Using colour in auroral imaging

N. Partamies, M. Syrjäsuo, and E. Donovan

Abstract: The prototype of an auroral colour camera named Rainbow was run at the Auroral Station in Adventdalen, Svalbard, Norway, during a Finnish optical campaign in February, 2004. Instead of narrow band-pass filters and grey-scale images, this imager records colour images of the aurora using four wide-band channels (a colour CCD) with the field-of-view of about 150 degrees.

In this study, we show the results of fitting the four Rainbow channels (cyan-magenta, cyan-green, yellow-magenta, yellow-green) to reconstruct the traditionally filtered auroral wavelengths: green (557.7 nm), red (630.0 nm) and blue (427.8 nm) which were simultaneously recorded by the Meridian Scanning Photometer (MSP) at the same station. This fit is qualitatively extremely good and almost linear throughout the data. In studying the auroral evolution during substorms, there is no significant difference whether MSP or Rainbow data is used. However, due to wide-band colour channels, the background illumination has a strong effect on the Rainbow data. During low signal levels (only background or faint aurora) the reconstruction errors are larger.

The data for this study were captured on the 21st of February, 2004. The time period of interest includes a substorm sequence, which is examined using colour auroral images and data from the MSP.

1. Introduction

Most of the auroral imaging nowadays is performed by using either white light imagers or cameras with narrow band-pass filters centered at the most common auroral emission lines: green at 557.7 nm, blue at 427.8 nm and red at 630.0 nm. Imagers utilising the filters provide quantitative information on emissions at each wavelength, but they are also expensive and replacing worn-out parts can be costly. White light (panchromatic) imagers, on the other hand, lose all the spectral information but can provide high temporal resolution (up to three seconds) of the evolution of the aurora at a lower cost.

As an example of currently used imaging systems the Finnish MIRACLE [7] and the Canadian NORSTAR [2] ground-based networks are the largest ones. The former consists of seven cameras with filters and filterwheels in Fennoscandia and Svalbard. The NORSTAR network includes five filtered imagers in addition to the meridian scanning photometers (MSP) and riometers. The ground-based segment of the NASA's THEMIS mission comprises 20 sites with white light images and magnetometers (16 of which in Canada) and will be fully operational in the autumn 2006.

We have two motivations for looking for a different imaging solution. On one hand, we are involved in European, Canadian, and US projects that are developing wide imager arrays (as mentioned above) to characterise the auroral distribution over continental scales. To save on cost and to ease the oper-

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ational difficulties, these projects are moving towards using simple white light imagers. While their fundamental objective is to provide quantitative information on morphology and timing, essentially all spectral knowledge is lost. If we could develop a colour version of these white light imagers that did not utilise a filter wheel, we could accomplish all of our goals and infer at least some spectral information.

On the other hand, we are involved in a program to automatically detect the presence of aurora and to classify auroral types in millions of images. The auroral type plays a critical role in the magnetosphere-ionosphere coupling, but has simply never been quantitatively dealt with. Both the filtered and white light images result in grey-scale images making it very difficult, sometimes even for a professional eye, to distinguish between, for example, patchy aurora and moonlit clouds or clouds coloured by light pollution from a nearby town. This difficulty is demonstrated in Fig. 1 where the moonlit clouds cannot easily be separated from the aurora in grey-scale (left) but are obvious in colours (right).

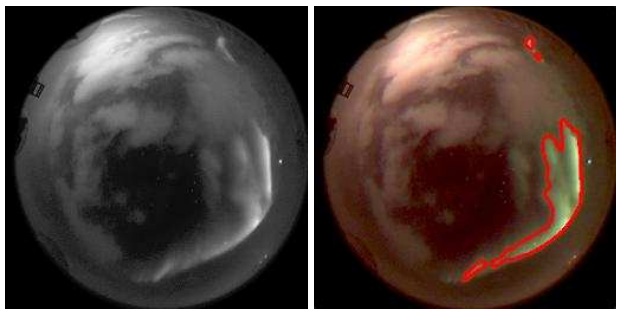

Fig. 1. Grey-scale image of the aurora and illuminated clouds (left) and the same image in colour (right). The auroral object, as separated by the red line, is obvious in the colour image but would be difficult to distinguish from the grey-scale image.

The colour imager called Rainbow described in this paper will move us significantly towards both objectives. In future arrays of inexpensive imagers, we would be able to extract some information on, for instance, the hardness of the auroral precipitation or the location of the open-closed field line boundary (see Section 4). The data from this new imager is also very suitable for automated detection of the aurora and thus, can play an important role in supporting the more expensive optical instrumentation. It is a low-cost — less than $10,000 — imaging system with a simple optical design. It is also most suitable for public outreach purposes providing colourful auroral images and animations. In this paper we show that this interesting new instrument is also capable of providing valuable physical information despite the wide wavelength bands of the recorded colour channels. To the best of our knowledge, digital colour cameras have not been used in automated auroral imaging before, neither have their images been utilised in gathering spectral information on the aurora. At the moment, we operate two of these cameras, one of which is on-line in realtime in Nyrölä, Mid-Finland (http://aurora.phys.ucalgary.ca/realtime/).

2. Rainbow the colour camera

We describe the imaging system only briefly here; the details can be found in [8]. The system consists of a computer controlled CCD camera, which is mounted inside a transparent dome. The computer controls the image acquisition and captures images of the night sky at the time intervals of 10–20 seconds, which is enough for most scientific purposes.

The optical design of the Rainbow auroral imager is shown in Fig. 2. A wide field-of-view (FoV) is accomplished by using a digital camera wide-angle converter lens attached to a 3.6 mm/F1.6 C-mount lens. This provides a FoV of about $150°$. Because the CCD is sensitive to infrared (IR) light,

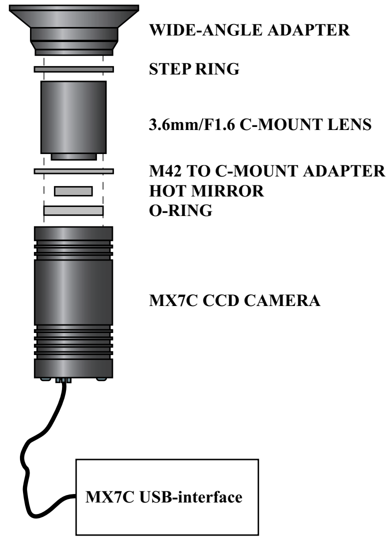

Fig. 2. The optical set-up of Rainbow with the FoV of about 150°. The hot mirror is used to block the IR and UV radiation. The CCD is designed for astronomical use and is connected to the computer via a USB interface.

a hot mirror (band-pass 400–700 nm) is placed between the CCD chip and the C-mount lens. The hot mirror reduces colour errors due to the IR sensitivity. It also minimizes image blur caused by different amounts of refraction at different wavelengths — the best foci are slightly offset for visible and IR light.

The CCD camera was selected because of its low price and 16-bit dynamic range. This CCD chip has an integrated colour filter array (CFA), the colours of which can fade in strong sunlight [6]. There is no space for an inline shutter in the optics, so one solution is to use an external shutter. Our design incorporates a servo motor used in radio controlled toys and a small computer interface board for controlling the servo. The servo moves a large shutter blade that covers the wide-angle adapter. The shutter is operated twice a day: in the evening the shutter is opened to enable imaging, and in the morning it is closed to block direct sunlight.

The integrated CFA of the Starlight Xpress MX7C camera contains filters for cyan, magenta, yellow and green [6]. Each pixel in a raw image thus represents a single colour without information about the three other colours. The MX7C uses an interlaced CCD, which requires two read operations to save a full resolution image. To speed up the reading of the image, the neighbouring pixel rows are binned together, so that the whole image can be read from the CCD at once. The colours of the combined pixels become cyan–magenta, cyan–green, yellow–magenta and yellow–green, and their responses are shown on the left hand side in Fig. 3. The total response (normalised sum of individual channels, thick grey curve in the figure) demonstrates that this CCD is most sensitive to green wavelengths ($\lambda \sim$550 nm).

The conversion to the RGB colour coordinate system results in wide-band red, green and blue channels [8]. On the right hand side in Fig. 3, these estimated responses are also scaled by the fitting parameters (the procedure described in Section 4). Because the colour channels are very wide, the background illumination has a significant effect on the intensities of the individual channels. Details about binning the pixels, colour conversion and colour calibration can be found in [8]. Note that the colour responses in Fig. 3 are provided by the vendor and have not yet been verified by a calibration.

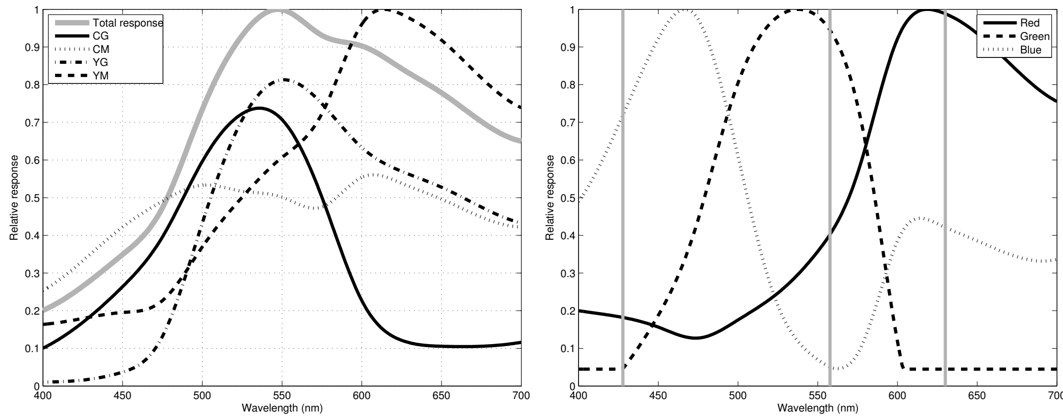

Fig. 3. Left: Relative responses of the four wide-band channels read from the colour CCD (after [6]): cyan–magenta, cyan–green, yellow–magenta and yellow–green. The thick grey curve on the background is the normalised total response. Right: The four channels' responses as converted into red, green and blue (RGB) channels (according to [8]) and scaled by the parameters obtained from the fit (Section 4). The vertical lines indicate the wavelengths of the three main auroral emissions recorded by MSP.

3. Substorm event

The data for this study were recorded at the Auroral Station in Adventdalen near Longyearbyen, Svalbard, Norway (78°N in geographic and 75.27°N in geomagnetic latitude) during a Finnish optical campaign on the 21st of February, 2004. We have analysed a two-hour period of the data (19–21 UT) from simultaneous measurements by Rainbow and the meridian scanning photometer (MSP). This time period contains an auroral substorm event. The substorm started south of Longyearbyen (above Bjørnøya, 74.50°N in geographic and 71.45°N in geomagnetic) at about 19 UT and expanded northward over Svalbard. The campaign took place during a new moon.

During this event, Rainbow was operated using 9 s exposure times and an imaging interval of 20 s. The data were stored as 16-bit images with lossless compression. Rainbow was pointed slightly towards the south so that the southern horizon was in the $150°$ FoV. The town of Longyearbyen is to the north from the station, so the strongest light pollution from the town was not recorded by the Rainbow imager.

The MSP [5] records north-south aligned zenith angle scans (180°) of the night sky. Its FoV is 1° and the band pass of the auroral emissions is $\sim$0.4 nm. The temporal resolution of the data is 16 seconds. Narrow bands of red, green and blue emissions are used here as a reference data set to see how well the same information can be gathered from the colour imager recordings.

This is the first time Rainbow was run side by side with an other optical instrument, from which the narrow-band auroral emissions can be obtained. We would prefer reference data from a calibrated narrow-band all-sky camera. However, this kind of simultaneous data are not yet available but will be analysed as soon as available.

4. Fitting the data

For the fit we assume that everything in the Rainbow green channel is due to the auroral emission at 557.7 nm, everything in the blue channel is due to the emission at 427.8 nm, and everything in the red channel is due to the emission at 630.0 nm. For low signal levels, when the background illumination becomes important, this may not be a reasonable assumption. This is why we concentrate on a time

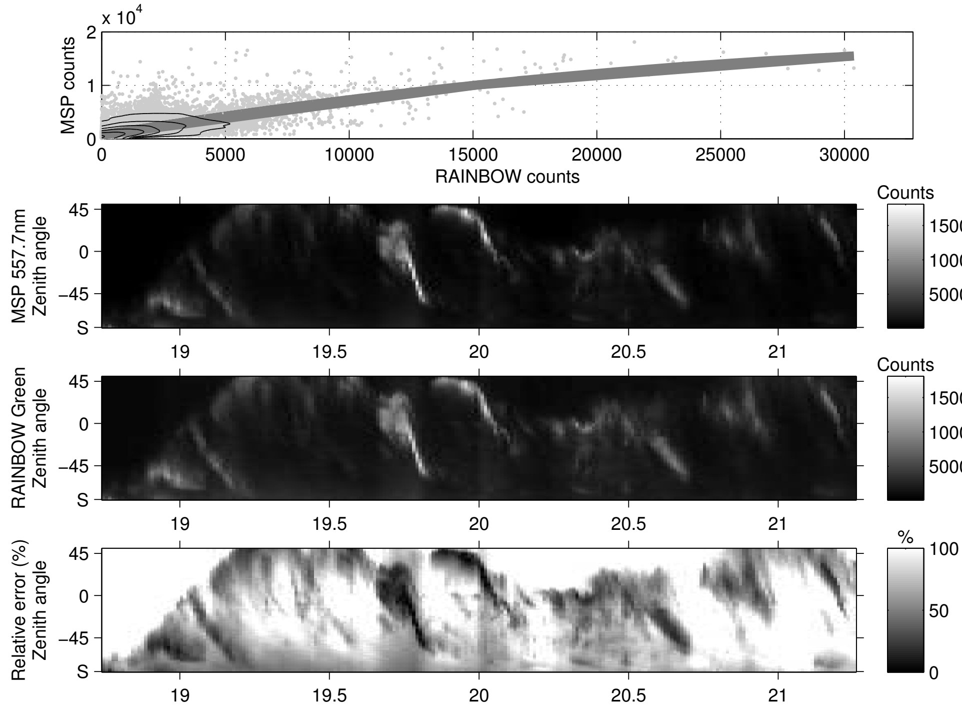

Fig. 4. Fit results for the green emission line. Top panel: scatter plot of the Rainbow and the MSP intensity counts in the corresponding pixels. The overlayed contours illustrate the sample point density, i.e. where most of the data points are. The thick line marks the fitted spline. Second panel: green line MSP data. Third panel: fitted green line Rainbow data. Bottom panel: relative error (%) of the fit in each data point.

period with strong auroral emissions. On the right hand side in Fig. 3, the vertical lines show the wavelengths of the narrow band-pass filters of the MSP as a comparison to the estimated and fitted RGB responses of the Rainbow imager. The actual response of the complete system including the hot mirror and the optics has not yet been measured. Assuming only the three emissions mentioned above were present, one would anticipate the green emission (as the strongest one) leaking into the Rainbow red channel as well as the red emission leaking into the Rainbow blue channel, while the blue emission is mainly recorded by the Rainbow blue channel.

In order to fit the colour imager keogram to the MSP data, we make simplifications that need to be re-evaluated when we have more reference data. The MSP pointing is assumed accurate and its intensity response reasonably smooth. Raibow pointing was determined by star calibration. We choose to use counts instead of absolute intensity values to emphasize the fact that Rainbow counts cannot be converted into meaningful absolute values in (Rayleighs). First both data sets were interpolated to the same temporal resolution (40 s). The corresponding two-dimensional rectangular regions in MSP and Rainbow keograms were determined by choosing the corner points that produced the highest correlation. There was not much stretching required in the zenith angle direction, neither was there a shift found in time. From the two matching keogram areas, we fit the intensity values of the corresponding pixels (about 30,000 data points in total) separately for green, blue and red emission. The function fitted to the data from each of the three channels is a cubic spline with very little curvature and 2–4 control points.

For both the green and blue channels (Figs. 4 and 5, respectively) the fit is very good. The relative

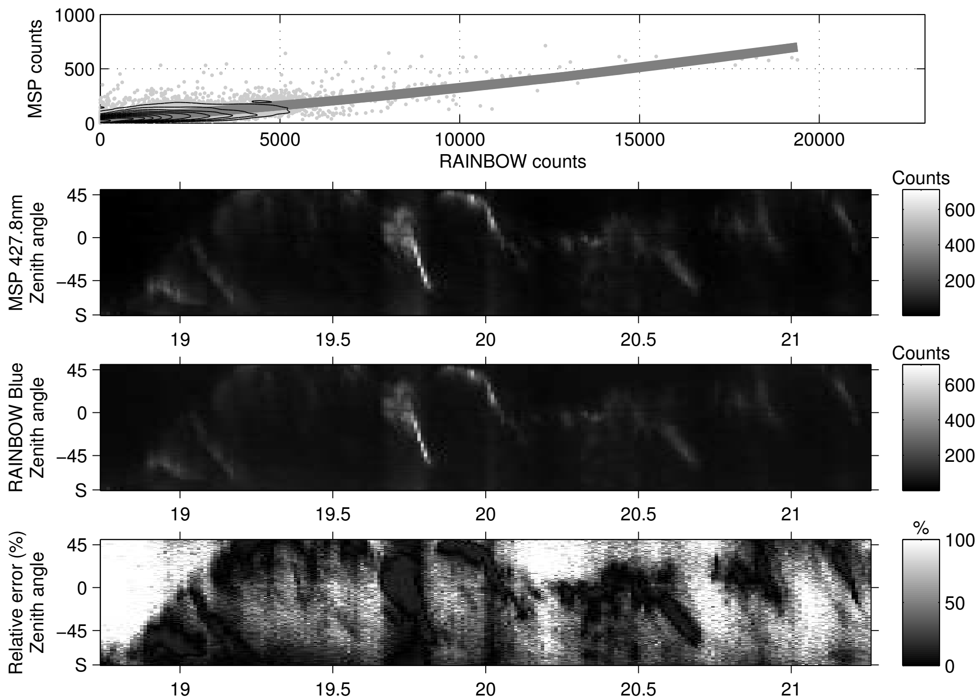

Fig. 5. Fit results for the blue emission line. Top panel: scatter plot of the Rainbow and the MSP intensities in the corresponding pixels together with the contours. The Thick line marks the fitted spline. Second panel: blue line MSP data. Third panel: fitted blue line Rainbow data. Bottom panel: relative error (%) of the fit.

changes in the intensity and the auroral evolution during the substorm are very well reproduced. The relative errors are small within the bright aurora (strong signal level), but clearly larger within very faint aurora or background illumination only.

The evolution of the auroral intensity and distribution are also well reproduced by the red channel fit, as presented in Fig. 6, but the relative errors are larger throughout the data and the background values are remarkably elevated. Although the individual data points show a significant scatter in the top panel of Fig. 6, the fitted spline follows well the centre of mass of the points shown by the overlayed contours. The higher relative errors for red channel are probably due to the higher contribution of background luminosity including light pollution and a possible leakage from green and blue channels (see the overlapping curves on the right in Fig.3).

Extracting a north-south aligned slice from both red channel keograms and plotting them together in Fig. 7, we can see that when a small, visually selected offset ($\sim$257 counts), is subtracted from the fitted Rainbow data, these two curves are essentially identical. Similar slice comparison was performed separately for each time step in the red channel keograms. The average offset for the whole two-hour period of data appears to be 270 ± 10 counts. Because the sharp increase of the luminosity (on the northern edge of the FoV in Fig.7) is so well reproduced, these data can easily be used to identify the open-closed field line (or polar cap) boundary. This boundary has been defined as the poleward boundary of the red emission [1], which is essentially a step function from the low luminosity values of the polar cap to strong precipitation of the auroral oval. The same algorithm run on both the MSP and Rainbow data produces the same location for the polar cap boundary.

Why there still is an offset in the red line data after the fitting procedure remains an open question,

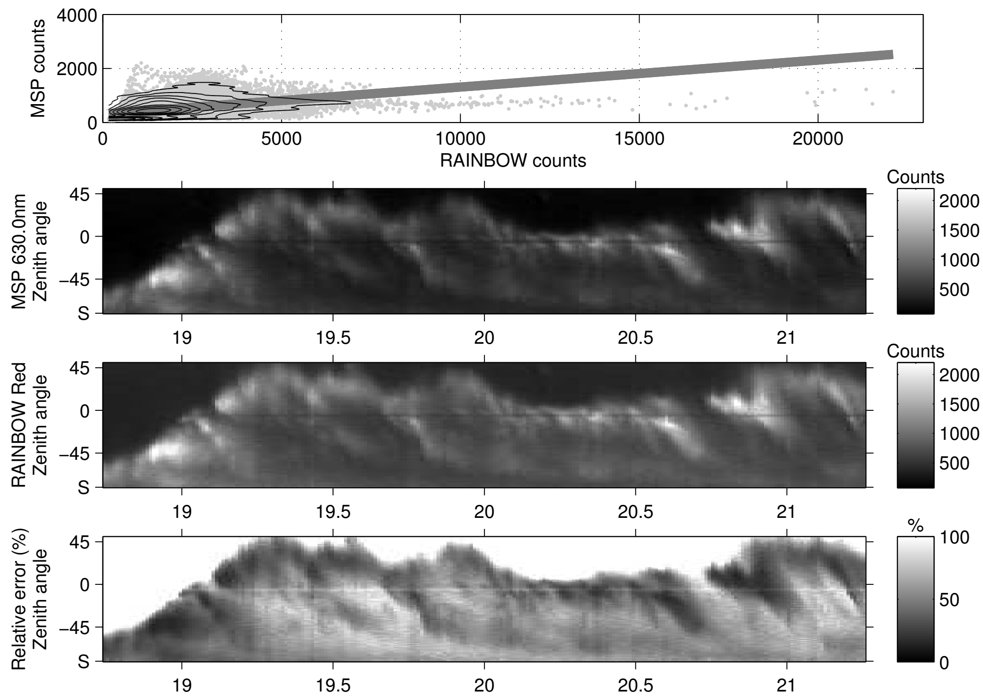

Fig. 6. Fit results for the red emission line. Top panel: scatter plot of the Rainbow and the MSP intensities in the corresponding pixels together with the contours. The thick line marks the fitted spline. Second panel: red line MSP data (counts). Third panel: fitted red line Rainbow data (counts). Bottom panel: relative error (%) of the fit.

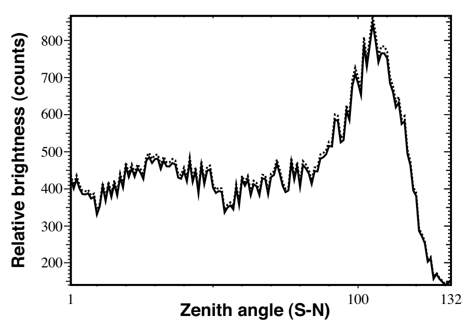

Fig. 7. Zenith slice from both the MSP red line (dotted curve) and the fitted Rainbow red channel (solid curve). An extra background offset of 257 counts has been subtracted from the Rainbow data to align the curves almost perfectly.

which we hope to answer as soon as more data are available.

5. Summary and conclusions

We have fitted the wide-band colour channels from a prototype colour auroral imager to reconstruct the narrow-band emissions (red at 630.0 nm, green at 557.7 nm and blue at 427.8 nm) measured by the Meridian Scanning Photometer. For this study, both instruments were operated simultaneously at the

Auroral Station in Adventdalen, Svalbard, Norway. The fit resulted in a surprisingly good agreement. Almost throughout the whole data set the fit is nearly linear. Visually these data look alike, and the relative errors are small whenever there is clearly visible aurora. The wide channels of the Rainbow imager, however, capture more than only the very distinct auroral emissions. Thus, larger relative errors are found within very dim aurora or solely the background.

This event was recorded in ultimate darkness: during a new moon on Svalbard. More data for a comprehensive statistical study will be needed to be able to examine the fit quality in different conditions. Instead of MSP data, calibrated and filtered all-sky images could also be used as a reference data set. If we are able to fit the Rainbow data so that it describes the true auroral emissions with a relatively good accuracy most of the time, and if we know when the fit will be poor, then at least the brightness of the aurora, the polar cap boundary, and the equatorward boundary of the electron plasma sheet can be deduced from the colour imager data. Other possibilities will be tested as soon as more simultaneous data are available. These possibilities could include e.g. colour imager data as an input into the inversion method [3] in order to convert the brightness into precipitating total electron energy flux, or an estimate of the average precipitation energy using the green line imager data and a cosmic ray absorption from a riometer [4]. In addition to the physical information mentioned here, the colour camera is a powerful tool for public outreach purposes. In the future, colour auroral imagers such as Rainbow, could be used to replace some of the very expensive filtered cameras or at least white light imagers especially when there is a calibrated MSP located nearby.

Acknowledgments

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