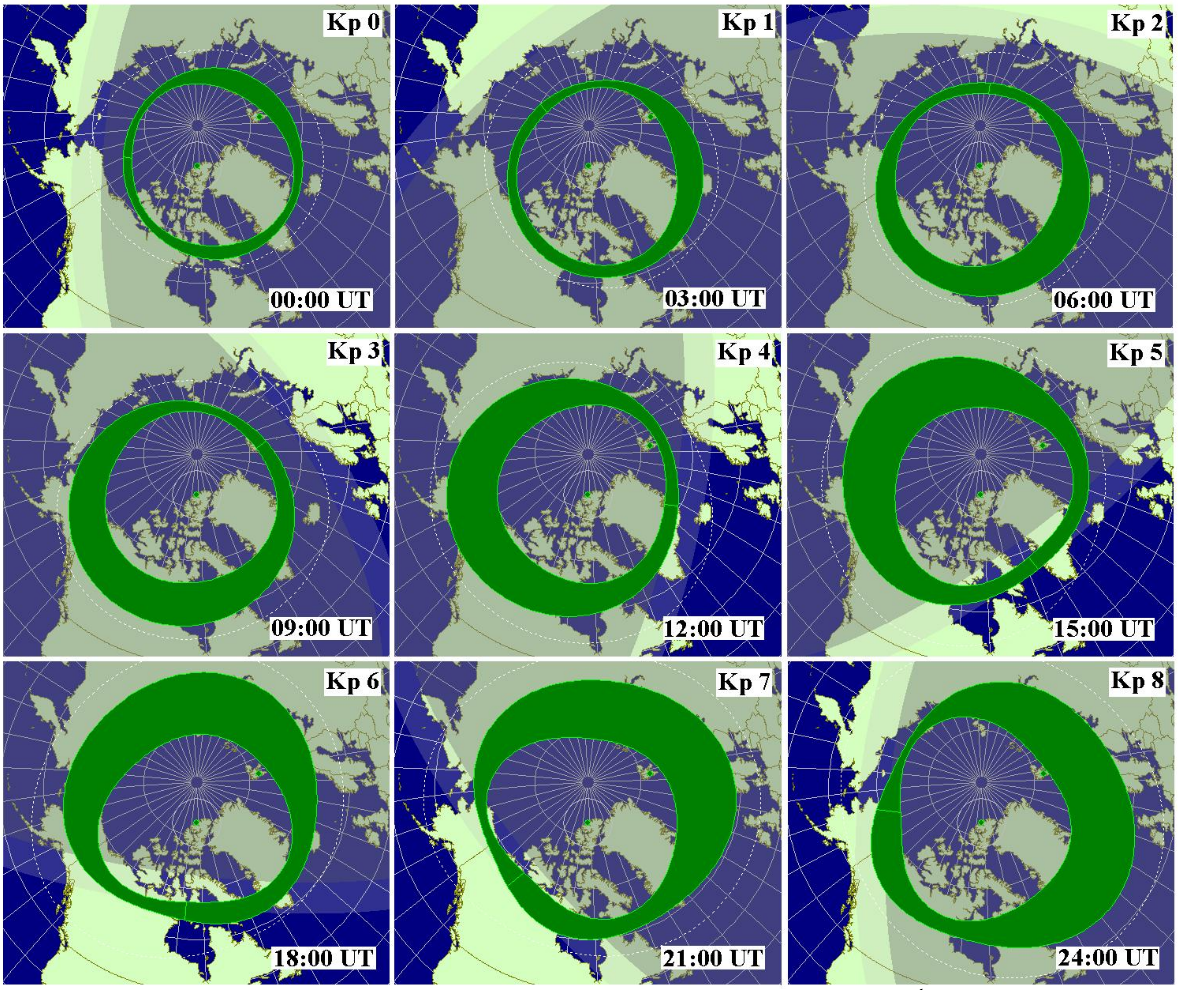

Fig. 2. Animated aurora ovals as a function of K_p index [0…8] and time for 24th December 2009

Finally, the geographic latitude and longitude of the ovals are given as

$$\theta' = \frac{\pi}{2} - \cos^{-1}(z) \qquad (8)$$

$$\psi = \tan^{-1}(y/x)$$

$$\phi' = \begin{cases} \psi & \forall \quad x > 0 \\ \psi + \pi & x < 0 \end{cases}$$

Note that the procedure is identical for the south magnetic pole if we assume that the K_p index is the same.

4. VISUALIZATION

The ovals are visualized with a stand alone 32-bit executable Windows program called SvalTrack II. The program is written in Borland's Delphi – Pascal and uses a Geographic Information System (GIS) unit called TGlobe [11]. It displays interactively mapping data in real time onto a three-dimensional spherical globe representing the Earth. The twilight zone, night- and dayside of the Earth are projected with grades of shade on the Globe as a function of time. The 3D globe can be rotated and zoomed to display a close-up of any region of the Earth.

Both the aurora Borealis and the aurora Australis ovals are projected as polygons onto the globe with an angular resolution of 1.5°. The equatorward boundary of the diffuse aurora is added as a polygonal line. The local position of the aurora observer is added as a point with corresponding state information of the Moon and the Sun. In addition, the circle of ~4.5° around the observer represents a 160° field of sky view. The latter is under the assumption that the auroral emissions peaks at an altitude of ~110 km. The program also maps the position of space objects. The orbits are calculated by the use of the Simplified General Perturbations model 4 for near and deep space objects (SGP4 / SDP4) [12]. The model input is compatible with the Two-Line Element sets (TLE data) from NORAD (North American Aerospace Defense Command).

All the above features are shown in Fig. 1. A textured map is used to visualize the Earth on 24th of December 2009. The twilight zone crosses most of Norway, and North America is on the nightside. The observer is located on the island of Svalbard in Longyearbyen, Norway (78.2°N, 16.0°E). The K_p = 3 oval is typically broader on the night- vs. the dayside, with magnetic noon or cusp located over the site at ~08:50 UT. The Moon is below the horizon, indicating favorable conditions to view the aurora. As an example, the satellite named Rapideye 1 is located at coordinates (73.4°N, 62.9°E) at an altitude of 631.5 km. The corresponding azimuth- and elevation angle for the observer are 86.9° to the East and 19.3° above the horizon, respectively. This feature can be applied to several satellites simultaneously, only limited by the number of elements in the TLE data file.

Fig. 2 shows different sized aurora ovals as a function of K_p index and time of day for 24th December 2009. As expected, the impact area or ovals are wider and more asymmetric with increasing K_p index. Also note that the island of Svalbard is uniquely located. It is possible to view both the day- and nightside aurora from this location midwinter.

The only input to the above visualization is time, TLE data and the estimated K_p index. The program is set up to update itself based on the predicted K_p index provided by the Space Weather Prediction Centre at the National Oceanic and Atmospheric Administration (NOAA). The index is predicted every 15 minutes by the use of the Costello Geomagnetic Activity Index model [7, 8], which takes into account the most recent response of solar wind parameters (neural network algorithm).

The net result is an aurora oval forecast up to approximately one hour in advance of real time installed to run automatically at the Kjell Henriksen Observatory (KHO) on Svalbard, Norway. The link is http://kho.unis.no.

5. CONCLUDING REMARK

A method to mathematically calculate the size and location of the aurora oval onto a solar illuminated Earth globe is presented as function of estimated K_p index and time. The system may be used as a forecast when the K_p value is estimated from satellite data one hour upstream in the solar wind.

Acknowledgement

We wish to thank the National Oceanic and Atmospheric Administration (NOAA) - Space Weather Prediction Centre for allowing us to download the predicted value of the K_p index every 15 minutes. The work is financially supported by The Research Council of Norway through the project named: Norwegian and Russian Upper Atmosphere Co-operation On Svalbard part 2 # 196173/S30 (NORUSCA2) and the Nordic Council of Ministers: Arctic Cooperation Programme # A10162.

REFERENCES

[1] Feldstein, Y.I., On morphology of auroral and magnetic disturbances at high latitudes, Geomagnetism and Aeronomy, 3, 183-192, 1963.

[2] Feldstein, Y.I., and G.V. Starkov, The auroral oval and the boundary of closed field lines of the geomagnetic field, Planet. Space Sci., 18, 501-508, 1970.

[3] Feldstein, Y. I., Auroral Oval, J. Geophys. Res., 78 (7), 1210-1213, 1973.

[4] Holzworth, R. H., and C. I., Meng, Mathematical representation of the auroral oval, Geophys. Res. Lett., 2, 377-380, 1975.

[5] Gussenhoven, M.S., D. A. Hardy, and N. Heinemann, Systematics of the equatorward diffuse auroral boundary, J. Geophys. Res, 88, 5692-5708, 1983.

[6] Helmholtz Centre in Potsdam, http://www-app3.gfz-potsdam.de/kp_index/description.html.

[7] Costello, K. A., Moving the Rice MSFM into a Real-Time Forecast Mode Using Solar Wind Driven Forecast Models, Ph.D. dissertation, Rice University, Houston, TX, June 1997.

[8] The Costello Geomagnetic Activity Index, http://www.swpc.noaa.gov/rpc/costello/index.html

[9] Starkov, G. V., Mathematical model of the auroral boundaries, Geomagnetism and Aeronomy, 34, 3, 331-336, 1994.

[10] Starkov, G. V., Statistical dependences between the magnetic activity indices, Geomagnetism and Aeronomy, 34, 1, 101-103, 1994.

[11] G. Knight, TGlobe component v. 4, Delphi 3-5 and C++ Builder, 1997 – 2001.

[12] Vallado, D. A., P. Crawford, R. Hujsak, and T. S. Kelso, Revisiting Spacetrack Report #3, American Institute of Aeronautics and Astronautics (AIAA), Report No. AIAA 2006-6753, 1-88, 2006.