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Gold dust

Quantifying and Monitoring Darkness over the RAO

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How dark is it?

How dark is it? A basic question about a fundamental concept. And it's a question that's asked whenever people interested in seeing the stars get together. I saw this question in a whole new light when it was posed to me by a councillor with the Municipal District of Foothills back in 2007. He was a neighbour who lived not too far from the Rothney Astrophysical Observatory, and who knew that paradigms were shifting and residential development was about to ramp up in this beautiful area on the welcome mat of the Rocky Mountains. This discussion began a process that led to the development of the MD's Dark Sky Initiative light-pollution bylaw instituted in 2009 www.mdfoothills.com/residents/planning/environment/dark_sky_initiative.html. And all through that process I was tasked with quantifying darkness.

It's actually a very difficult thing to do, made even more complicated when you want to use a language that the average person can grasp. My first attempts utilized RAO telescopes and astronomical filters and careful photometric calibration using Landolt standard stars. But that was far too involved for the purpose of this bylaw. There had to be a better way.

I can't recall exactly, but it was probably a member of the RASC Calgary Centre who told me about it in 2009. A new gizmo called the Sky Quality Meter (SQM) might be the just the thing I was looking for. So in short order a model with internet connectivity, and an internal lens for more focused directionality, was strapped to the Clark-Milone Telescope, pointing to the sky. The goal at this point was to learn the characteristics of the SQM and determine if it was indeed to right tool for the job.

Over the next ~3 years, that SQM-LE was pointed all over the sky and it was found to be very sensitive and stable. With the observatory situated SW of Calgary, when the CMT tracks an object the SQM sees more and more of the sky away from the city, pointing progressively westward toward the mountains. The SQM was sensitive enough to measure the sky slowly darkening while tracking, whether the Moon was up or not. It was also surprising to discover that, when opening the dome in the middle of the night to begin a late-night observing run, the SQM revealed what looked like a very dark Moonless sky was actually brighter than the inside of the closed dome.

And during this testing phase it was consistently found, when detailed photometric calibrations were made of star fields when doing scientific work, that the photometric zeropoints in the V filter came out quite close to what the SQM was measuring during the darkest part of the observing run. So the SQM actually lets one know what photometric limit to expect while observing. During the nicest darkest Moonless RAO nights the CMT-SQM reported that the "brightness" of the sky bottomed out between 20.65 and 20.75 magnitudes per square arcsecond. All things considered, the SQM is an awesome tool for quantifying the darkness of the nighttime sky.

The Units of Radiance

But what on Earth is a magnitude per square arcsecond? This jargon-laden unit is the one major challenge of using this instrument to communicate to the public exactly what darkness is. So simply put, the SQM measures the *radiance* of the sky. Historically, radiance was measured in candelas per square metre; meaning a brightness spread over some area. Being an astronomical tool, the brightness is described using the magnitude scale. Used by astronomers for centuries, it is a logarithmic scale where, counterintuitively, higher numbers describe fainter objects. For the RASCals reading this, the magnitude scale is probably quite familiar so no further elaboration is required.

If one quotes the magnitude of a patch of empty sky, rather than the magnitude of a star, and picks a very small patch of sky equal to one arcsecond by one arcsecond, then one has described the apparent surface brightness, or radiance, of the sky in magnitudes per square arcsecond (mag/arcsec^2). A careful calibration of the response of the SQM to light input shows that a reading of 20.0 mag/arcsec^2 S equates to 1.080 x 10^{-3} candelas per square metre. Conversions between these units are given here http://unihedron.com/projects/darksky/magconv.php?ACTION=SOLVE&txtMAGSQA=20

All sorts of technical specs of the SQM can be found in the 2005 paper by Pierantonio Cinzano www.lightpollution.it/download/sqmreport.pdf. Of particular note is the shape of the responsivity of the SQM. The filter used is very broad with a 50% or higher transmission from 360 nm to 600 nm. The peak transmission is close to 90% between 500 nm and 540 nm. Cinzano reports that this is quite similar to the bandpass of the Johnson V, or visual, astronomical filter. So the SQM "sees" the sky much like a CCD camera through a Johnson V-band filter. This explains why the zeropoints being derived from photometric V-band calibrations matched so closely to the SQM's reading. The field of view of the SQM-LE is about 20 degrees. That's like looking at a patch of the sky through a toilet-paper roll held right up to your eye. Details of the filter response and field of view can be found here http://unihedron.com/pipermail/sqm/2008-October/000023.html

A Second SQM for the RAO

So, after examining the CMT-SQM over those initial years, it was found that the device was not only scientifically valuable, it would indeed be the ideal tool for monitoring sky darkness at night over the observatory. And while it was handy to have an SQM that could be pointed around the sky, nobody else using them mounted theirs to a telescope. In order to join the community of researchers monitoring Artificial Light At Night (ALAN), a second SQM-LE was put into service at the RAO in the summer of 2012. At that time, an AllSky camera was being used at the RAO to assist with remote observing, so it was natural to assemble the two instruments together. The Zenith-SQM and AllSky camera are shown in their weather-proof housing in Figure 1.

Except for mostly minor interruptions, the two instruments have run constantly, even to this day. Real time data can be found online here http://ucalgary.ca/rao/multimedia. There was an extended time in 2015 (September and October) where the Zenith-SQM started to hang intermittently and so was sent back to the manufacturer to be diagnosed. It turned out the SQM was fine, and the problem was the data cable connection had become loose. The big idea was that the SQM data could be correlated to the weather conditions as captured by the AllSky camera, and an accumulated archive of data could someday be analyzed.

Almost Too Much Data

The analysis presented here finally happened in the summer of 2016, with the impetus coming from two sources. First was a very interesting analysis done by James Cleland of light pollution data from the *Great World Wide Star Count* and from the *Globe At Night*. His findings were reported in the June 2016

Figure 1 — The Zenith-SQM (A) and AllSky camera (B) inside their weather-proof housing, which is weighted down and reinforced against strong winds. The camera is level and oriented north and east. The SQM is mounted to the north side of the camera housing and points straight up. The photo on the right shows the Plexiglas weatherproof bubble that covers the instruments.

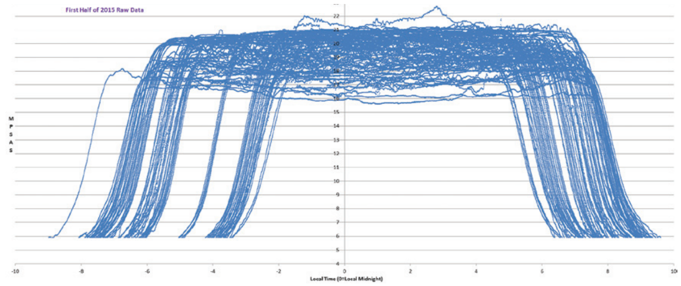

Figure 2 — Over 100,000 raw Zenith-SQM data points covering roughly the first half of 2015. The plot shows the radiance of the sky in Magnitudes per Square Arcsecond (mag/arcsec²) from sunset to sunrise.

Journal of the RASC, Vol. 110, No.3 www.rasc.ca/jrasc-2016-june. One result in particular caught my eye—the sky over Calgary got darker between 2007 and 2014. Given the growth of Calgary over that interval, could this be possible? Would the Zenith-SQM corroborate this?

And the second was the appointment of a very talented and eager summer student, the coauthor of this article. When the mountains of Zenith-SQM data and AllSky images dating back to 2012 were finally gathered and peered into, it was terrifying. For the first few years, the software running the Zenith-SQM was configured to take a measurement every 15 seconds, day and night. Then an upgrade to the software allowed readings to stop when the Sun was above the horizon. Then measurements were taken every 30 seconds. The philosophy was it was better to have the data in hand and worry about details of its analysis later, but this was definitely overkill. Figure 2 shows over a 100,000 raw Zenith-SQM data points for roughly the first half of 2015. Despite the daunting task, BG masterfully corrected and reduced all the data. It was essentially a four-step process.

The first-order modifications to the data included both a time shift so that all the time stamps corresponded to Mountain Standard Time and a sensible averaging process so that the data set could be reduced by a factor of ~10. The second-order modification involved removing all the data corresponding to the phase of the Moon being greater than 0.75, and the Sun being less than 5 degrees below the horizon. After all this work, it was painfully obvious that the "weather factor" had to be addressed. Since the goal was to monitor star-filled nighttime skies, nights of cloud cover, snow cover, rain drops, fog, frost, and aurora had to be removed. The third-order modification involved going through the entire archive of AllSky images and removing nights where ill weather affected the data for more than half the night. This analysis removed ¾ of all the data. Figure 3 shows examples of AllSky camera images used for this purpose.

And finally, two fourth-order corrections had to be carefully done. First, when the Zenith-SQM was sent back to its

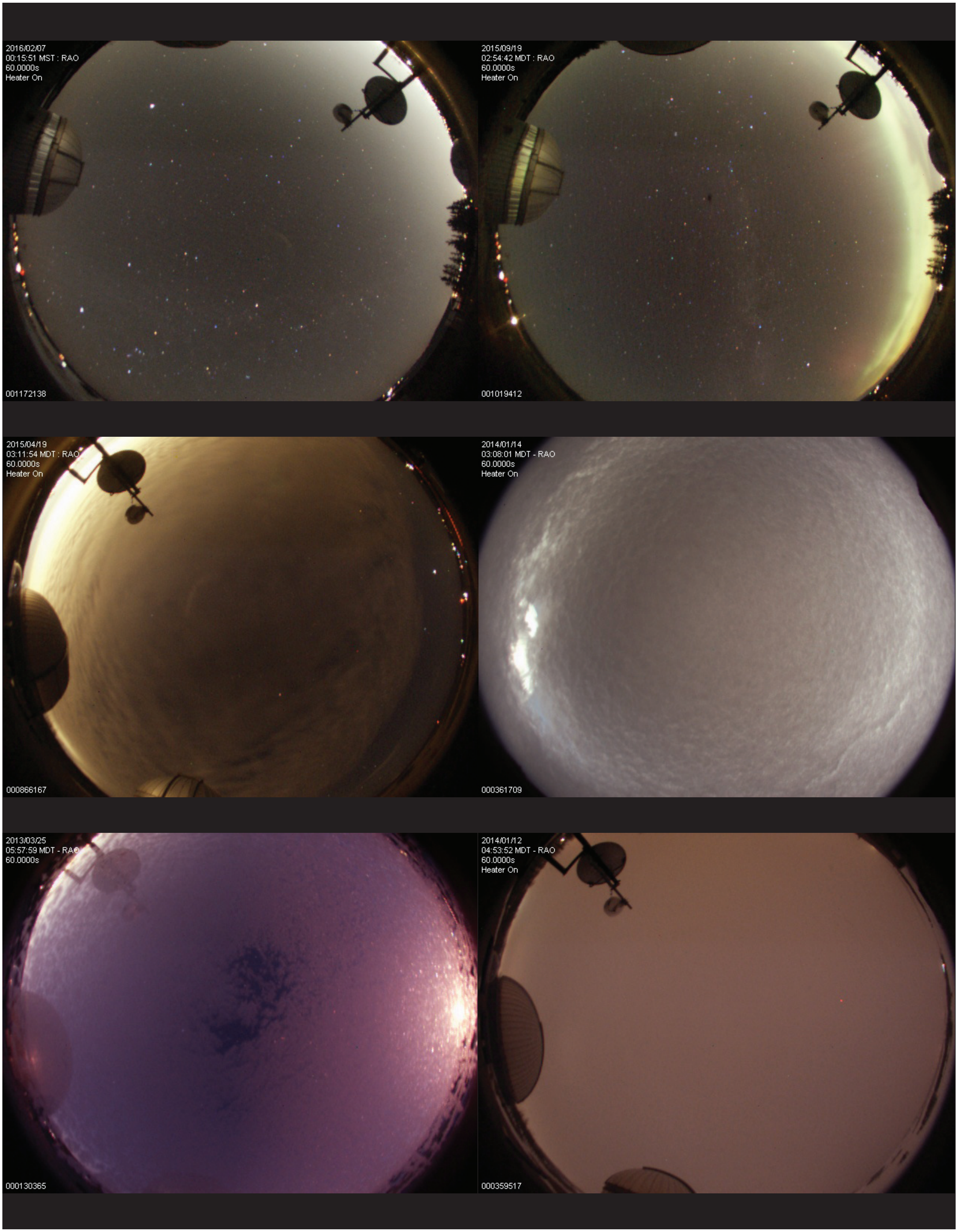

Figure 3 — Examples of 60-second exposure nighttime images recorded by the AllSky camera. These images were used to critique weather conditions that might skew the Zenith-SQM data. The microwave dishes in the images indicate the NE direction, toward the city of Calgary.

manufacturer in September-October 2015 for inspection, a re-calibration was performed. It was discovered that an additive offset of -0.06 mag/arcsec^2 was needed to get the Zenith-SQM measuring precisely again. Forty months earlier, when the unit was initially put into service, no such offset was needed. After consulting with the manufacturer it was concluded that having been exposed constantly to sunlight and the out of doors in an essentially air-tight housing, the plastic coating on the sensor likely was degrading. Under consultation, it was deemed that the degradation was linear with time, so an additive offset of -0.0015 mag/arcsec^2 per month was added to the Zenith-SQM data. The Zenith-SQM was measuring the sky to be darker than it actually was.

The second fourth-order correction is needed to account for the loss of light due to the Plexiglas bubble cover. The manufacturer of this cover is not known, but it was purchased in the 1970s to be used with solar observing experiments on a high-altitude balloon payloads. It is very likely that the payload team was aware of potential UV damage problems and thus purchased a high quality UV-resistant bubble. That was indeed the hope when it put into use over the Zenith-SQM and AllSky camera in 2012.

So, over the years, the data has been inspected for evidence of a gradual loss of transparency, and the cover has been visually inspected every three or four months each time it was cleaned. Neither the data nor the inspections suggest that the transparency of the bubble has changed over time. This makes the second fourth-order correction a straight forward additive constant. To determine that constant it was a simple matter of comparing the measurements of the Zenith-SQM with the Plexiglas cover both on and off. It was found that when the Plexiglas cover is on, the Zenith-SQM reads 0.066 mag/arcsec^2 higher, so this value has to be subtracted from all the data.

The Results in Natural Sky Units

The ~3 years of carefully parsed data is ready to be presented. The challenge now is deciding how to display it all in a way that allows straight-forward conclusions. With regard to those cumbersome mag/arcsec^2 units, a 2015 paper in *Scientific Reports* had an interesting idea. Discussing *Worldwide Variations in Artificial Skyglow*, www.nature.com/articles/srep08409, Christopher Kyba et al. described sky darkness as measured with SQMs in Natural Sky Units, or NSU.

The conversion between mag/arcsec^2 and NSU is defined according to the power-law relation NSU = 10^{0.4(21.6 – SQM)}, where SQM is the reading from one's sky quality meter in the units of mag/arcsec^2. Notice that if your reading is 21.6, this equation gives NSU = 1. The reason that the baseline value of 21.6 mag/arcsec^2 is used is because that is the average SQM reading at Kitt Peak National Observatory under dark, moonless conditions. This is also, more generally, the darkness of a typical historic clear night sky, according to Kyba et al.

So if your location has night skies of NSU = 1, your sky is as dark as at Kitt Peak. An NSU value of 2 corresponds to exactly two times as much sky radiance overhead compared to Kitt Peak (corresponding to 20.85 mag/arcsec^2), and an NSU value of 3 means your night sky is three times "brighter" than Kitt Peak (20.41 mag/arcsec^2). Describing the darkness of the sky at night in NSU makes the concept more linear, and unlike the magnitude scale, higher numbers mean brighter skies. So NSU as a brightness unit that represents sky radiance is perhaps more intuitive for the general public.

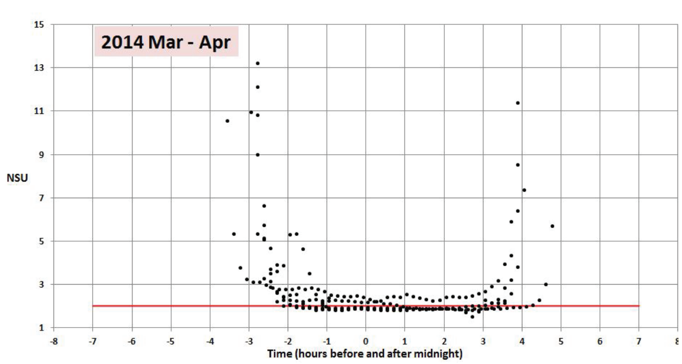

Figure 4 — A representative example of a two-month set of parsed SQM data plotted in NSU. On a few nights the radiance of the sky over the RAO got below 2 NSU.

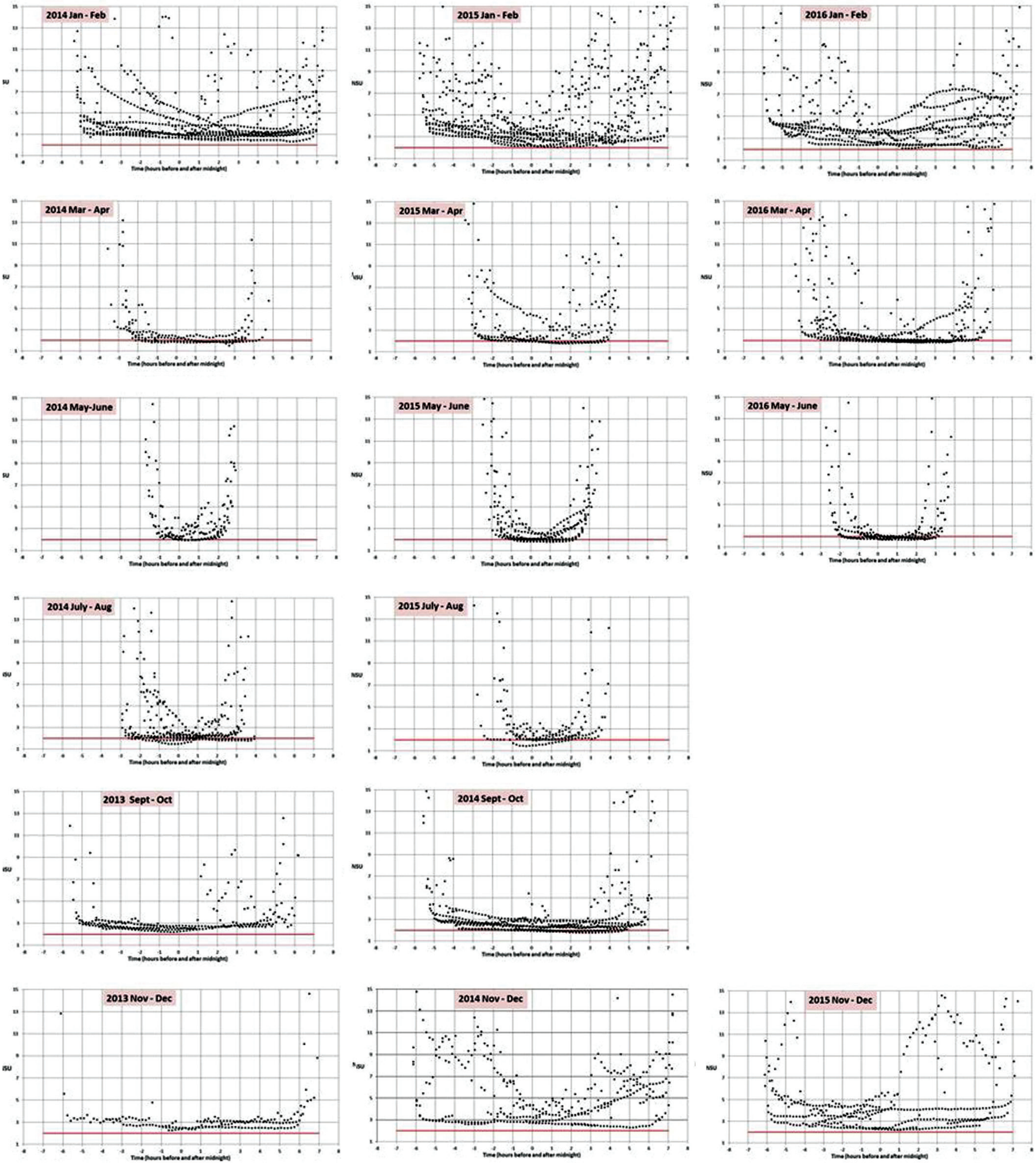

Figure 5 — A bi-monthly comparison of nighttime sky brightness over the RAO from late 2013 to mid-2016. The Sept–Oct 2015 data is missing because the Zenith-SQM was down for repairs. Sky darkness is displayed in NSU between sun setting and sun rising.

Figure 4 shows the radiance of the nighttime sky over the RAO as measured by the Zenith-SQM over the two-month block of time of March and April 2014. Radiance in NSU is plotted as a function of time relative to local midnight. A red horizontal line corresponding to 2 NSU is included to help guide the eye. The change in the duration of the night is noticeable over this time span. There is a small range in radiance minimum, but on a couple of nights the radiance goes slightly below 2 NSU. For the RAO, these are very dark nights.

Figures 5 shows the overall results in two-month interval bins so that the change in that interval over the years can be examined. There appears to be some seasonal variation between winter and summer, with summer nights reaching NSU = 2 consistently. The winter month nights are generally ~0.5 NSU brighter, which might be attributable to snow cover and seasonal festive lighting.

Looking across the ~3 years of data, the sky brightness seems to be holding quite constant, with perhaps a hint of a slight darkening. If so, this would be consistent with Cleland's observations in his *JRASC* 2016 article. Even a constant sky radiance is quite amazing, given the marked population growth of Calgary and subsequent development. Perhaps the City Planners are getting things right with regard to smart lighting.

The RAO is extremely fortunate to be sitting under such lovely dark skies, when the clouds and the Moon cooperate.

The true importance of this analysis is that it serves as a baseline of comparison for the future. As stated in the introduction, development is ramping up in the rural areas around the observatory. The Dark Sky Initiative bylaw has been on the books for seven years now, and for the most part, the RAO's neighbors are doing a great job keeping their lights down and off. But looming in the near future is the construction of the last leg of the City's ring road, and a new residential development, bringing many bright lights closer than ever before. We're working hard to keep stakeholders and neighbours educated so as to keep the RAO under dark skies for as long as possible.

Two final notes. First, the RAO has several hand-held SQMs which are available for loan. If any RASCal would like to give them a try, feel free to contact the author to make arrangements. And second, the 2018 Annual General Meeting of the RASC is being held in Calgary. This is a very special AGM for the RASC as it marks the 150th anniversary of the Society in Canada, and the 60th anniversary of the Calgary Centre. If you come to Calgary to partake you are invited on a free tour the RAO. Transportation and meal will be provided. ✶