Auroral studies by starlight

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Stars and the aurora have almost nothing in common, except that both can be seen in the clear night sky. While stars remain steady and fixed in the celestial sphere, the aurora flicker and dance, reflecting the dynamic interaction of the solar wind with the Earth's magnetic field.

Aurora are often highly variable and quite bright relative to every celestial object except the sun and moon. Consequently, professional astronomers see auroral light as just another source of noise to be avoided or removed. In turn, auroral scientists typically act as if stars don't even exist, as their contribution to most measurements is negligible. However, a careful analysis of starlight provides information that can be used in the field of auroral research.

At the University of Calgary Institute for Space Research we study the aurora in a variety of ways. Satellites in space, rocket flights through the aurora, and observations from the ground each tell us something important about the cause of the aurora and its effect on the upper atmosphere.

Some of the earliest auroral observations were carried out using ground-based all-sky cameras. As the name suggests, these took photographs of the aurora through a "fish-eye" lens in order to obtain pictures of the entire night sky. This broad field of view is essential for studies of large scale auroral patterns. Today we still use similar instruments updated with modern optics, filters, and detector technology.

By far the most important advance for modern instruments is the use of cooled charge-coupled device (CCD) detectors instead of photographic film. These not only provide enhanced sensitivity, but also allow images to be easily stored in digital format and processed in ways that were previously very difficult.

Many of our cameras also have image intensifiers to allow operations at very low light levels. This is important because we typically use narrow-band (2 nm) interference filters to isolate specific auroral wavelengths (e.g. 486.1, 557.7, and 630.0 nm). Each exposure thus contains a small fraction of the total auroral spectrum, but an even smaller amount of light due to other "background" sources such as stars.

A complete all-sky imager (ASI) system consists of a CCD camera, filter-wheel, image intensifier, and miscellaneous optics and electronics. Our systems are controlled by PCs running Linux which acquire images according to a pre-set schedule. These allow operations to be automated so that data can be gathered at unattended field sites in the remote Arctic during the long winter nights.

Modern ASIs are superb scientific instruments for auroral studies. They are, however, not very good telescopes. All-sky lenses provide an unparalleled field of view, but have certain fundamental limitations. It is difficult to achieve perfect focus everywhere in the image, and the best compromise settings cause point sources (such as stars) to be blurred by tens of arc-minutes. Even with ideal optics, mapping a 180° field of view onto a 512×512 pixel CCD results in a resolution limit of approximately $\frac{1}{3}^\circ$. Using megapixel CCDs might permit arc-minute resolution, but arc-seconds are definitely out of the question.

Any particular star in the sky is thus imaged very poorly in each recorded image. This is partially compensated for by the fact that *every* celestial object above the horizon appears in *each* image. It is (at least in theory) possible to project

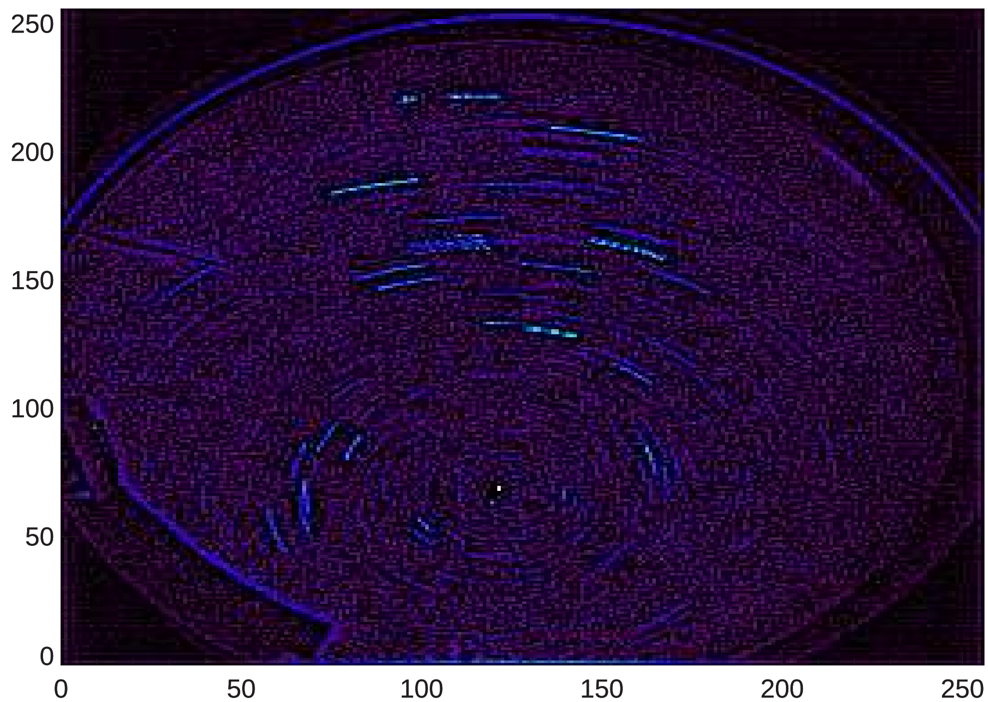

Figure 1: A one hour sequence with 59 background frames from Gillam, Manitoba during 06-07 UT December 21, 2001. Edge-enhancement has been used to emphasize star tracks. The Big Dipper is visible to the left of Polaris, which is a single point source at pixel coordinates 122,67. An overhead power line can be seen in the upper portion of the frame, with a GPS antenna and light-shield in the lower left corner.

each image into celestial coordinates by correcting for the effects of the Earth's rotation. A sequence of images from such a digitally despun telescope can be combined to produce a composite image of the entire night sky. Data can be merged from an hour, a night, or even an entire winter of observations to obtain very high contrast images.

Projecting raw images into celestial coordinates requires accurate knowledge of camera optics and orientation. This brings us to a crucial question: where are we looking? Ridiculous as this may sound to even a novice stargazer, it is a real problem for us. Our instruments are often installed at remote arctic sites under less than ideal conditions. When standing on the top of an unsteady ladder it is difficult to ensure that a mounting frame is perfectly level, much less aligned to the proper azimuth. Fortunately, imperfect alignment is not really a problem, just so long as we can find out what the orientation errors actually are. It turns out that using stars as reference sources allows us to determine instrument orientation very precisely.

For example, a poor estimate of instrument orientation might map CCD pixels onto a right-ascension/declination grid as shown in the first panel of figure 2. Stars in the big dipper (Ursa Major) are clearly offset from their proper locations and smeared due to erroneous compensation for the Earth's rotation. Results from a better estimate of camera orientation are shown in

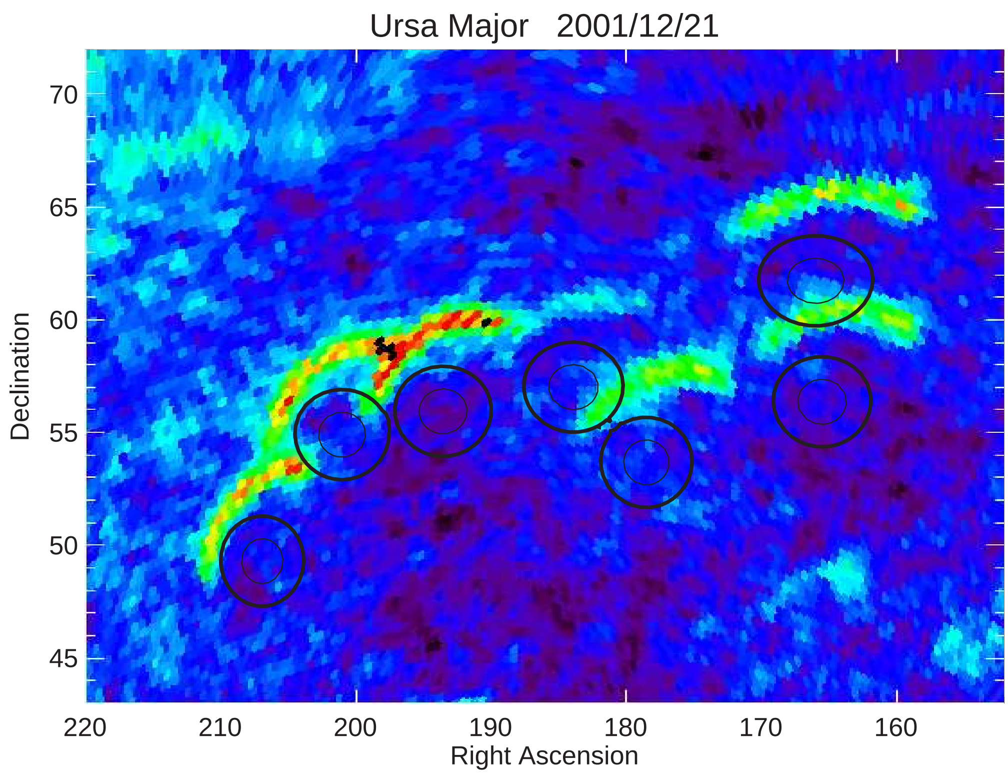

Figure 2: A composite image of the Big Dipper produced from 150 1-second exposures over a 7-hour interval, but using slightly erroneous pointing information. Circles of 1° radius are centered where stars should be located.

figure 3. Pointing accuracy in this case is clearly better than $\frac{1}{2}^\circ$. This would be considered poor for a typical narrow field telescope, but is quite good for an all-sky imager with a 180° field of view, and more than sufficient for auroral research.

The Big Dipper is an extremely useful feature for this kind of work because it contains several bright stars which are always visible in the Arctic night sky. This constellation was known as Tukturjuit (caribou) to the Inuit people, who used it to determine the passage of time. It is also interesting that Polaris is virtually useless for navigation in the Arctic, as it is close to the zenith and does not clearly indicate the direction of North.

Using the stars as celestial reference sources essentially solves the problem of unknown instrument alignment. A computer program can search through all possible orientations until it finds parameters which focus stars to their correct locations in celestial coordinates. Modern desktop computers can determine optimal results overnight. This is sufficiently fast considering that we only need to determine camera orientation once at each site when the instrument mounting frame is first installed.

Correct camera orientation can be confirmed in some visually appealing ways. For example, figure 4 contains an image of the entire northern celestial hemisphere which is a composite of almost one thousand individual exposures gathered over nearly 24 hours. Stars in most regions are well “focused”, with exceptions due to limitations in our knowledge of certain optical characteristics of the instrument. A composite im-

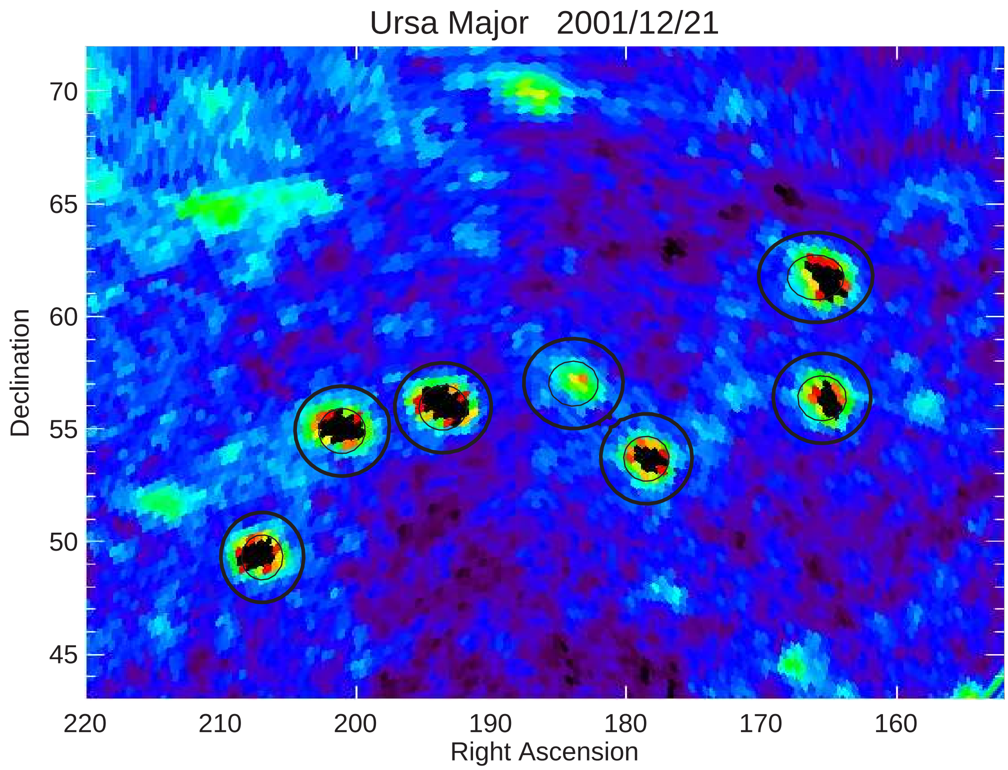

Figure 3: As figure 2, but using correct pointing information.

age built up from several weeks of observations would show the apparent motion of the planets (such as Jupiter, which was the brightest feature in the sky at this time).

Our ability to project all-sky images into celestial coordinates has uses beyond determining instrument orientation. Stars also provide luminosity standards which can be used for absolute calibration of instrument sensitivity. Although we carry out extensive darkroom calibration, an independent confirmation using stellar sources is extremely valuable, as it allows us to monitor the performance of an auroral imager over years of operation in the field.

Relative brightness also provides important information for estimating viewing conditions. Our current image catalog contains more than a million images, and visual examination of each frame for clouds is not feasible. Certain empirical algorithms for automated image classification do exist, and are generally effective, but a more physically meaningful approach would be preferable. This can be accomplished by first projecting images into celestial coordinates, and then using standard bright star catalogs to separate “signal” and “background” contributions. Clouds will tend to remove photons from stellar sources, while scattered light will appear more or less uniform across all regions. Consequently, automated determination of cloud cover can be obtained relatively easily by tracking the difference between signal and background estimates.

Digital wizardry allows us to use auroral images in a variety of ways that were never part of our original plans. It is not, however, clear whether any of this could play a useful role in real astronomical observations. Our need for image transformation was a direct consequence of the extremely wide and fixed field of view of our instrument. A much easier way to acquire

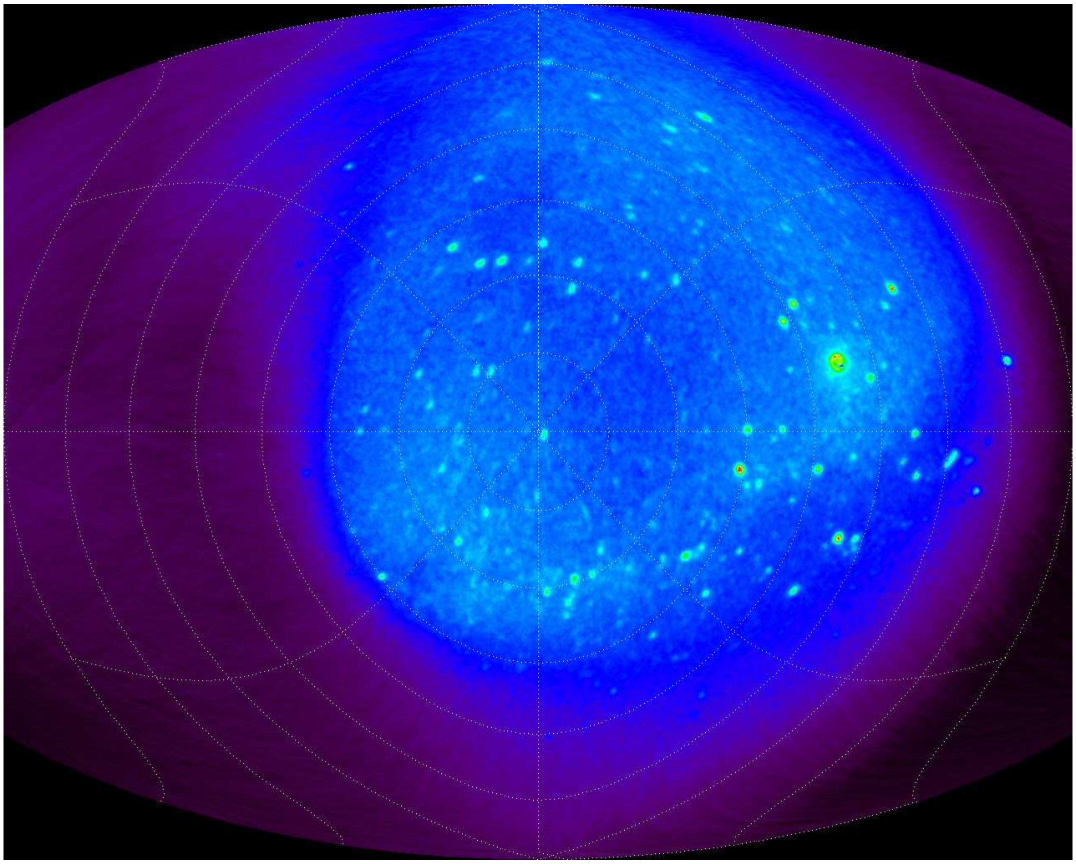

Figure 4: Composite of the northern celestial hemisphere constructed from nearly 1000 different all-sky images obtained during a 12-hour interval.

high quality astronomical images would be to simply use a good quality narrow field telescope with tracking capabilities. Long exposure times could then be achieved without any computer assistance, and larger mosaics built up over time. Still, perhaps our experience will help inspire other new uses of CCD cameras in combination with digital image processing. We have certainly enjoyed our brief excursion into the field of stellar cartography, continuing in the long tradition of looking to the sky for immutable (and beautiful) reference sources.

About the authors: Drs. Jackel, Trondsen, and Donovan study the aurora with optical and other techniques. They are currently operating a network of all-sky imagers in the Canadian Arctic, more information can be found at `http://www.phys.ucalgary.ca/NORSTAR`.