Auroral activity during the Cusp-Region EXperiment (C-REX) rocket campaign width measured barium cloud intensities

F. Sigernes[1], L. Baddeley[1], D. A Lorentzen[1], P. G. Ellingsen[1], M. Conde[2], D. Hampton[2], M. Dhadly[2], J. Ahrns[2], M. Larsen[3], B. Barker[3], A. Kiene[3], Y. Kakinami[4] and A. Aruliah[5]

[1]*University Centre in Svalbard (UNIS), 9171 Longyearbyen, Norway*
[2] *Geophysical Institute, University of Alaska Fairbanks, USA*
[3] *Department of Physics and Astronomy, Clemson University, USA*
[4] *School of Systems Engineering, Kochi University of Technology, Japan*
[5] *Atmospheric Physics Lab, University College London, UK*

Abstract: This study reports on the general auroral activity and geomagnetic conditions as observed from the Kjell Henriksen Observatory (KHO) during the Cusp-Region Experiment (C-REX) rocket campaign. Hyperspectral all-sky measurements of the barium clouds released from the rocket show absolute intensities up to ~100 *kR* with a decrease in time twice as fast as expected.

Background

The Kjell Henriksen Observatory (KHO) (78.148°N, 16.043°E) was part of the Cusp-Region EXperiment (C-REX), a NASA sounding rocket mission that released a large constellation of barium clouds into the ionosphere above the Greenland Sea. The rocket was launched from Andøya Space Centre (ASC) at 08:05 UT on 24th of November, 2014.

Sky map

Fig. 1 shows a sky map as seen from KHO 10 minutes after launch time of the C-REX rocket. The graphics is generated by our auroral forecast service software [1]. The green belt in the East-West geomagnetic direction is the estimated location of the auroral oval. The measured planetary Kp-index from the Helmholtz Centre in Potsdam was Kp = 1.0 for the event. The auroral / geomagnetic activity was classified as low.

The one hour estimated Kp-index [2] by the NOAA Space weather prediction center matched the measured index from Potsdam. As a consequence, Fig.1 served as a solid forecast of the sky conditions 1 hour prior to launch.

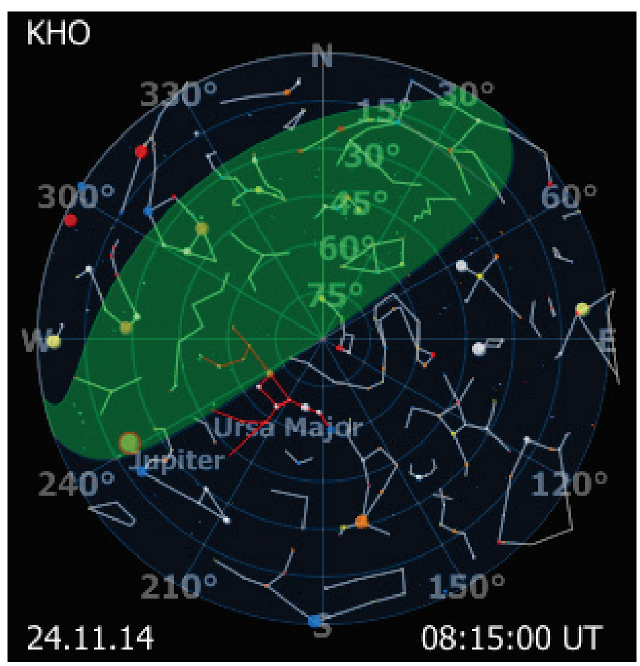

Fig.1 Sky map as seen from The Kjell Henriksen Observatory (KHO) at 08:15:00UT, 24.11.2014.

The planet Jupiter was used as a reference for the pointing direction of the narrow field of view cameras which were utilized to image the artificial clouds released from the rocket. The rocket was launched ~50 minutes before magnetic noon at KHO. This corresponds to dayside Cusp conditions at the site, and the aurora should, by definition, be more red than green in color.

Hyperspectral images

A hyperspectral all-sky camera named NORUSCA II [3] was operative during the C-REX campaign. The instrument is an all-sky camera capable of imaging the night sky as a function of wavelength with no moving parts.

Table 1. NORUSCA II center wavelengths.

Channel #	Wavelength [*nm*]	Emission lines	FWHM [*nm*]
1	486.1	H_β	6.19
2	557.7	[OI]	7.10
3	630.0	[OI]	8.02
4	500.2	NII	6.37
5	589.0	NaI	7.50
6	636.4	[OI]	8.10
7	656.3	H_α	8.35
8	670.5	$N_2$1P(5-2)	8.53
9	676.4	N_2	8.61

The camera was setup to record 9 wavelength channels covering the visible spectrum of auroral emissions. Table 1 lists the center wavelengths, the origin of the emissions and the bandpass of the instrument. The emissions lines at wavelengths 486.1 and 656.3 *nm* are from proton impact excitation of hydrogen (H_β and H_α), while the forbidden 557.7, 630 and 636.4 *nm* emissions are due to electron impact excitation of atomic oxygen [*O*I]. The N_2 bands at 670.5 and 676.4 *nm* are excited by electron impact as well as cascading from higher levels. The emission at 500.2 *nm* is caused by electron impact ionization of nitrogen (NII). The 589 *nm* emission is from an excited layer of NaI atoms located at an altitude of 80 – 105 *km*, known as the Sodium layer. The emission line is also present in low pressure sodium vapor lamps used as outdoor lighting, which make it useful for quantifying light pollution.

The exposure time was set to 5 seconds per channel. The sequence of 9 exposures started on a minute boundary. There is a 1/2 *s* delay between each exposure. The instrument then waits 11 *s* for the next sequence to start. Fig. 2 shows color composite RGB images from the camera. Channels 1, 2 and 3 are used to represent red, green and blue components to the RGB images, respectively. These are the 3 first exposures in the sampling sequence that starts every minute. The effective sampling time or epoch of each color composite image is 16 *s*.

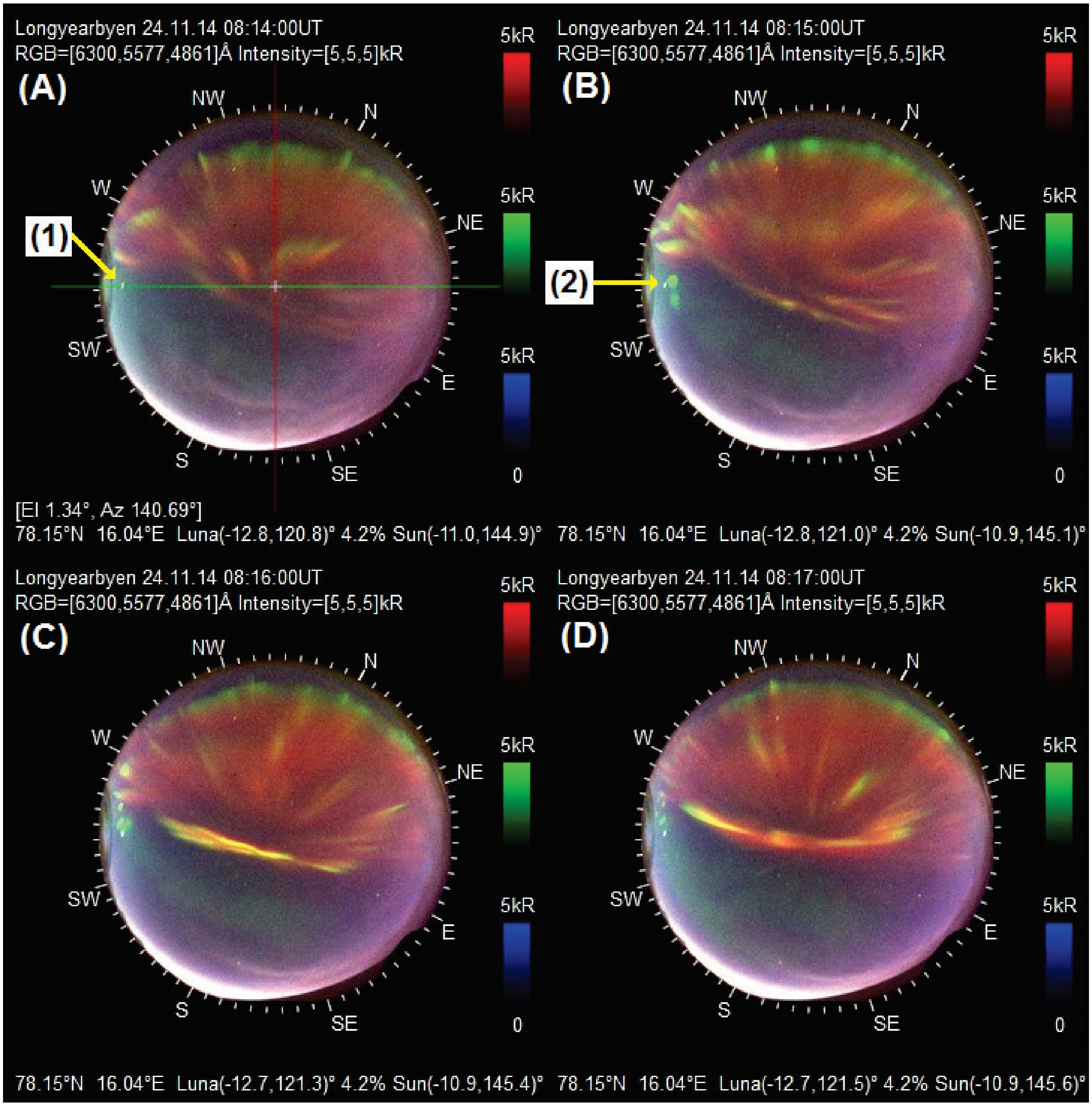

Fig. 2. NORUSCA II all-sky color composite images from the Kjell Henriksen Observatory (KHO), 24.11.2014. The Red, Green and Blue color channels are from center wavelengths 6300, 5577 and 4861 Å, respectively. Labels (A) to (D) represent time from 08:14 to 08:17 UT. Jupiter is marked with arrow (1) in panel (A). Arrow (2) in panel (B) marks the first releases of the artificial clouds.

Panel (A) of Fig. 2 shows typical dayside cusp aurora just prior to the first release of the artificial Barium / Strontium cloud at 08:14 UT. The aurora is, as expected for this MLT, more red than green in color and located roughly in the North-East and North-West quadrants of the field of view. The intensities are ~ 5 *kR.* A weak ~2 *kR* green auroral belt is seen south of the red aurora with a dark region in-between that represent the open closed field line boundary of the magnetosphere.

The two first artificial clouds were detected by the camera at 08:15 UT in panel (B). As the canisters were released from the rocket, 8 more clouds were detected over a time period of ~2 minutes, see panels (C) and (D). The diffuse pink colored band close to the horizon in the East is scattered light from low altitude clouds. Likewise, the bright white rim in the South is scattered light from the rising Sun.

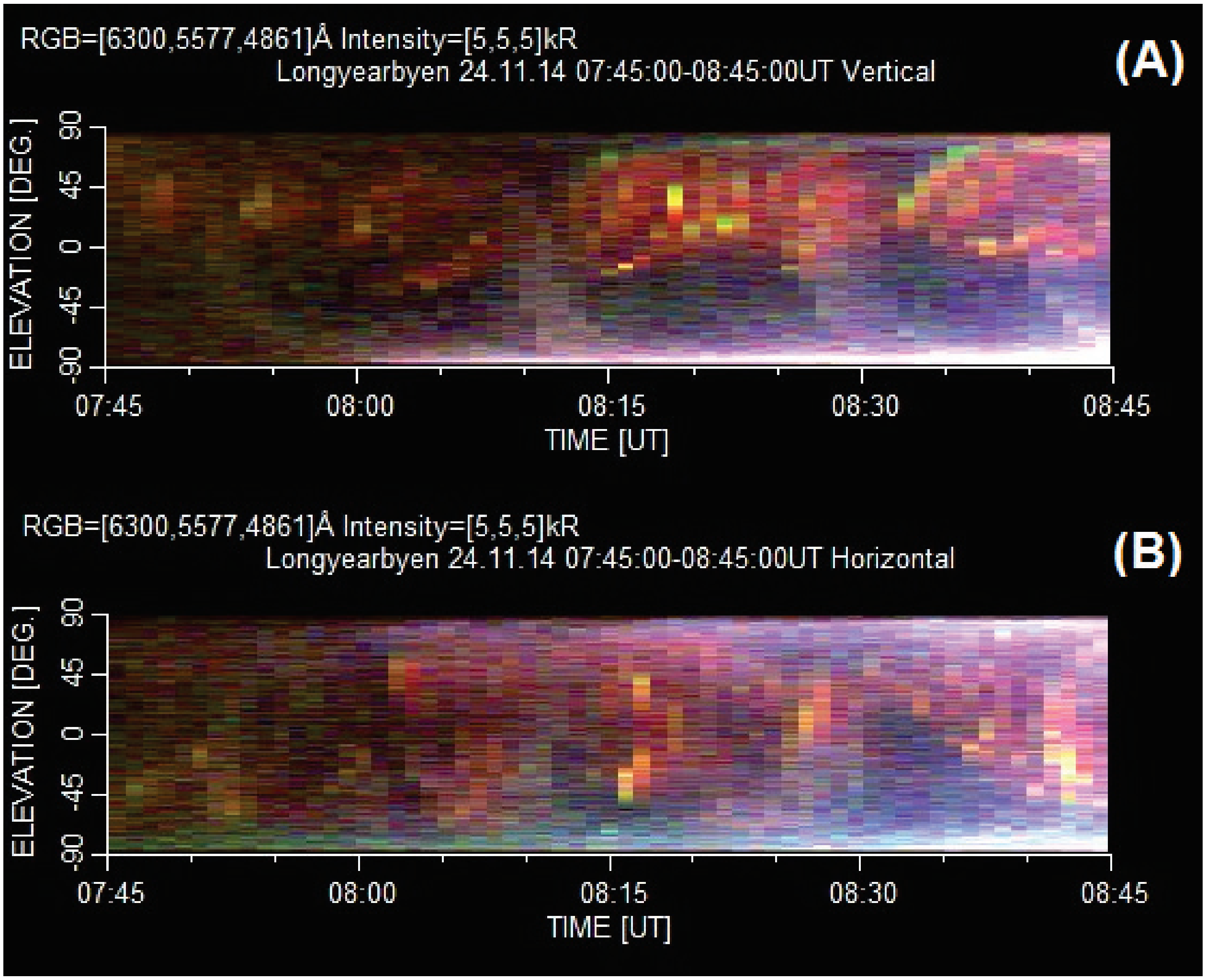

Fig. 3. NORUSCA II all-sky color composite Keograms from the Kjell Henriksen Observatory (KHO), 24.11.2014. The Red, Green and Blue color channels are from center wavelengths 6300, 5577 and 4861 Å, respectively. Panel (A) shows the vertical Keogram in the North-South geomagnetic direction. North is up at $+90^{o}$. Panel (B) is the Keogram in the East-West geomagnetic direction. East is $+90^{o}$ up.

Keograms

A time line of the auroral activity can be obtained by plotting time versus elevation and intensity sliced cross-sections of the images (Keograms). The vertical center column of the images is oriented parallel with the geomagnetic meridian plane at KHO. The red line in panel (A) of Fig. 2 marks the geomagnetic plane. Up points towards the geomagnetic North pole. Correspondingly, the green line marks the East-West geomagnetic plane.

Fig.3 shows the composite RGB Keograms for both directions from 07:45 to 08:45 UT, centered at the first cloud release at 08:15 UT. The auroral activity is throughout the time period dominated by stable cusp auroral arcs. Panel (A) shows that they are located approximately north of zenith moving northward. The arcs have a positive intensity versus time slope. The increase in scattered light from the sun is seen in the South from 08:00 to 08:45 UT. Panel (B) shows the corresponding East-West motion of the aurora. Low altitude clouds are seen to move in and out from the East at ~08:05 UT. Fortunately, they did not block the field of view to the narrow field of view cameras and the expected view direction to the cloud releases, ~20^{o} above the horizon at azimuth ~240^{o}.

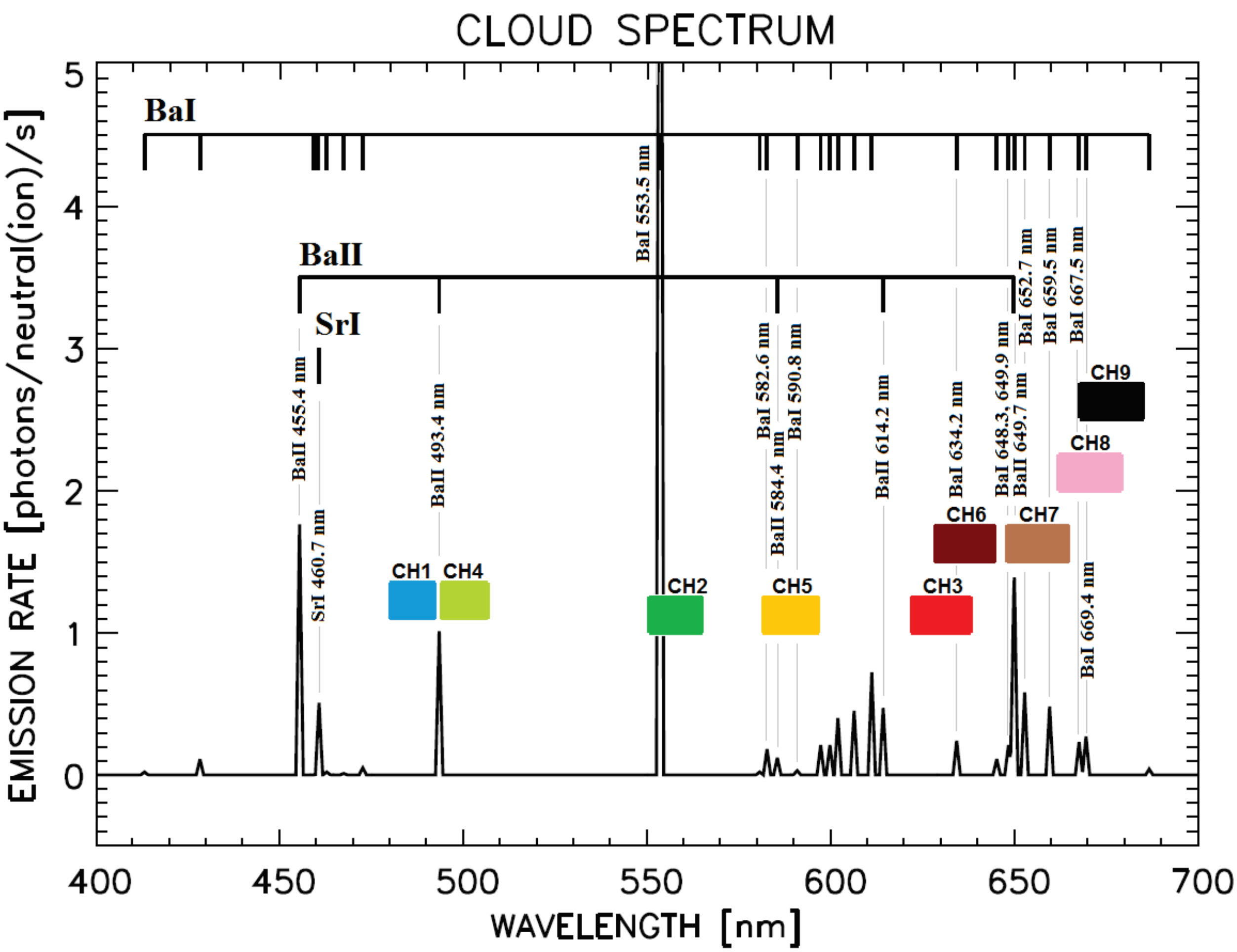

Fig. 4. Synthetic cloud spectrum in the visible part of the spectrum. The emission rates per neutral atom or ion are adopted from [5]. Top ruler line marks the position of the neutral barium emission lines (BaI). Five ion lines (BaII) and one neutral strontium line (SrI) are also marked. The spectrum is calculated with a theoretical bandpass of 0.1 *nm*. The length of the colored boxes represents the bandpass of the NORUSCA II all-sky camera channels.

Intensity of the artificial clouds

The emitted light from the artificial clouds is due to photoionization and resonant scattered sunlight [4]. Both neutral and ionized barium lines appear with different colors. Strontium is also added to the barium mixture to enhance the neutral drift detection. Fig. 4 shows a synthetic cloud spectrum based on observed barium emission rates [5]. The strongest emission line is the neutral barium line (BaI) at 553.5 *nm* with an emission rate close to 11 *photons neutral*$^{-1}$ *s*$^{-1}$. It is within the detection window of channel 2 of the NORUSCA II all-sky camera. The latter is unfortunately not true for the neutral strontium (SrI) line and the ionized barium (BaII) lines at 460.7, 455.4, 493.4, and 614.2 *nm,* respectively. The BaII line at 493.4 *nm* is missed by both channel 1 and 4. The ion BaII line at 649.7 *nm* in channel 7 is detected, but 4 neutral BaI lines at 648.3, 649.9, 652.7 and 659.5 *nm* overlap. The weak BaII line at 584.4 *nm* of channel 5 is also overlapped by BaI lines at 582.6 and 590.8 *nm*. Channel 3 and 6 measure both the same BaI line at 634.2 *nm*. These two channels should measure equal intensities, if the exposures where taken simultaneously. Channel 8 covers the two BaI lines at 667.5 and 669.4 *nm*. Channel 9 only covers the BaI line at 669.4 *nm*.

The above setup is not ideal for the study of separation and drift of the ion versus the neutral cloud since no clear distinct ion lines are measured by the camera. For future experiments, a redistribution of the channels should match above synthetic spectrum to include the barium ion lines at 455.4 and 493.4 *nm* and the strontium line at 460.7 *nm*. On the other hand, the image resolution of an all-sky camera is not sufficient to study motion of drift and separation of the artificial cloud releases. The field view per pixel is too wide to obtain details. Intensities are however possible to obtain if we assume the clouds be optically thin and isotropic within the pixels field of view [6].

Due to the sequential setup of the camera, it is first necessary to identify clouds as a function of time.

Table 2. C-REX artificial cloud time release and look angles detected by all-sky cameras at KHO

Cloud ID	Time [UT]	~Lifetime [s]	Azimuth [^{o}]	Elevation [^{o}]
1	08:14:18	54	231.52	28.87
2	08:14:54	70	243.10	26.47
3	08:14:54	70	242.80	24.26
4	08:15:25	16	240.95	22.41
5	08:15:51	103	245.85	19.75
6	08:15:51	103	251.63	17.86
7	08:15:51	103	244.52	17.85
8	08:16:15	75	255.44	15.06
9	08:16:15	75	248.10	13.35
10	08:16:15	75	253.45	12.52

Table 2 lists the release time of 10 detected clouds together with an estimate of lifetime and look angles. The release time and lifetimes of the clouds are from visual inspection of color EMCCD all-sky camera frames (Media 1).

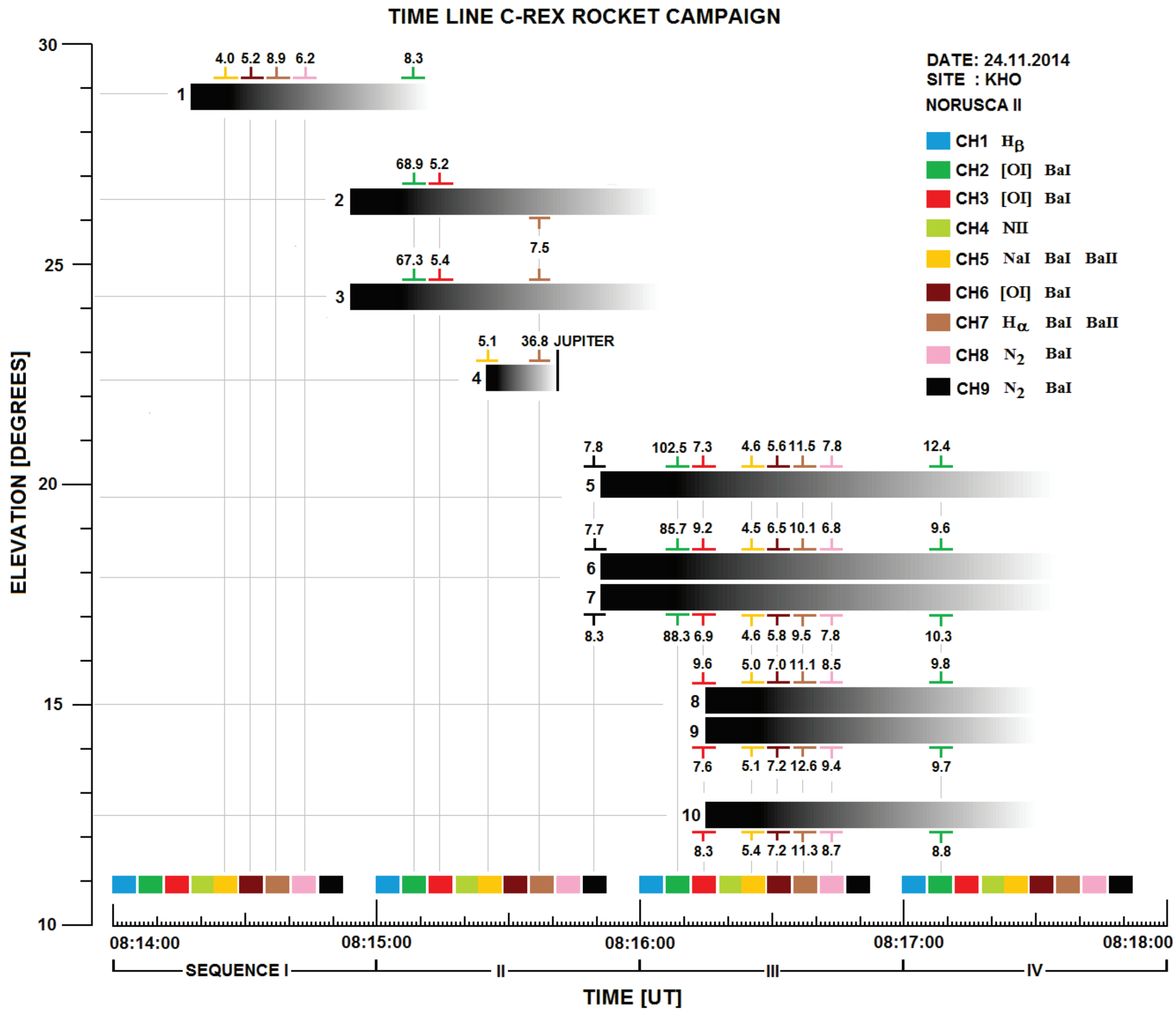

Fig. 5. NORUSCA II exposure sequence and C-REX cloud release as a function of elevation and time as seen from KHO. The colored bar line marks 5 second exposures by the NORUSCA II camera. The different colors represent channels or wavelength settings of the camera. The left side numbered gray scaled bars are cloud releases by the C-REX rocket. The length of the bars indicate lifetime of the clouds. Floating point numbers are peak intensities of the clouds in units of *kR*.

Note that it was hard to determine the exact time when the clouds disappeared due to background sky conditions and aurora. In addition, as seen from KHO, cloud number 4 was released close to Jupiter. It is hard to distinguish them from each other in the all-sky data.

To proceed, it is now possible to construct a time line of the cloud releases as a function elevation and exposure sequence of the NORUSCA II camera based on the data of Fig. 4 and Table 2. The results are illustrated graphically in Fig. 5. Furthermore, the camera is calibrated in sensitivity. The calibration method is described in detail by [7]. Any point in the image is calibrated both in view angle and intensity. For each frame in the spectral animation of the event (Media 2), clouds are identified according to time and position. The peak intensity of each cloud is recorded in units of *kR*.

In general all channels detected neutral BaI lines in accordance to the intensity of the synthetic spectrum in Fig. 4, except channels 1 and 4 where no cloud emissions are present. The strongest recorded intensities are in the green channel 2 due to the BaI line at 553.5 *nm*. Up to 100 *kR* are detected even after ~15 seconds of the initial release of clouds 5, 6 and 7. The clouds still glow green at a level 10 *kR* after ~75 seconds.

The next signal that stands out clearly above the background level are detected in the deep colored red channel 7. These exposures are 30 seconds after the green channel 2 width intensities close to the 10 *kR* level. As noted above, 4 neutral BaI lines at 648.3, 649.9, 652.7 and 659.5 *nm* contribute to channel 7 together with the ion BaII line at 649.7 *nm*. The emission rate of the BaII at 649.9 *nm* is relatively high close to 1 *photon* $neutral^{-1}$ s^{-1} compared to the low 0.4 *photons* ion^{-1} s^{-1} for the BaII line at 649.7 *nm.* As expected, the latter makes it impossible to distinguish these emissions from each other. The same applies to channel 5.

The BaI line at 553.5 *nm* dropped in intensity by a factor of roughly 10 over a time period of 60 seconds for clouds 5, 6, and 7. This is 2 times faster than the *1/time* assumption for neutral intensity decrease of the clouds [5]. This contradiction can be solved by reducing the numbers of channels of the camera to sample faster. For future experiments, a 3 channel setup of the camera is recommended with focus on the emission lines BaII at 455.4 or 493.4 *nm*, the SrI line at 460.7 *nm* and the BaI line at 553.5 *nm*.

Summary

On the 24th of November 2014 the C-REX rocket was launched from Andøya Space Center (ASC) successfully into the dayside cleft region above Svalbard. The planetary Kp index was equal to unity with geomagnetic activity classified as low. Red cusp auroral arcs were as expected observed slightly to north of zenith at the Kjell Henriksen Observatory (KHO). A thin layer of low altitude clouds drifted in and out from the East, but did not block the field of view to the cloud releases. 9 channel intensity measurements were conducted with the NORUSCA II hyperspectral all-sky camera. Neutral Barium cloud intensities have been found to range from just a few *kR* up to ~100. The clouds dropped 2 times faster in intensity than the *1/time* assumption predicts.

Acknowledgement

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References

[1] F. Sigernes, M. Dyrland, P. Brekke, S. Chernouss, D.A. Lorentzen, K. Oksavik, and C.S. Deehr, Two methods to forecast auroral displays, Journal of Space Weather and Space Climate (SWSC), Vol. 1, No. 1, A03, DOI:10.1051/swsc/2011003, 2011.

[2] Wing, S., J. R. Johnson, J. Jen, C.-I. Meng, D. G. Sibeck, K. Bechtold, J. Freeman, K. Costello, M. Balikhin, and K. Takahashi (2005), Kp forecast models, J. Geophys. Res., 110, A04203, doi:10.1029/2004JA010500.

[3] F. Sigernes, Y. Ivanov, S. Chernouss, T. Trondsen, A. Roldugin, Y. Fedorenko, B. Kozelov, A. Kirillov, I. Kornilov, V. Safargaleev, S. Holmen, M. Dyrland, D. Lorentzen, and L. Baddeley, Hyperspectral all-sky imaging of auroras, Opt. Express, Vol. 20 (25), 27650-27660, 2012. DOI: http://dx.doi.org/10.1364/OE.20.027650.

[4] C. S. Deehr, E. M. Wescott, H. C. Stenbaek-Nielsen, G. J. Romick, T. J. Hallinan, and H.Foppl, A critical velocity interaction between fast barium and strontium atoms and the terrestrial ionospheric plasma, Geophys. Res. Lett., Vol. 9, No. 3, 195-198, 1982.

[5] H. C. Stenbaek-Nielsen, E. M. Wescott, and T. J. Hallinan, Observed Barium Emission Rates, J. Geophys. Res., Vol. 98, No. A10, 17491-17500, 1993.

[6] D. J. Baker and G. J. Romick, The Rayleigh: interpretation of the unit in terms of column emission rate or apparent radiance expressed in SI units, Applied Optics, Vol. 15, No. 8, 1966-1968, 1976.

[7] F. Sigernes, S. E. Holmen, D. Biles, H. Bjørklund, X. Chen, M. Dyrland, D. A. Lorentzen, L. Baddeley, T. Trondsen, U. Brändström, E. Trondsen, B. Lybekk, J. Moen, S. Chernouss, and C. S. Deehr, Auroral all-sky camera calibration, Geosci. Instrum. Method. Data Syst. Discuss., 4, 515-531, 2014.