Readme_all_eoefficients

Updated 4/19/2014

Table of contents

1. Purpose of this document

This document and the accompanying text file of data, **all_coefficients12.txt**, describe extinction and transformation coefficients obtained in the Lowell "solar photoelectric photometry project (originally known as the "Solar Variations Program") from 1972 through 2012. The principal data products of this program are annual Strömgren *b, y* magnitudes of the planets Uranus and Neptune and Saturn's moon Titan plus ancillary magnitudes of standard stars and the annual pairs of comparison stars used for the differential photometry of each planetary object. Most of the data have been published in a series of papers, usually in Icarus.

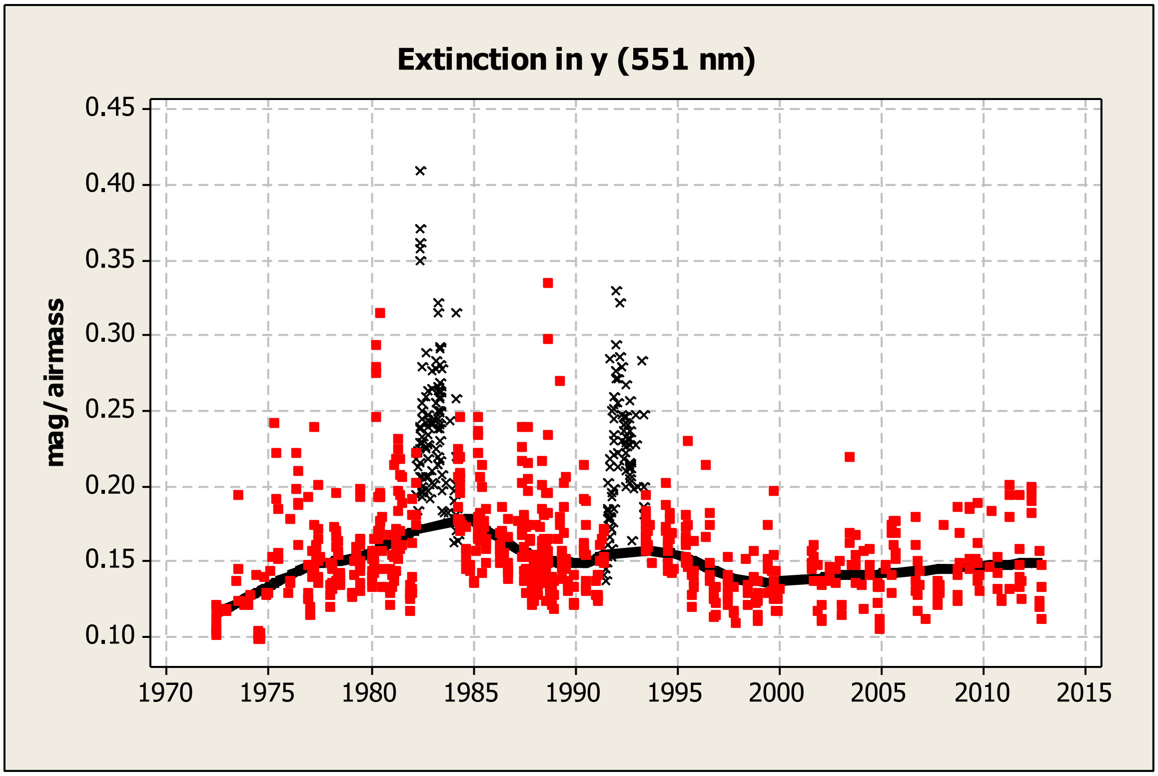
We used the Lowell 21-inch reflecting telescope on the observatory campus on Mars Hill in Flagstaff, AZ, for nearly all the observations of standard and comparison stars (863 nights total), during apparitions of Saturn, Uranus, and Neptune. Brief exceptions are:

5/19/1972 - 6/20/1972 Lowell 24 inch telescope on Mauna Kea, Hawaii
12/1/1972 - 1/25/1974 Lowell 42-inch telescope near Flagstaff, AZ
6/23/1074 - 7/15/1974 Lowell 24 inch telescope on Mauna Kea, Hawaii

There were no changes in equipment during this entire 40 year interval other than replacements of the data collection computer (DEC PDP11/04 with Teletype printing and punched paper tape recording; DEC PDP11/20 with 8-inch floppy disk recording; IBM compatible 286, later 386 with 5.25 inch, later 3.5-in floppy disk recording). Most notably, the same Strömgren *b, y* interference filters and EMI 62556S photomultiplier survived the decades intact. Therefore the photometric transformation coefficients provide a reliable continuous record of very slow changes in the photometer response function over the decades. The extinction coefficients are also highly homogeneous and document the history of atmospheric transparency at Flagstaff, Arizona including two noteworthy episodes of global high extinction following volcanic eruptions (El Chichón in 1982, Pinatubo in 1991). In recent years, prescribed forest fuel reduction by low ground fires are common in the spring and fall, but this occasional and strictly local intrusion into perfect sky clarity seems to have left no discernible signal in the trend of extinction coefficients.

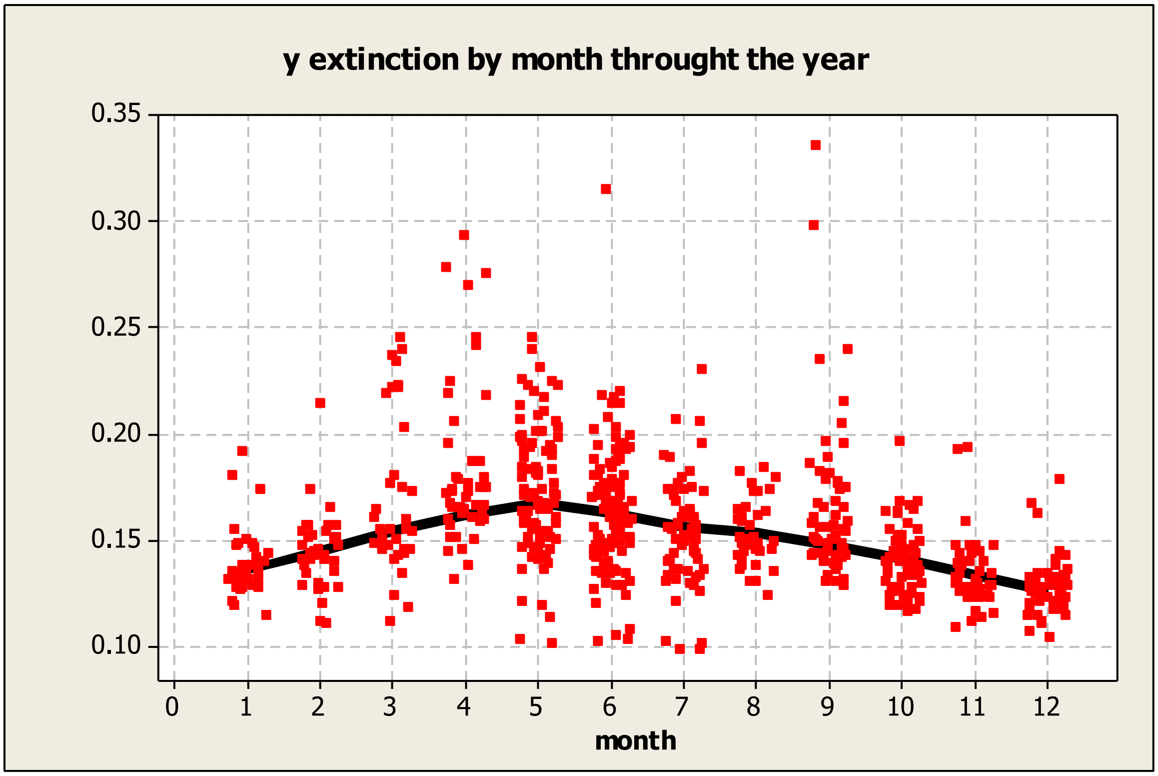
The illustrations that follow present basic information about the changes in the transformation coefficient (mainly of technical interest for generating final internally consistent planetary magnitudes already published or pending) and extinction coefficients (of interest as a record of atmospheric transparency from a fixed site in Arizona).

2.1 Extinction coefficients, year by year



Extinction in the y filter (0.551), Flagstaff, AZ, (red squares) with a lowess smoother applied to show the long term trend. Volcanic episodes (black x) in the 24-month intervals following two major eruptions (El Chichón in 1982, Pinatubo in 1991) are omitted from the smoother, leaving a total of 660 nights. Plausible causes for the few dozen non-volcanic outliers include thin clouds, desert dust (especially in springtime) or forest fire smoke aerosol. The shifting intra-annual distribution of nights over time as Titan, Uranus, and Neptune moved eastward may affect the overall trend above. See further discussion below.

2.2 Extinction, month by month

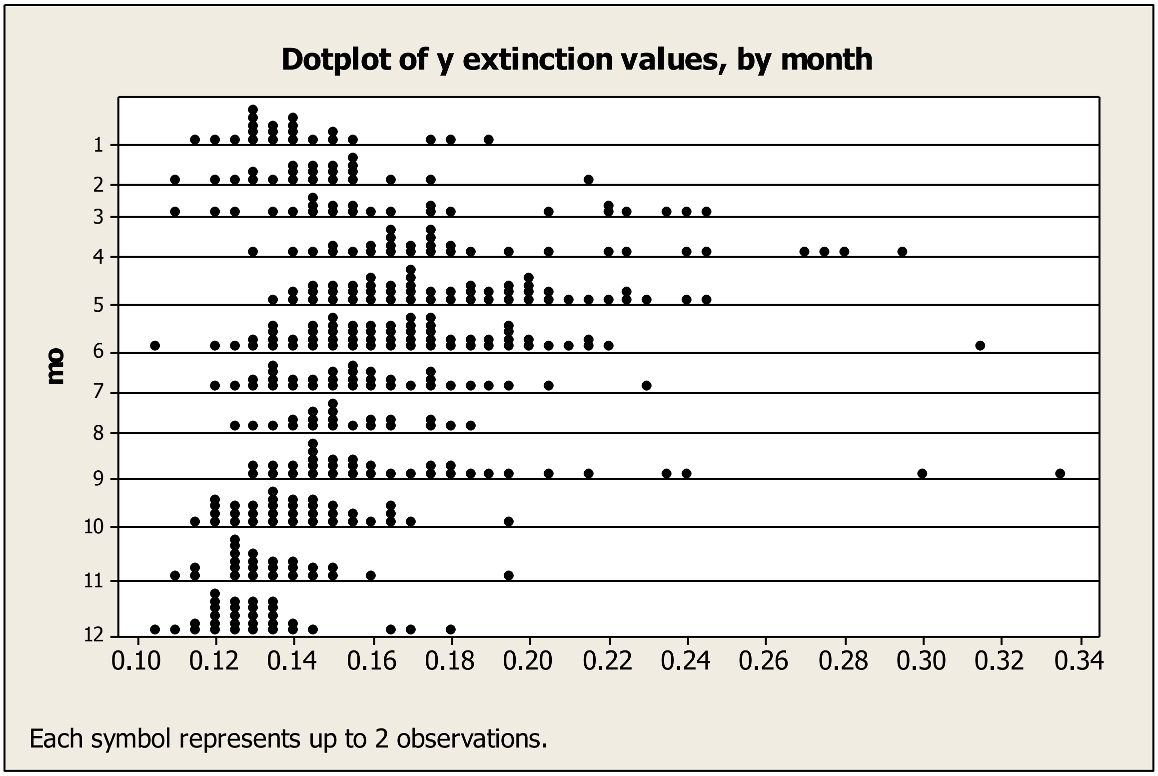


Seasonal variation of extinction at 551 nm month by month with horizontal jitter added for clarity. A lowess smoother illustrates the slow seasonal variation. Values range from nearly pure Rayleigh scattering in winter, ~0.14 mag/airmass, to the spring maximum about ~0.17 mag/airmass when considerable aerosol is added to the mix. Volcanic intervals are omitted from this chart. Large outliers are most common in March and April, consistent with springtime winds and blowing dust, but we have no obvious explanation for high values in September.

Excluding volcanic episodes, here are the month by month mean y extinction values with 95% confidence intervals. The seasonal trend is remarkably steep in the first half of the year as spring aerosol ramps up.

```
                              Individual  95%  CIs  For  Mean  Based  on  Pooled
StDev
Level     N     Mean    StDev  ---------+---------+---------+---------+
 1       36  0.13967  0.01584       (---*---)
 2       37  0.14481  0.01801         (---*----)
 3       34  0.17094  0.03782                     (---*----)
 4       45  0.18416  0.03890                            (---*---)
 5       89  0.17747  0.02640                          (--*-)
 6      107  0.16618  0.02795                     (-*--)
 7       56  0.15754  0.02237               (---*--)
 8       36  0.15389  0.01557             (---*---)
 9       59  0.16598  0.03765                    (--*--)
10       61  0.14052  0.01599        (--*---)
11       44  0.13441  0.01686    (---*---)
12       56  0.12845  0.01330  (--*---)
                               ---------+---------+---------+---------+
                                      0.140     0.160     0.180     0.200

Pooled StDev = 0.02588
```



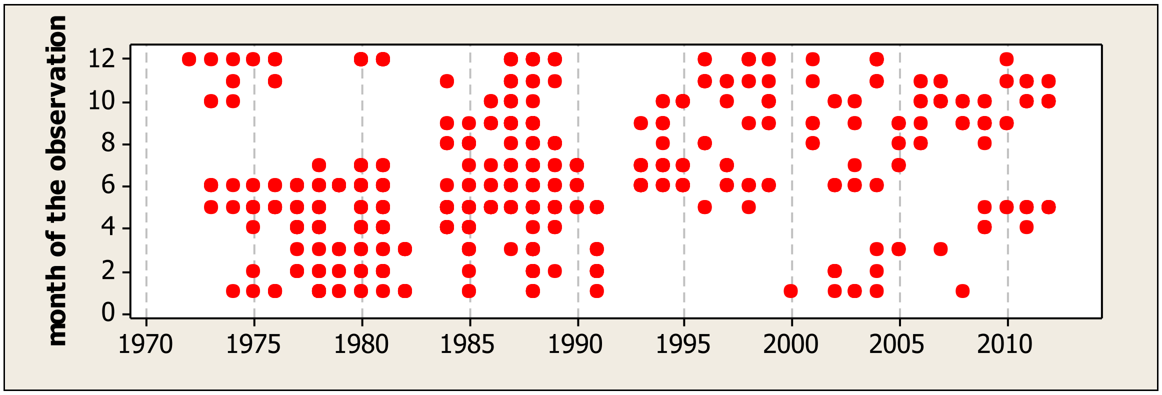
Dotplot for non-volcanic intervals, 660 nights total from 1972 through 2011 showing the distribution of data within each month. Obviously, assuming a nominal extinction based on the monthly mean rather than determining it by measurement introduces significant error.

Here are the descriptive statistics for the y extinction coefficient, month by month for the non-volcanic intervals

Descriptive Statistics: k (extinction coefficient for the y filter)

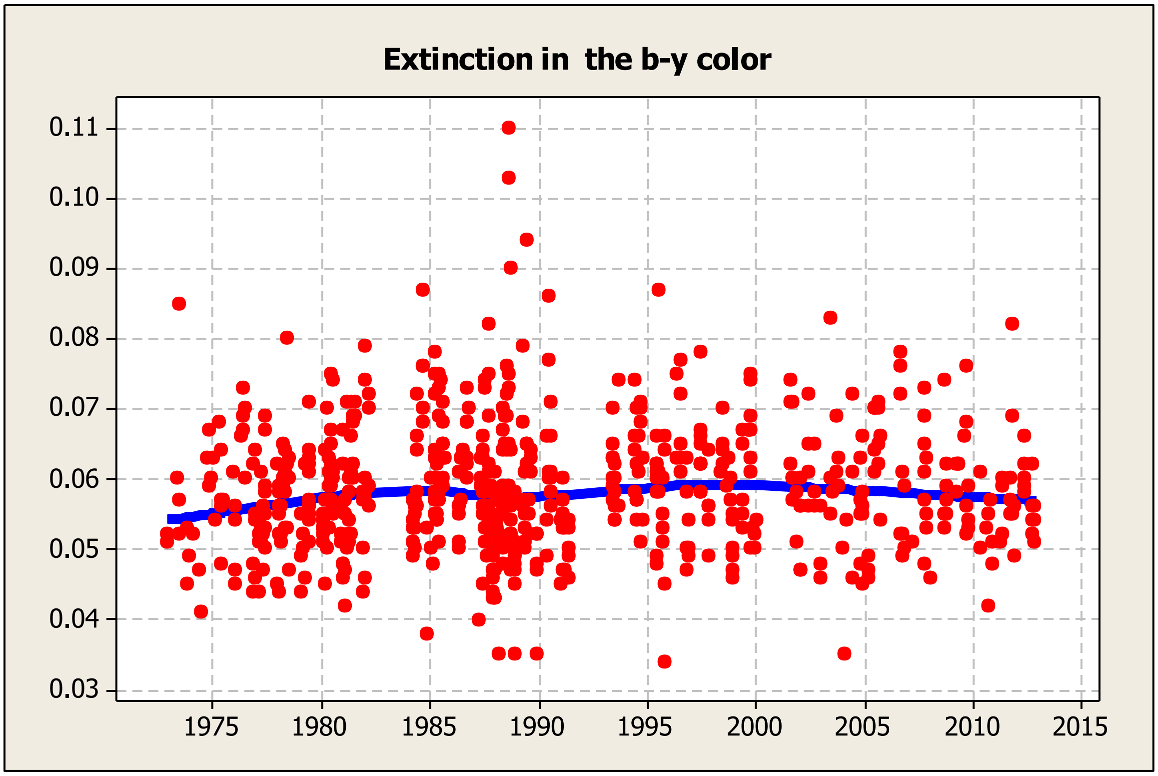
```
Variable  mo     Mean    StDev  Minimum       Q1   Median       Q3  Maximum
k          1  0.13967  0.01584  0.11500  0.12975  0.13650  0.14625  0.19200
           2  0.14481  0.01801  0.11100  0.13550  0.14400  0.15350  0.21500
           3  0.17094  0.03782  0.11200  0.14600  0.15500  0.20700  0.24600
           4  0.18416  0.03890  0.13200  0.16050  0.17300  0.19150  0.29400
           5  0.17747  0.02640  0.13700  0.15600  0.17200  0.19800  0.24600
           6  0.16618  0.02795  0.10400  0.14700  0.16400  0.18100  0.31500
           7  0.15754  0.02237  0.12200  0.14025  0.15500  0.17250  0.23100
           8  0.15389  0.01557  0.12400  0.14350  0.15050  0.16475  0.18500
           9  0.16598  0.03765  0.12900  0.14300  0.15500  0.17700  0.33600
          10  0.14052  0.01599  0.11700  0.12800  0.13900  0.15000  0.19700
          11  0.13441  0.01686  0.10900  0.12525  0.13000  0.14000  0.19400
          12  0.12845  0.01330  0.10500  0.12025  0.12750  0.13300  0.17900
```

2.3 The seasonal distribution of extinction measurements over 40 years

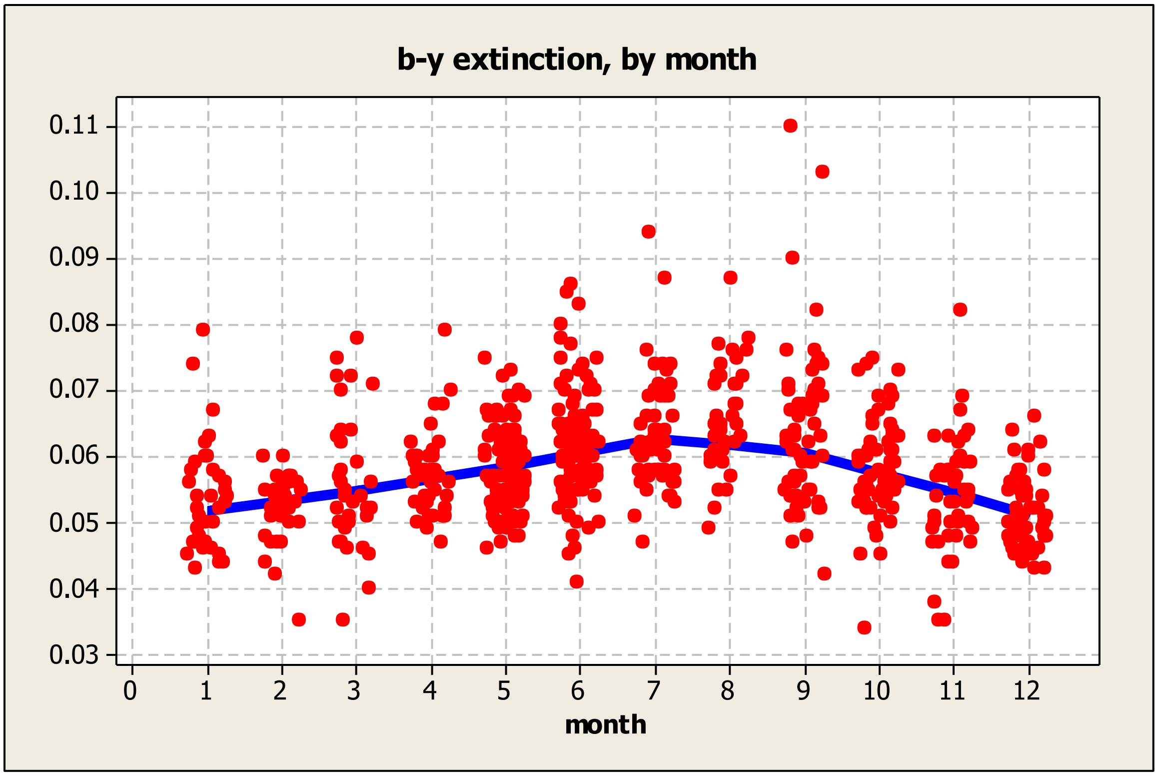


This chart shows the distribution of measurements within the year over the 40 year span of the observations. The overall trend in time (illustration in section 2.1) may thus be biased by the changing seasonal distribution over time.

2.4 Extinction in the *b-y* color



The extinction coefficients for *b-y* color show little discernible trend in the lowess smoothed fit for the non-volcanic intervals shown here (660 nights).



Seasonal variation in the *b-y* extinction, for the non-volcanic intervals, horizontal jitter added for clarity. Atmospheric aerosol has a roughly $\lambda^{-0.87}$ wavelength dependence (determined by spectrophotometric measurement in 1976 for Lowell in springtime, by Tüg, White, and Lockwood 1977).

3. Transformation color terms.

We transform raw “all sky” Strömgren *b, y* photometry of *uvby* standard stars and planetary comparison stars to our local standard system via the following equations:

$C_1 + C_2(b\text{-}y) + K_2X = (b\text{-}y)_x$
$A_1 + A_2(b\text{-}y) + K_X = y_x - y$

where
K is the extinction coefficient in y in magnitudes/airmass,
K_2 is the extinction coefficient in *b-y* color in magnitudes/airmass,
A_1 and C_1 are the zero points for *y* and *b-y*, respectively,
A_2 and C_2 are the color terms for *y* and *b-y*, respectively,
y, *b-y* are the local standard values on the Strömgren system,
y_x. $(b\text{-}y)_x$ are observed (raw instrumental) values,
X is the airmass

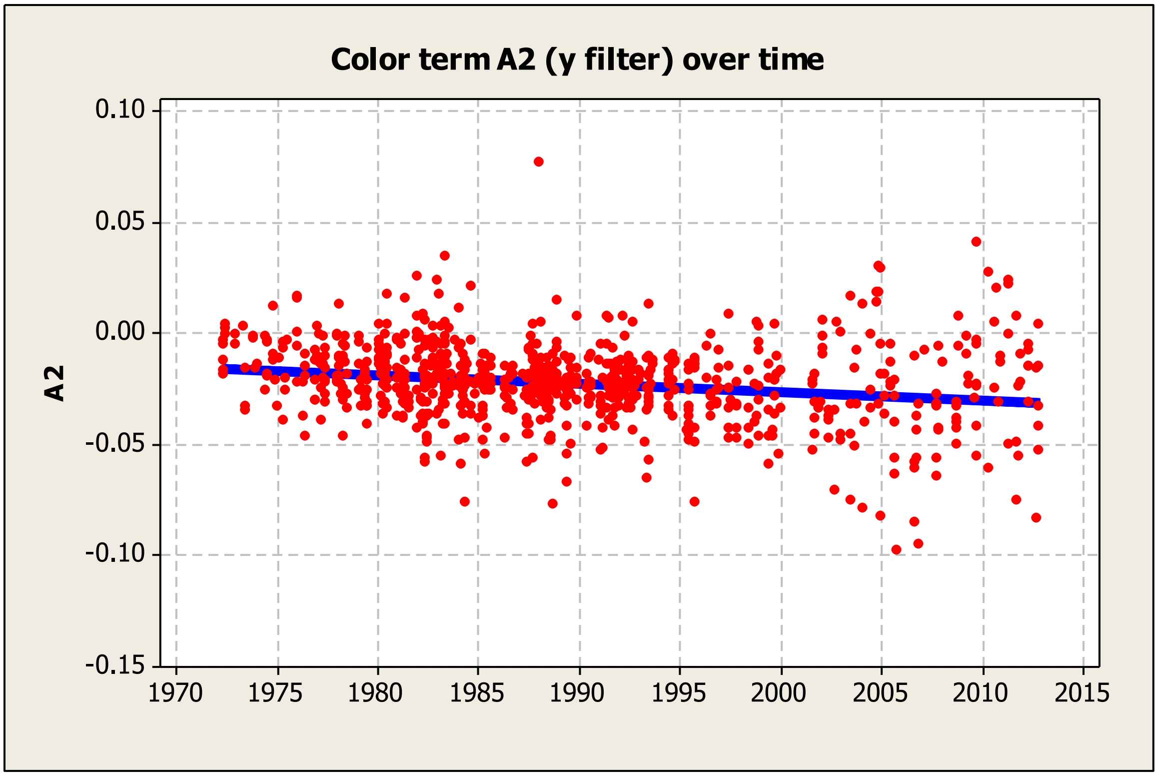
Further explanation is in Lockwood, 1977, Icarus 32, p. 427.

Strömgren *b, y* magnitudes of 56 standard stars are given in Lockwood and Thompson, 2002, Icarus 156, p. 48. These were subsequently revised slightly following a 2006 iterative grand re-reduction of 700+ nights of *b, y* photometry; new values will be documented elsewhere.

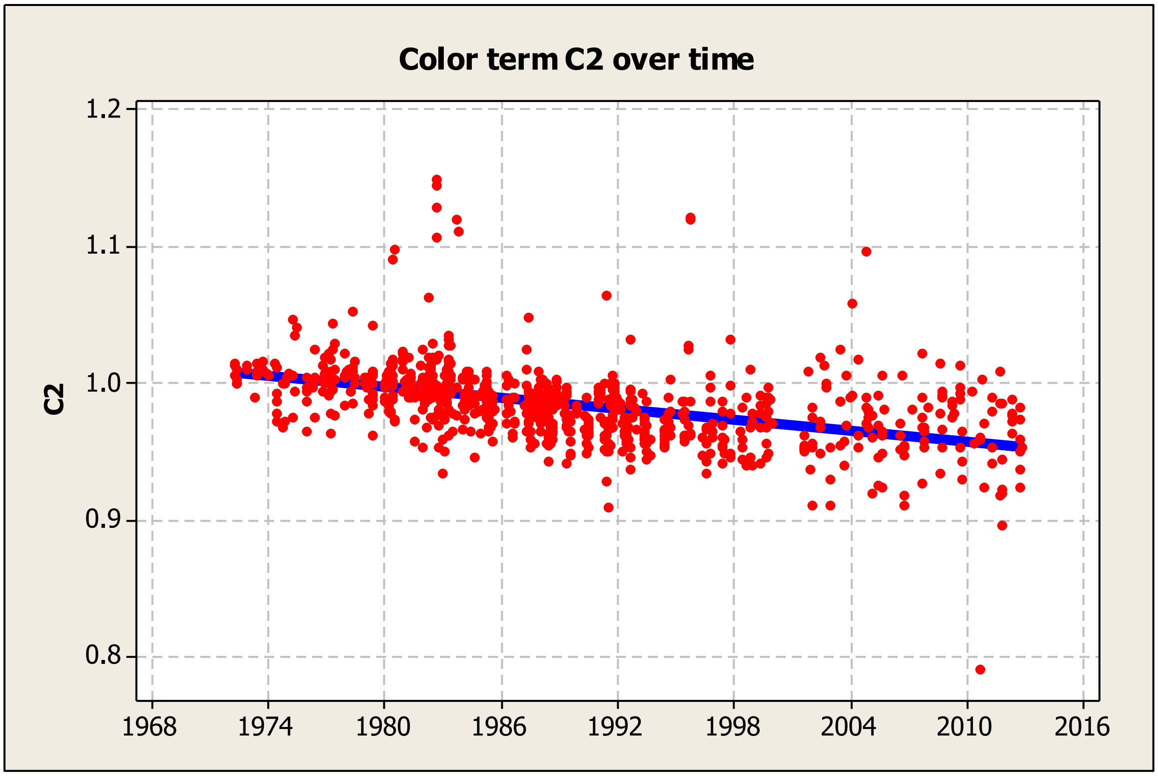
Planetary differential photometry referred to nearby comparison stars during each apparition is recorded and processed on the instrumental system. Final nightly and annual values must therefore be adjusted to the standard Strömgren system by applying a color term determined either from comparison star “all sky” measurements in the same apparition or by the trend in the ensemble of such measurements over time. Nightly color terms are notoriously noisy due to their small leverage (small range of *b-y* color) in the regression equations, so the usual procedure is to average color terns for a number of nearby nights over a few weeks. This is the procedure we used for published magnitudes of Uranus and Neptune where the color terms are rather small and hence contribute little to error, even if noisy. For Titan, however, whose *b-y* color is ~0.8, several tenths of a magnitude redder than the usual comparison stars, we found a smoothed long term linear trend gave a better result (viz., a smoother light curve), and we have therefore adopted that scheme for future publications.

3.1. Long term trends in the color terms.

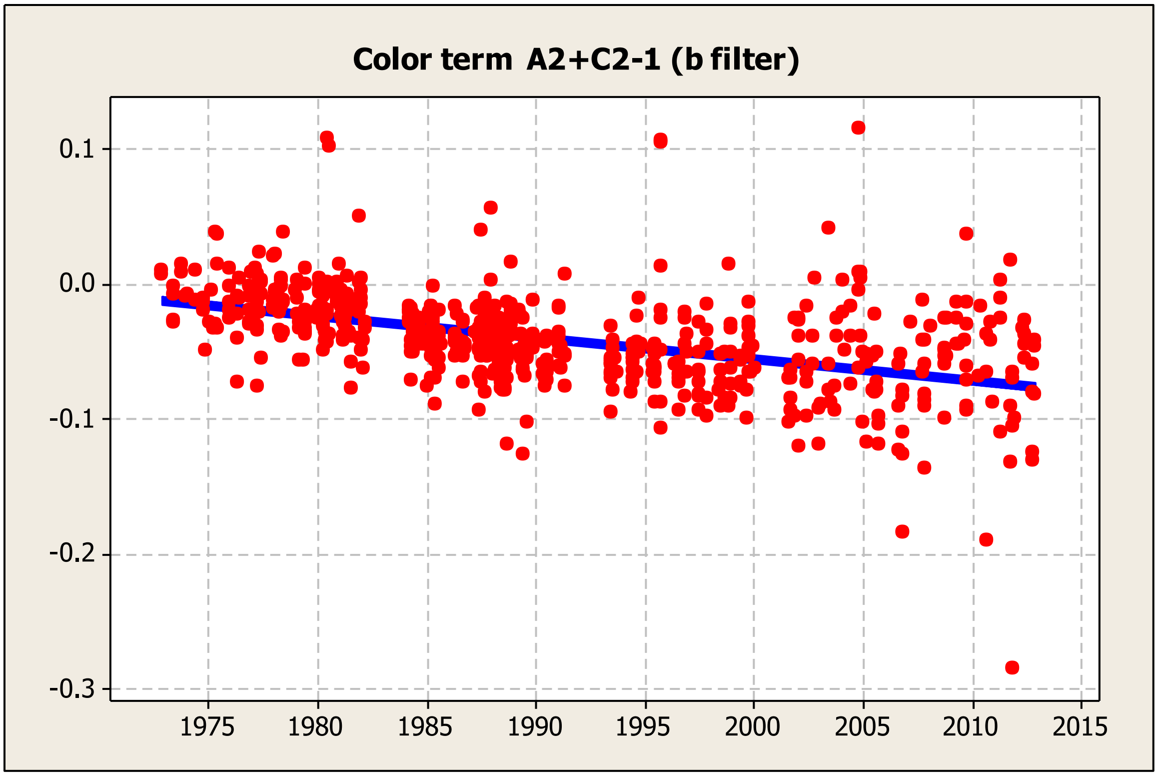
We do not understand the cause of slowly changing color terms. The likely suspect, in our view, is a slow change in the spectral response of the photomultiplier tube, now 40 years old. This seems rather more plausible than a change in *both* interference filters, since when filters fail, they usually do so catastrophically with obvious consequences not only in derived transformation coefficients but also by developing visible white light pinholes or interior coating degradation.



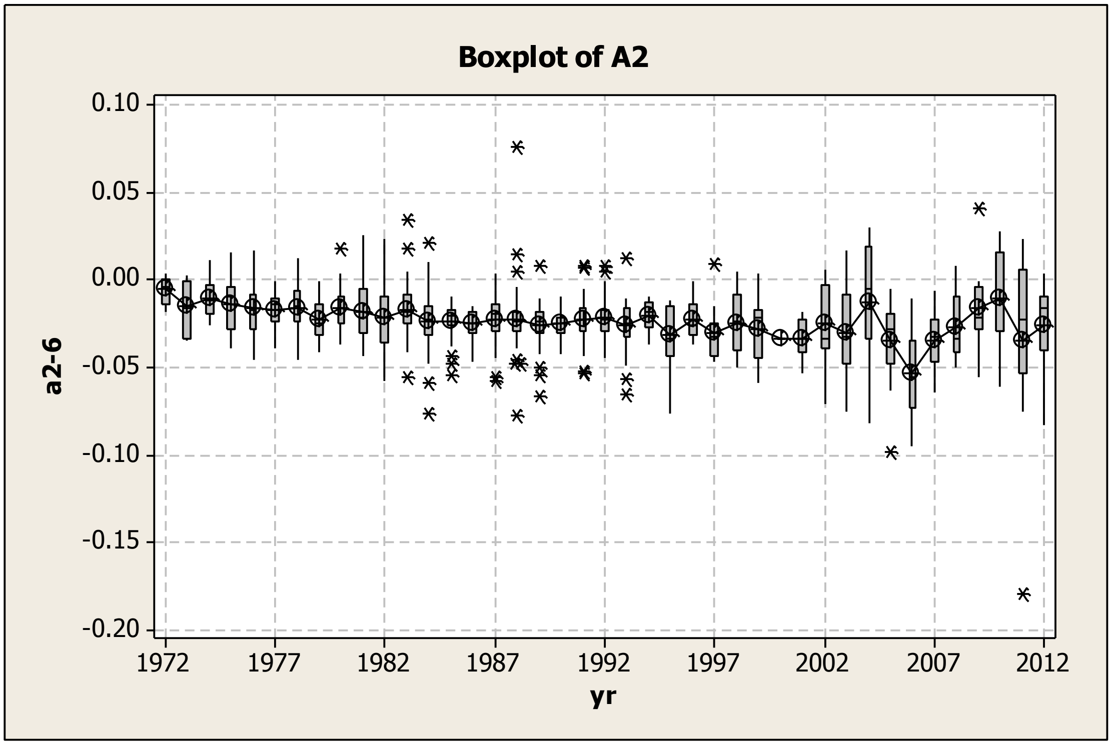
Color term A_2 for the y filter. The regression equation is $A_2 = 0.720 - 0.000373$ yr

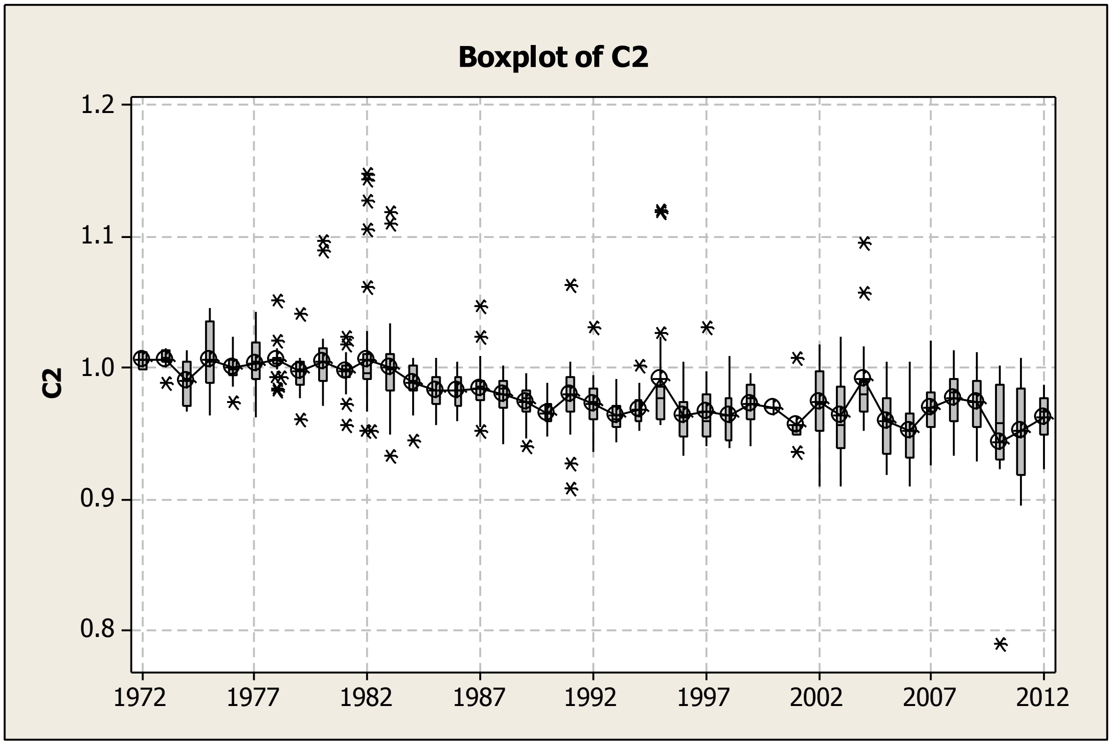


Color term C_2 for the *b*-*y* color. The regression equation is $C_2 = 3.45 - 0.00124$ yr



Color term $A_2 + C_2 -1$ for *b* The regression equation is A2+C2-1 = 3.17 - 0.00161 y. The scatter for both of these essential quantities seems to have increased since about 2000 and shown quantitatively by the boxplots of A_2 and C_2 below. The regression equation is $A_2+C_2-1 = 3.17 - 0.00161$ yr

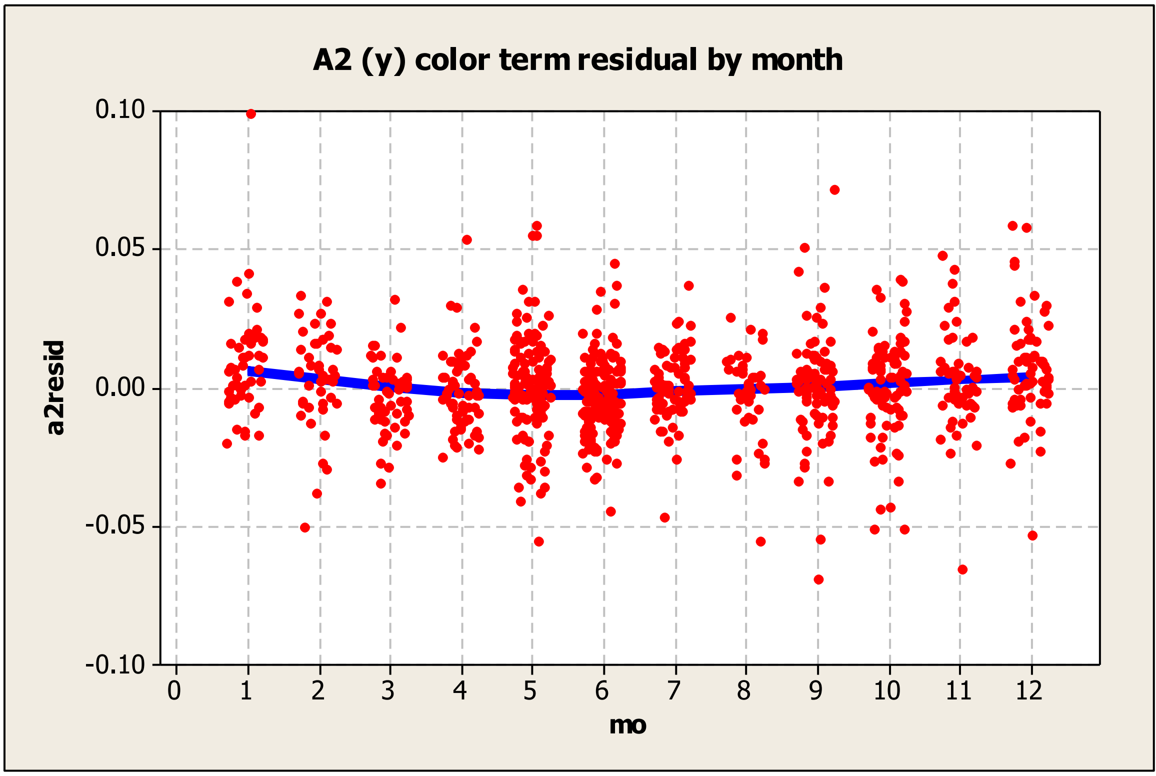




Boxplots of the color terms, year by year. Grey boxes indicate the interquartile range. The larger year to year variation after 2000 may be due to the smaller number of nights each year.

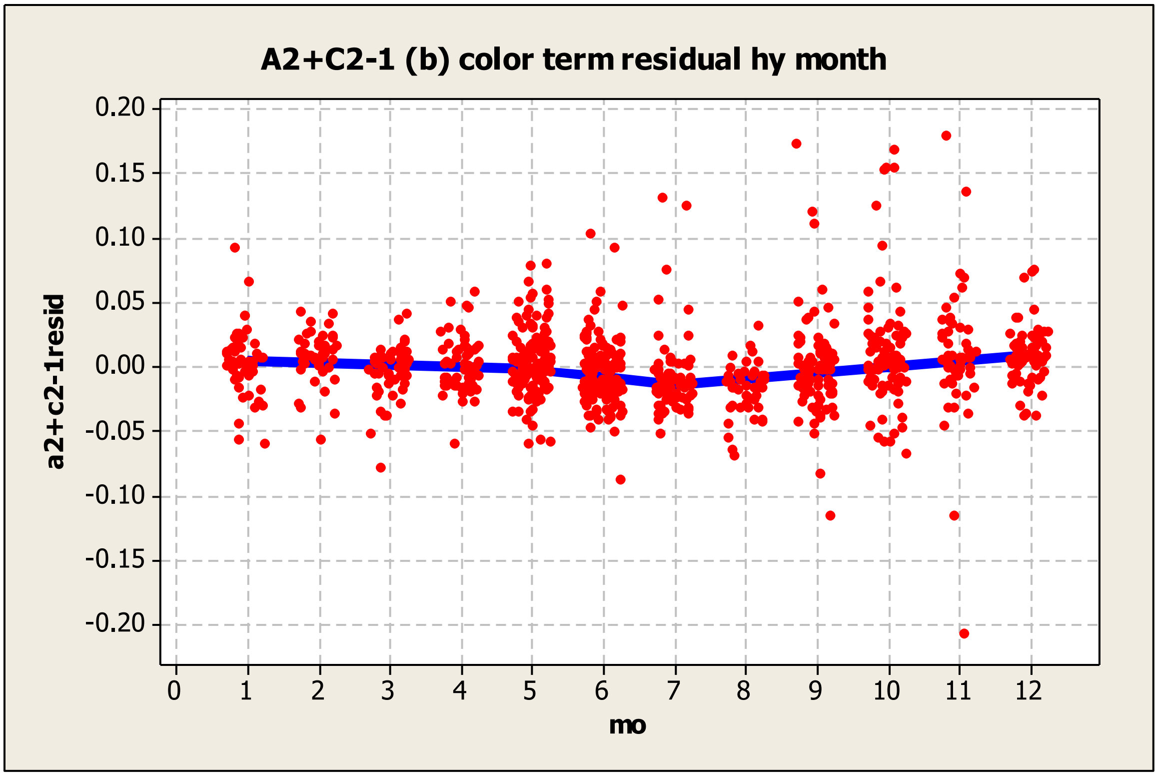
3.2 Residual color terms by month

A seasonal (by month and ambient outdoor temperature) effect might be expected in color terms since the filter temperature is not controlled. The internal temperature of the photomultiplier is thermostatically controlled and is therefore not thought to vary with outside temperature. To examine this possibility we analyze the residuals from the regressions shown above.



p

A_2 residual by month with horizontal jitter added for clarity. If there is a seasonal (ambient temperature effect, it’s very small.



The color term for the *b* filter alone (as distinct from the b-y color) is A_2 +C_2 -1. There is, as for the y filter, a small seasonal variation amounting to less than 0.01.

Are these seasonal variations shown above statistically significant? Let’s look at a formal AOV

One-way ANOVA: a2resid versus mo

```
Source   DF        SS        MS     F      P
mo       11  0.010645  0.000968  3.16  0.000
Error   851  0.260860  0.000307
Total   862  0.271505

S = 0.01751   R-Sq = 3.92%   R-Sq(adj) = 2.68%

                               Individual 95% CIs For Mean Based on
                               Pooled StDev
Level     N      Mean     StDev  ----+---------+---------+---------+-----
 1      51   0.00889  0.01909                       (-------*-------)
 2      43   0.00280  0.01779            (--------*-------)
 3      52  -0.00378  0.01251  (-------*-------)
 4      59  -0.00233  0.01426     (------*-------)
 5     125  -0.00041  0.01814          (----*----)
 6     139  -0.00374  0.01384     (----*----)
 7      72   0.00050  0.01269          (------*------)
 8      43  -0.00292  0.01541  (--------*--------)
 9      80  -0.00013  0.01976         (------*-----)
10      80  -0.00021  0.01840         (------*-----)
11      53   0.00030  0.02820         (-------*------)
12      66   0.00658  0.01838                    (------*------)
                               ----+---------+---------+---------+-----
                                -0.0060    0.0000    0.0060    0.0120
Pooled StDev = 0.01751
```

One-way ANOVA: a2resid versus mo

```
Source   DF        SS        MS     F      P
mo       11  0.010645  0.000968  3.16  0.000
Error   851  0.260860  0.000307
Total   862  0.271505

S = 0.01751   R-Sq = 3.92%   R-Sq(adj) = 2.68%

                               Individual 95% CIs For Mean Based on
                               Pooled StDev
Level     N      Mean     StDev  ----+---------+---------+---------+-----
 1      51   0.00889  0.01909                       (-------*-------)
 2      43   0.00280  0.01779            (--------*-------)
 3      52  -0.00378  0.01251  (-------*-------)
 4      59  -0.00233  0.01426     (------*-------)
 5     125  -0.00041  0.01814          (----*----)
 6     139  -0.00374  0.01384     (----*----)
 7      72   0.00050  0.01269          (------*------)
 8      43  -0.00292  0.01541  (--------*--------)
 9      80  -0.00013  0.01976         (------*-----)
10      80  -0.00021  0.01840         (------*-----)
11      53   0.00030  0.02820         (-------*------)
12      66   0.00658  0.01838                    (------*------)
                               ----+---------+---------+---------+-----
                                -0.0060    0.0000    0.0060    0.0120
Pooled StDev = 0.01751
```

The answer here seems to be “no” or at least mostly “no” especially from March through November. December and January fall outside the 95% CI and as December-January-February are the coldest months in Flagstaff, the possibility of small temperature sensitivity cannot be ruled out. On the other hand, since the dates when Uranus and Neptune comparison stars are observed drift later in the year over 40 years, there are systematic effects in the data sample that might yield a spurious artifact. For the time being, therefore, we adopt the linear trend in A_2 and $A_2 + C_2 - 1$ as good enough, leaving the question so a true seasonal effect open.