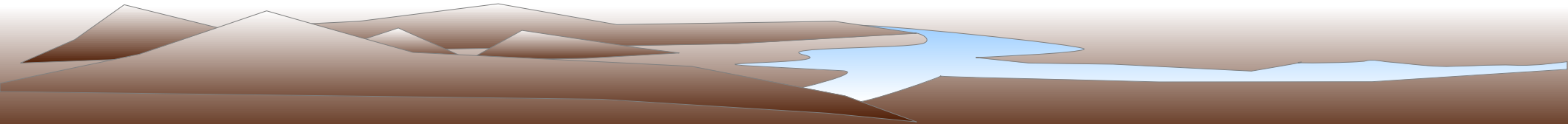


Converting from Classical to Robotic Telescope Operation

Marc W. Buie
Southwest Research Institute
Boulder, CO



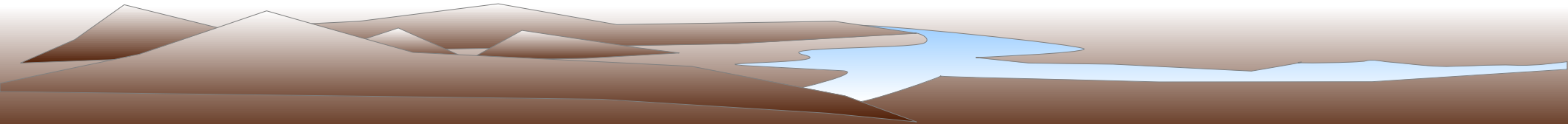
Lowell 0.8-m Telescope: Case Study



Lowell 0.8-m Telescope: Case Study

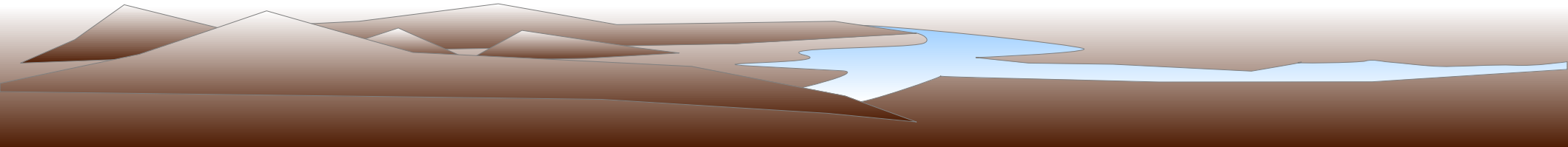
Adv. Ast., 2010, 130172

- ☉ 2000 – Initial attempt with then current data system. → Absolute failure. Unstable code base and overly complicated feature set.
- ☉ 2001 – January code development started
 - ☉ Linux camera driver already available
 - ☉ Basic remote commanding telescope available
 - ☉ 2001-Feb-17 first (science) observations
- ☉ 2001-now – improvements and upgrades
- ☉ Yet to come – support for autoguider



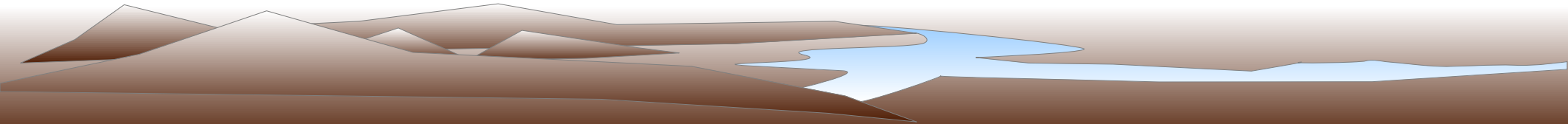
Philosophical Approach

- ☉ Robotic mode was a new option, not a conversion
- ☉ Observing with no oversight during the night
 - ☉ No image display
 - ☉ Log and data files are only source of feedback
- ☉ Foundation of system is an automaton
- ☉ Modular and layered design (C, C++)
- ☉ Linux/Solaris platform
- ☉ No off-site network connectivity required



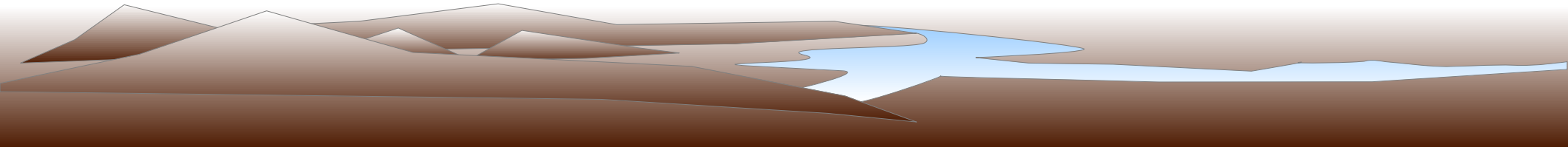
Ground Rules and Other Constraints

- ☉ Zero impact allowed on classical observing
 - ☉ Reverse is not true, sadly
- ☉ Continue to support instrument changes
 - ☉ No longer common, thankfully
- ☉ Essentially no funding or institutional support
- ☉ Do no harm to people or equipment
- ☉ Minimal effort required for operational support



System Overview

- ☪ One process per system
 - ☪ move – telescope interface layer
 - ☪ roboccd – camera operation
 - ☪ cmdr – observing queue
- ☪ Communication via IPC messages
 - ☪ Fast and tight communication
 - ☪ Simple program design
- ☪ Everything is modular and separate, TCP/IP layer can easily be added as a separate task.



Telescope

- ☉ 0.8-m aperture, Anderson Mesa Station
- ☉ English-yoke equatorial mount
 - ☉ 60°N pointing limit, very stable but tracks poorly
- ☉ Closed-tube made of aluminum
 - ☉ Very strong temperature/focus relationship
- ☉ Digital stepper motors, RA/DEC and focus
- ☉ Ash dome
 - ☉ upper/lower shutter with narrow power pad
 - ☉ Bar code reader for absolute position knowledge

Camera(s)

☪ PCCD (2001-2005)

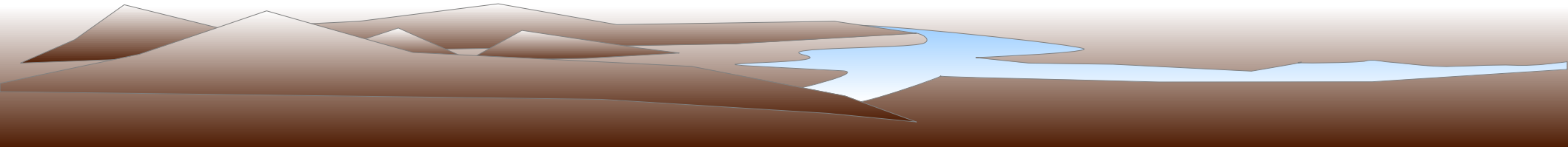
- ☪ Photometrics TH7883 CCD (384x576), 1.3"/pix
- ☪ Thermoelectrically cooled: -43°C
- ☪ 10-position filter wheel

☪ NASAcam (2007-present)

- ☪ EEV 2k CCD, 0.45"/pixel
- ☪ Leach Gen3 readout electronics
- ☪ Cryotiger cooling: -112°C
- ☪ Two 10-position filter wheels

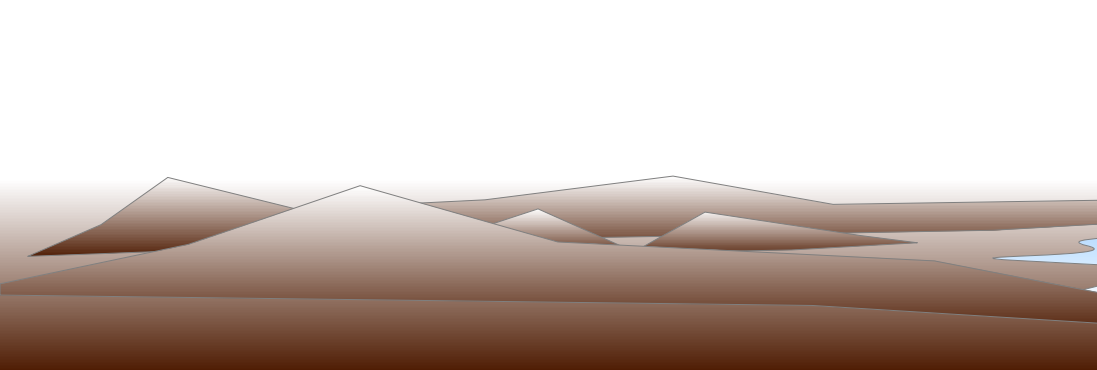
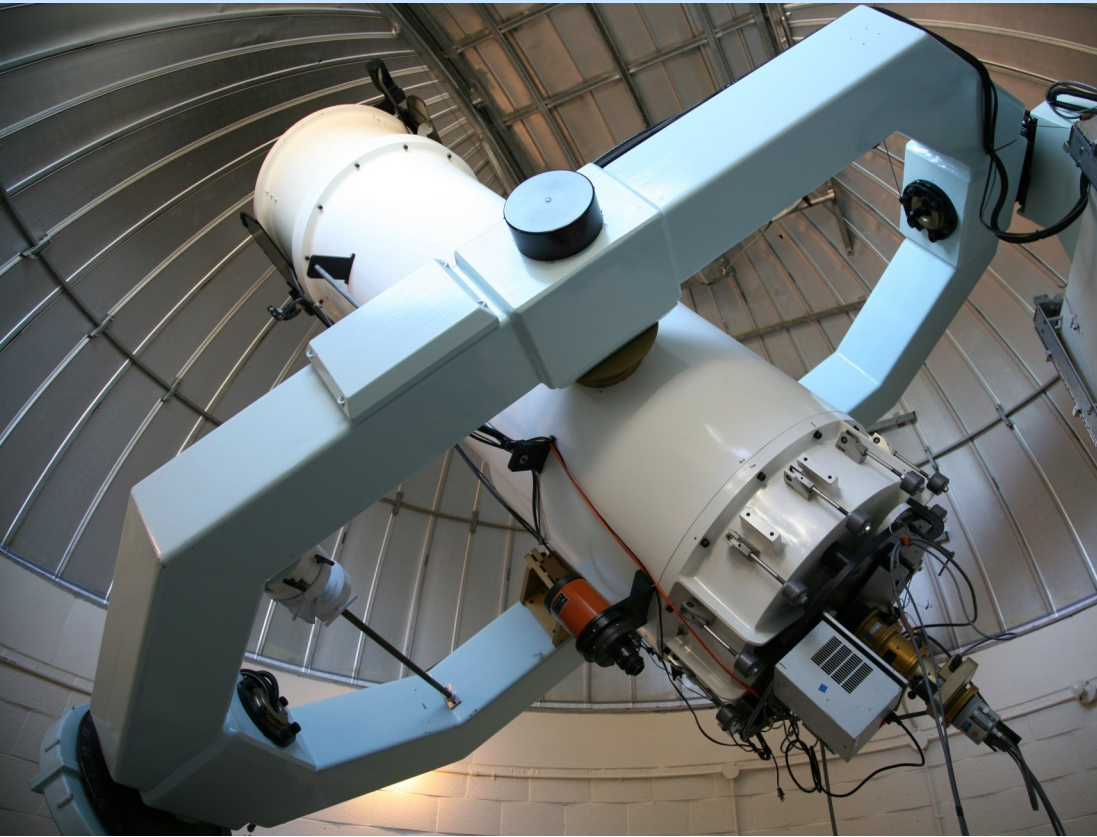
Environmental Data

- ☉ Davis weather station with server/logger
- ☉ Color day-time webcam (90° FOV)
- ☉ B/W high-sensitivity night camera (90° FOV)
- ☉ Dome CCTV monitoring camera
- ☉ Boresight high-sensitivity camera (10x14° FOV)
- ☉ Tube, mirror, and dome air temperature



Telescope and Instrument 2011

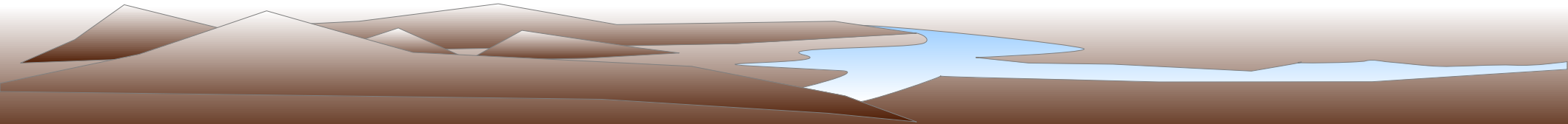
2001




Interesting Lessons Learned

☪ How much real-time analysis?






- ☪ Peak pixel: x , y , DN, FWHM, aperture flux
- ☪ Sky background: mean, standard deviation



Peak pixel

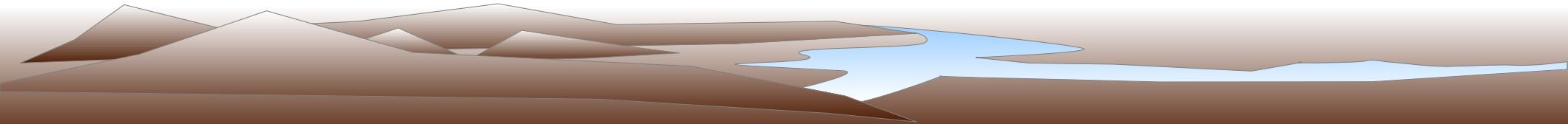
 x,y

Target acquisition

-  observed position used to generate small offset for a pointing update
-  Self-acquisition for an isolated source
-  Local reference
 -  self-acquisition on nearby isolated source
 -  small blind offset

DN, FWHM, aperture flux

-  Used to support focus operation

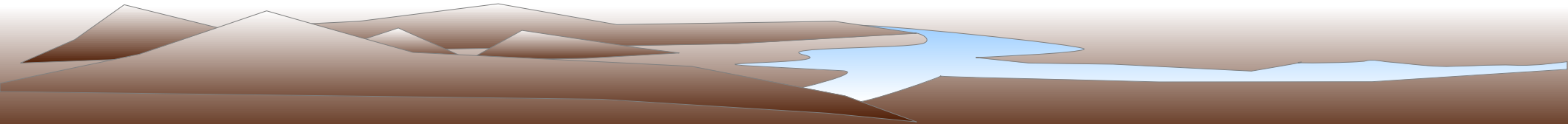


BigAcq – large field acquisition

- ☉ Special operation used on first robotic night
- ☉ Chose and slew to star brighter than 3rd magnitude
- ☉ Full-frame image (16' FOV), 2 ms exposure
- ☉ Brightest pixel used for star position and pointing update, provided FWHM is “sensible”
 - ☉ chance for confusion vanishingly small
 - ☉ can be done in bright twilight in suitable filter
 - ☉ star usually saturated, this is a coarse peak-up
 - ☉ very resilient against clouds

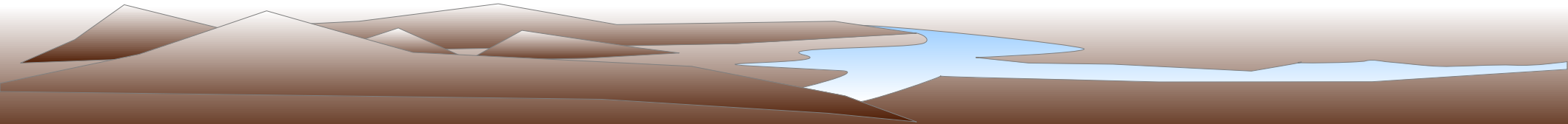
Normal Acquisition

- ☉ Reconfigure to a 3 arcmin FOV
- ☉ Target source must be the brightest object within 3 arcmin to match acquisition FOV. Source usually chosen to be between $R=7 - 8$.
- ☉ Take 1-second exposure in R
- ☉ Use position of peak source to update pointing
- ☉ Operation takes less than 10 seconds (ignoring slew)



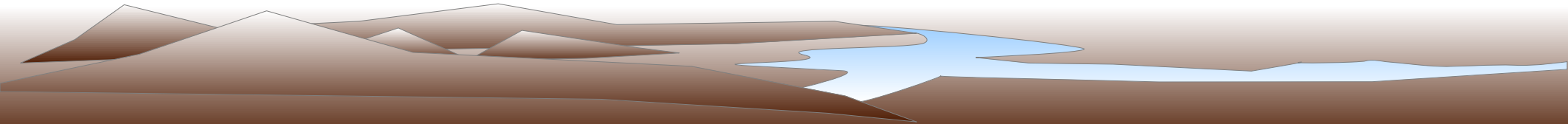
Flat Field Collection (Twilight)

- ☉ Flats are best when done at correct focus
 - ☉ Dawn flats are best but with care dusk flats work
- ☉ Use detector and data to adjust exposure time
- ☉ Control parameters
 - ☉ Number of images for choice of filter
 - ☉ mingood/maxgood → Signal must be in this range
 - ☉ minbest/maxbest → Signal desired in this range
 - ☉ minexp/maxexp → valid range for exposure time

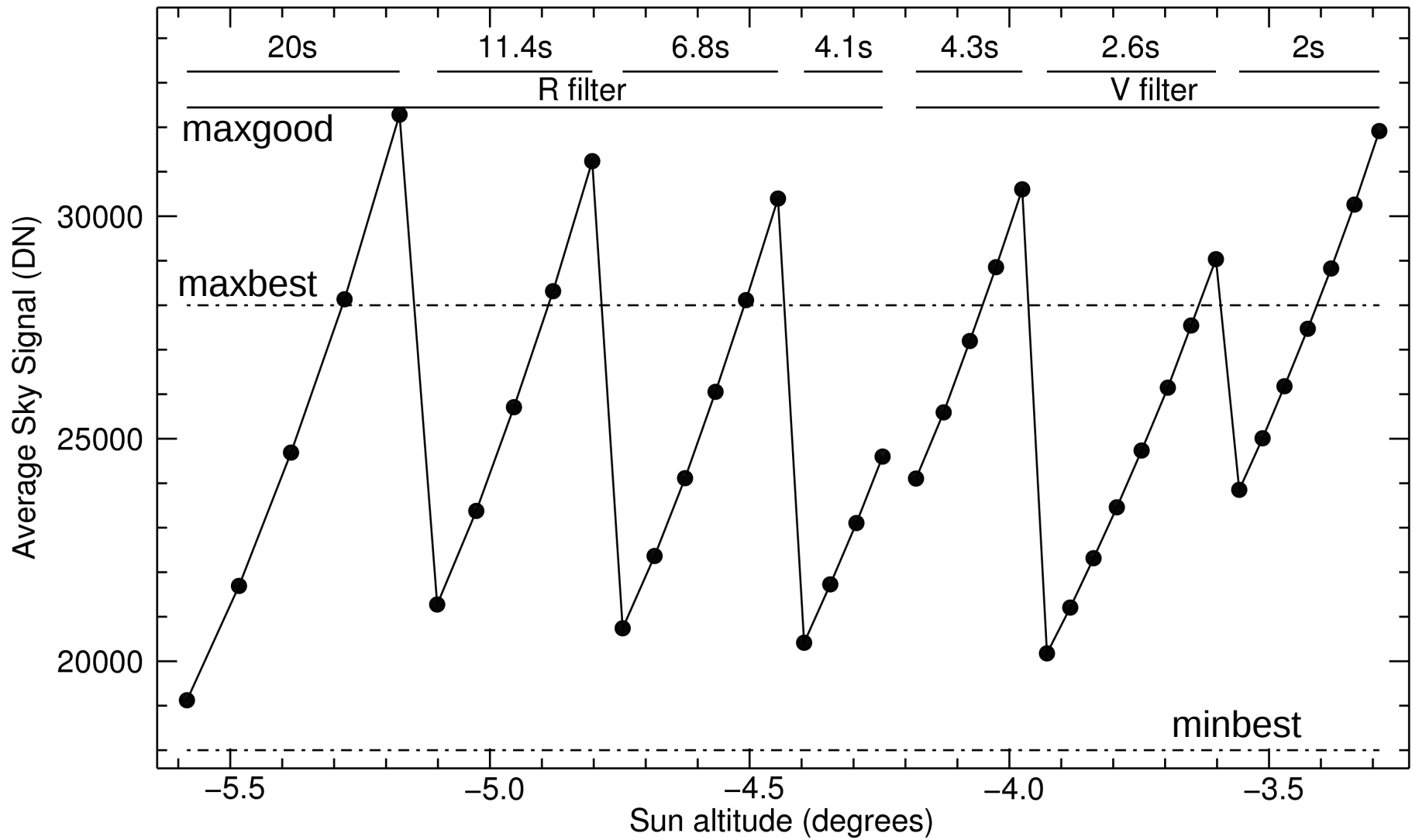


Dawn Flat Field Sequence

- 1) Take one 2 msec small sub-array exposure
- 2) If sky signal < 6000 DN, wait 1 minute, retry #1
- 3) Take one 1 second small sub-array exposure
- 4) If sky $< \text{mingood}/\text{maxexp}$ or sky $> \text{maxgood}/\text{minexp}$, wait 5 seconds, retry #3
- 5) try to set exposure time to put signal at minbest
- 6) if too faint, use maxexp
- 7) if too bright, use minexp



Example Flat Sequence



Interesting Lessons Learned

☪ How much real-time analysis?

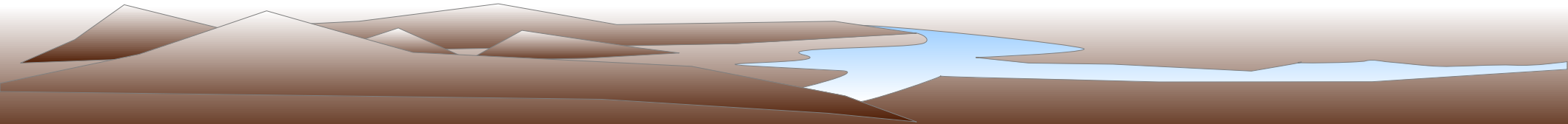
☪ Peak pixel: x , y , DN, FWHM, aperture flux

☪ Sky background: mean, standard deviation

☪ How to focus?

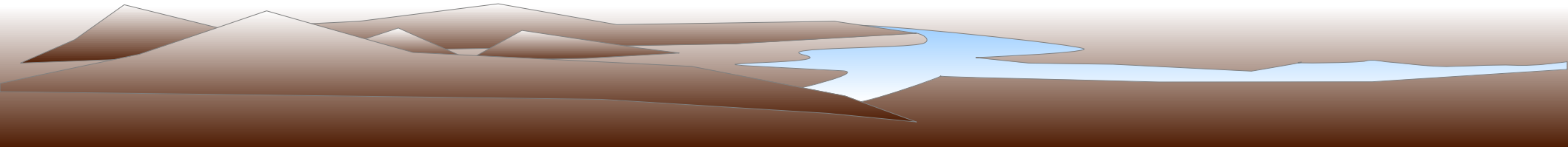
☪ Focus sweep, 1 second, total time needed 1 minute

☪ No fitting, find best figure-of-merit (peak/flux)



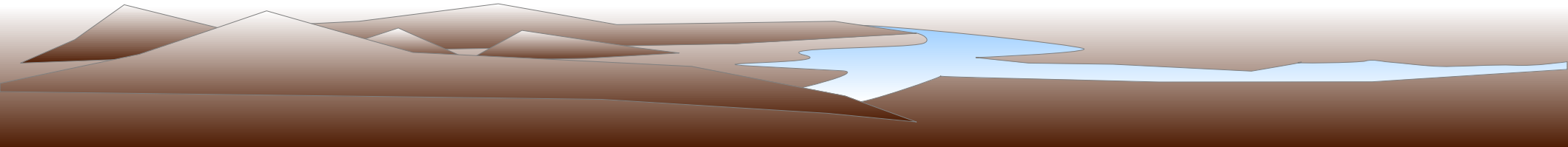
Focus

- ☉ Focus stars are pre-defined and eternal
 - ☉ $R=7 - 8$ (good S/N in 1 second)
 - ☉ start declination = latitude
 - ☉ one star for each hour of right ascension
 - ☉ chose the one nearest the zenith
- ☉ One variable: delta = step size between successive focus positions.
- ☉ One image per step, small sub-array for speed
- ☉ Record metrics at each focus position



Focus, continued

- ☪ Sweep is 9 focus steps above and below the current focus setting. First and last setting are always ± 100 steps from current focus.
- ☪ Compute figure of merit (FOM), peakDN/flux
- ☪ best FOM is a candidate for best focus
- ☪ Conditions are graded as good as long as the best FOM is more than double the worst FOM
- ☪ Update focus if conditions good, return to previous setting if not
- ☪ One retry is allowed if the answer is at the edge



Focus log data

2008/09/16 02:15:04 focus sequence started, initial setting 5532
0+3 18:01:34.2 +25:29:21 W00:28:57 1.02 71.4 71.16 67.91 67.08 65.6

focus	fwhm	peak	flux	fom	
5442	8.8	5838.5	8.83e+05	0.0066	9.32e+05
5478	7.5	7455.2	9.06e+05	0.0082	9.4e+05
5484	7.5	7473.1	9.04e+05	0.0083	9.35e+05
5490	6.1	12186.5	9.07e+05	0.0134	9.34e+05
5496	6.2	9605.1	9.15e+05	0.0105	9.42e+05
5502	6.4	10254.2	9.09e+05	0.0113	9.36e+05
5508	5.8	12706.1	9.13e+05	0.0139	9.37e+05
5514	5.2	16459.0	9.09e+05	0.0181	9.33e+05
5520	4.6	21323.4	9.21e+05	0.0232	9.41e+05
5526	5.6	13870.8	9.11e+05	0.0152	9.38e+05
5532	5.1	18311.9	9.19e+05	0.0199	9.44e+05
5538	5.8	13096.3	9.02e+05	0.0145	9.33e+05
5544	5.4	14560.1	9.08e+05	0.0160	9.32e+05
5550	4.6	20875.6	9.18e+05	0.0227	9.39e+05
5556	4.8	18259.7	9.15e+05	0.0200	9.37e+05
5562	5.3	15199.2	9.12e+05	0.0167	9.34e+05
5568	5.4	13516.1	9.04e+05	0.0150	9.29e+05
5574	6.6	10648.2	9.05e+05	0.0118	9.35e+05
5580	5.2	16511.2	8.95e+05	0.0184	9.2e+05
5586	5.7	14966.3	9.04e+05	0.0166	9.31e+05
5622	6.7	10717.9	8.6e+05	0.0125	9.3e+05

Best focus should be at 5520

0.45 arcsec/pixel

Focus log data

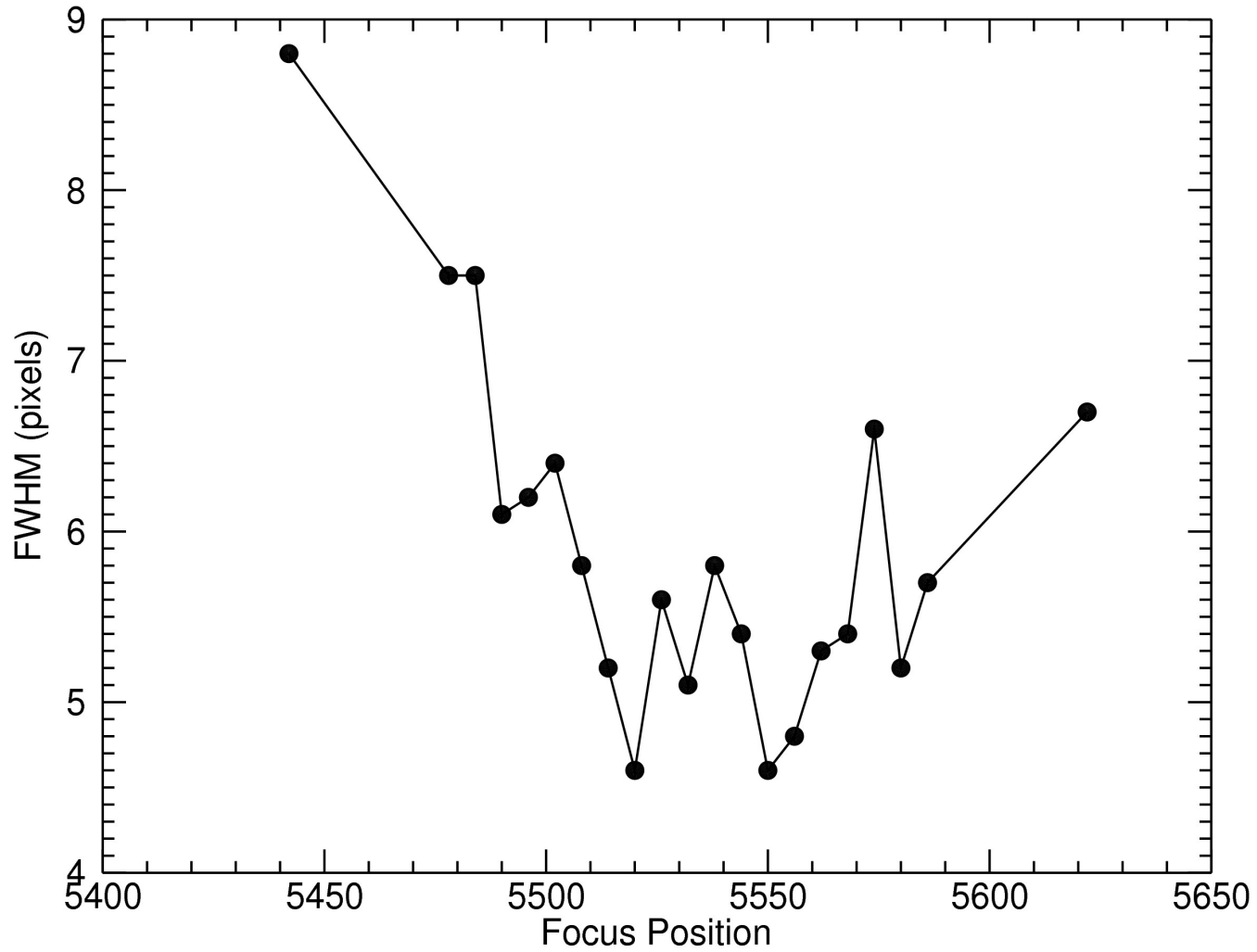
2008/09/16 02:15:04 focus sequence started, initial setting 5532
0+3 18:01:34.2 +25:29:21 W00:28:57 1.02 71.4 71.16 67.91 67.08 65.6

focus	fwhm	peak	flux	fom	
5442	8.8	5838.5	8.83e+05	0.0066	9.32e+05
5478	7.5	7455.2	9.06e+05	0.0082	9.4e+05
5484	7.5	7473.1	9.04e+05	0.0083	9.35e+05
5490	6.1	12186.5	9.07e+05	0.0134	9.34e+05
5496	6.2	9605.1	9.15e+05	0.0105	9.42e+05
5502	6.4	10254.2	9.09e+05	0.0113	9.36e+05
5508	5.8	12706.1	9.13e+05	0.0139	9.37e+05
5514	5.2	16459.0	9.09e+05	0.0181	9.33e+05
5520	4.6	21323.4	9.21e+05	0.0232	9.41e+05
5526	5.6	13870.8	9.11e+05	0.0152	9.38e+05
5532	5.1	18311.9	9.19e+05	0.0199	9.44e+05
5538	5.8	13096.3	9.02e+05	0.0145	9.33e+05
5544	5.4	14560.1	9.08e+05	0.0160	9.32e+05
5550	4.6	20875.6	9.18e+05	0.0227	9.39e+05
5556	4.8	18259.7	9.15e+05	0.0200	9.37e+05
5562	5.3	15199.2	9.12e+05	0.0167	9.34e+05
5568	5.4	13516.1	9.04e+05	0.0150	9.29e+05
5574	6.6	10648.2	9.05e+05	0.0118	9.35e+05
5580	5.2	16511.2	8.95e+05	0.0184	9.2e+05
5586	5.7	14966.3	9.04e+05	0.0166	9.31e+05
5622	6.7	10717.9	8.6e+05	0.0125	9.3e+05

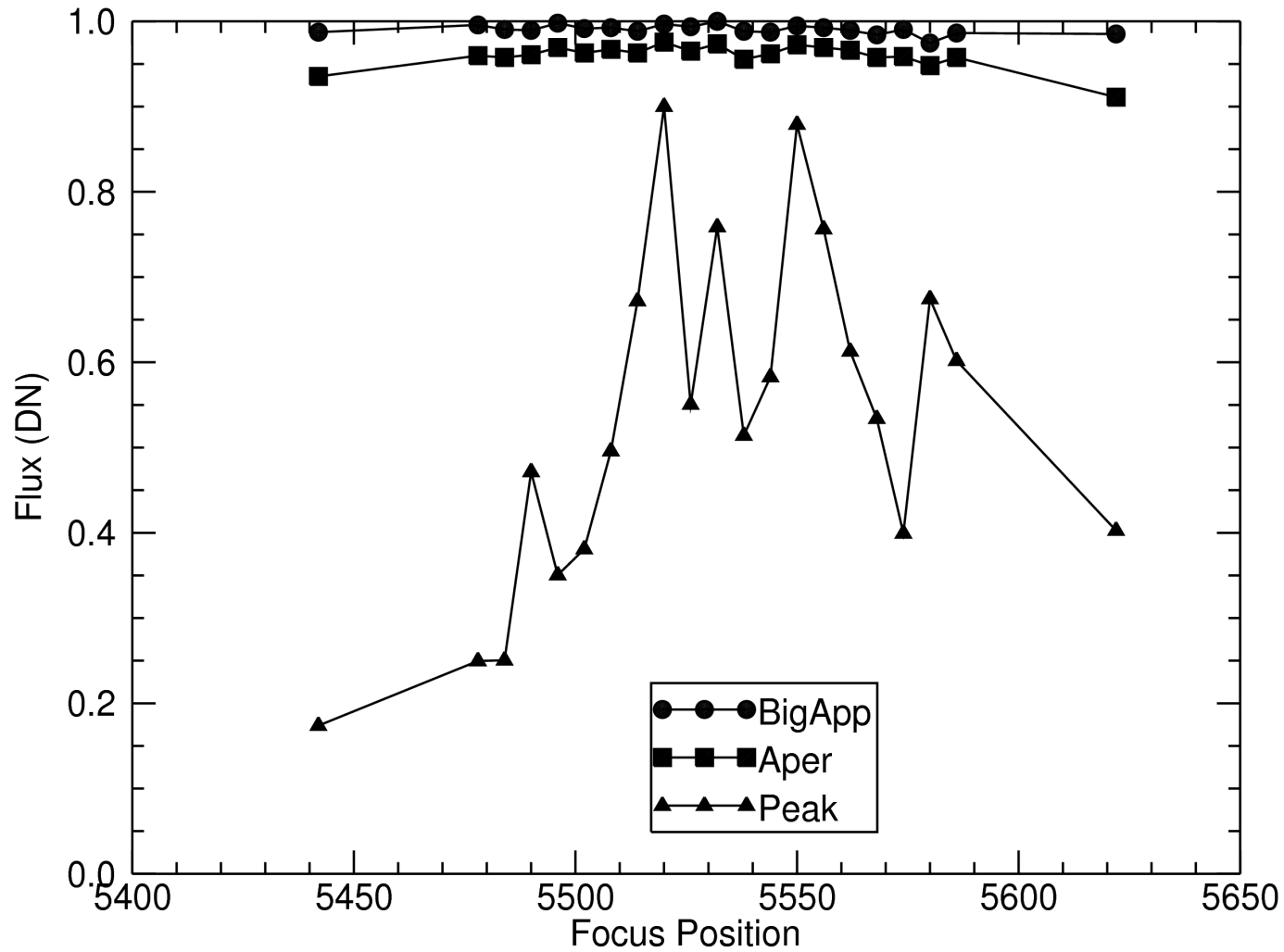
Best focus should be at 5520

0.45 arcsec/pixel

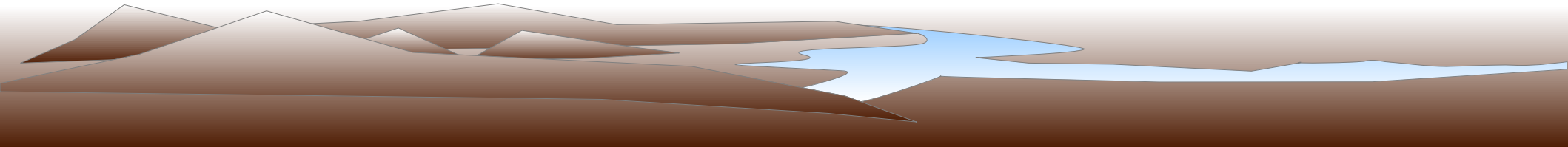
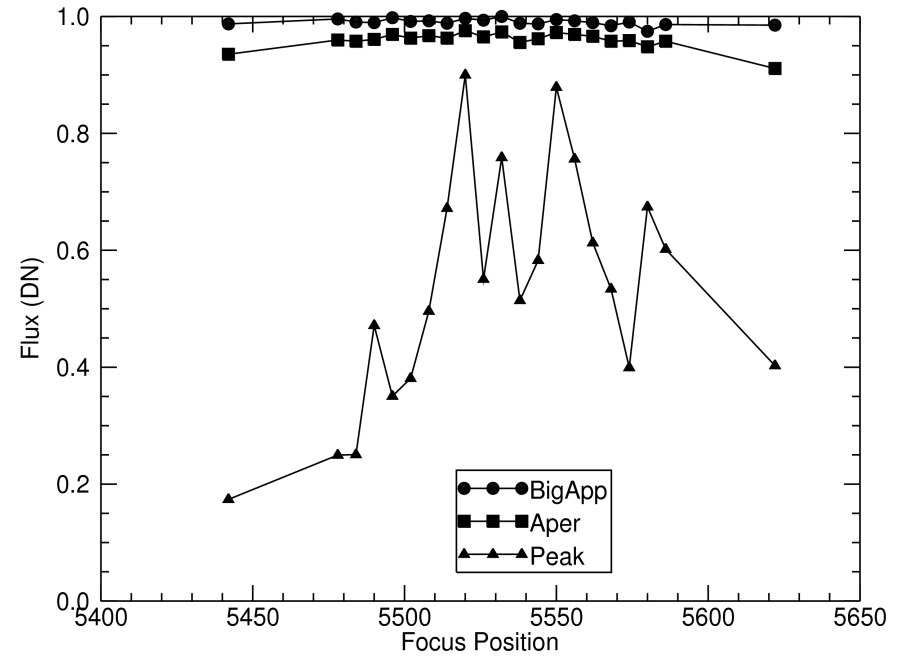
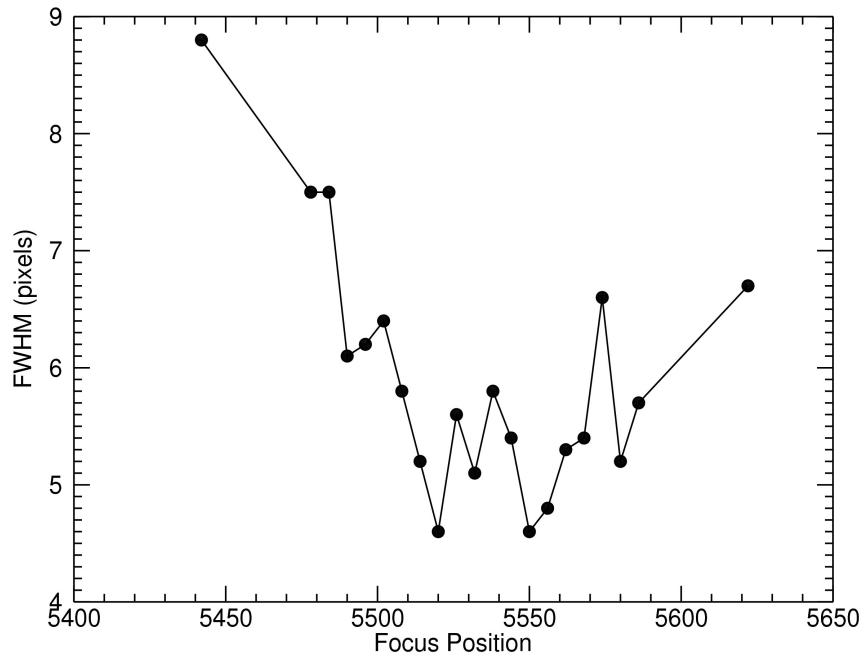
Focus data plot



Focus data plot

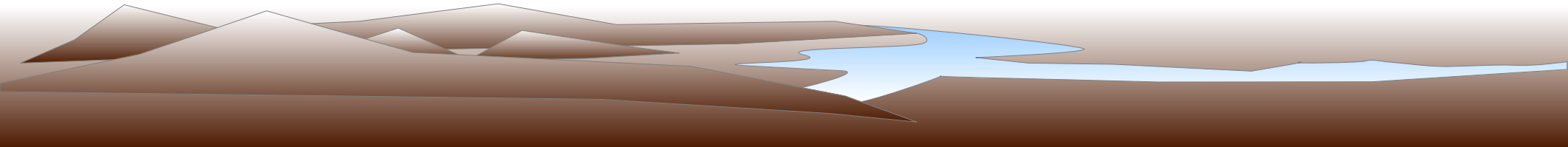


Focus data plot



More focus subtleties

- ☉ Focus needs to be close, no more than 1.5 times further away than the scan half-width
- ☉ Temperature-based focus model used for initial setting at the start of every night
- ☉ Focus must be often enough to prevent getting too far away from best focus.
- ☉ Need to be robust against clouds and really bad seeing and not drive the focus too far away from the correct value
- ☉ Log all focus data



Interesting Lessons Learned

☉ How much real-time analysis?

☉ Peak pixel: x , y , DN, FWHM, aperture flux

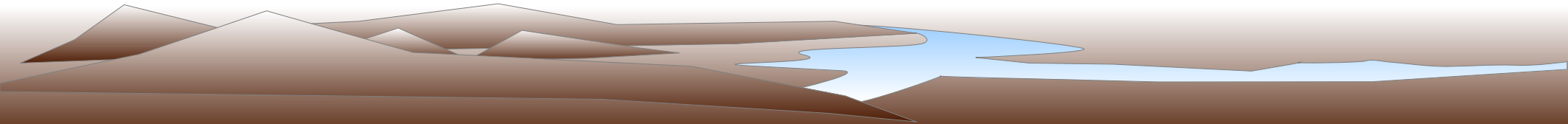
☉ Sky background: mean, standard deviation

☉ How to focus?

☉ Focus sweep, 1 second, total time needed 1 minute

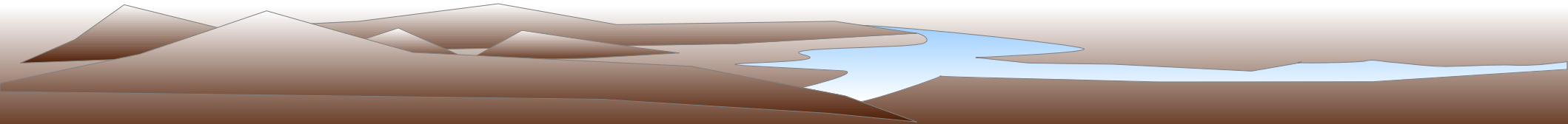
☉ No fitting, find best figure-of-merit (peak/flux)

☉ Timing control – LST is your friend



LST – Local Sidereal Time

- ☉ Coordinate that is relative to the visible sky
- ☉ LST range on observation request is resilient to variations of execution time
 - ☉ systematic error in overhead can accumulate through the night leading to real problems at the end of the night
- ☉ LST-defined block can be used night after night, year after year



Interesting Lessons Learned

☪ How much real-time analysis?

☪ Peak pixel: x , y , DN, FWHM, aperture flux

☪ Sky background: mean, standard deviation

☪ How to focus?

☪ Focus sweep, 1 second, total time needed 1 minute

☪ No fitting, find best figure-of-merit (peak/flux)

☪ Timing control – LST is your friend

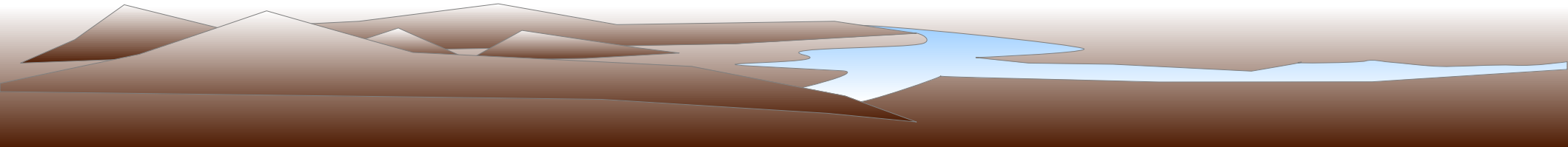
☪ No automated error recovery

☪ Supervised recovery, only one failure allowed



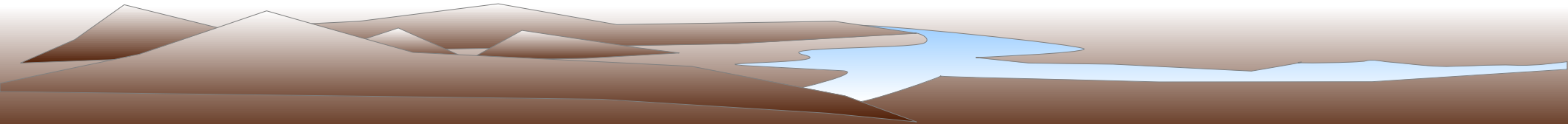
Error recovery

- ☉ Deterministic recoveries ok (ie., focus at the edge of the sweep range)
- ☉ Failures that trace back to hardware must be respected. That means cease operation until human intervention.
- ☉ Remote recovery is allowed one attempt to restore completely normal operations. Failure to do so requires physical on-site inspection and debugging.



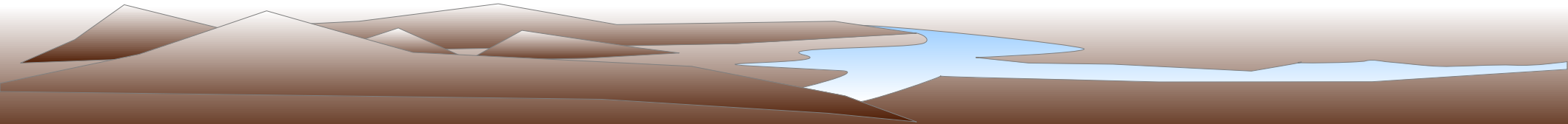
New manifestation of “Murphy's Law”

- ☪ New errors come up all the time (few a year)
- ☪ The rate of occurrence for a new problem is NOT proportional to how long you've worked without seeing this problem.
- ☪ Any such error WILL come up over and over again if you push the problem off to “another day”



Interesting Lessons Learned, cont'd

- ☪ Good log files are critically important
 - ☪ Balance required between too much and too little
 - ☪ Use good search string markers for use with grep
 - ☪ Time-tag *everything*
 - ☪ *All* machines involved need good time, use ntp



roboccd log

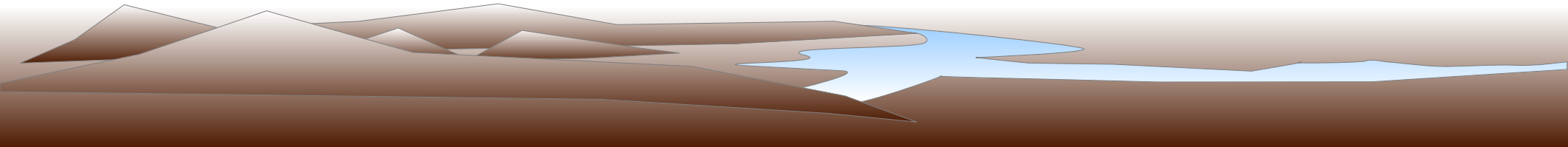
```
2008/06/14 03:23:10 Filter::GoTo: 1174 msec to move 1:(0->0) 2:(3->2)
2008/06/14 03:23:40 [Camera::Expose] Setting 2052 rows, 2138 columns for readout
2008/06/14 03:23:40 [Camera::Expose] shutter open for 100 msec
2008/06/14 03:23:48 [Camera::Expose] Readout/write to disk completed
2008/06/14 03:23:48 [Camera::Expose] time for readout 8424 msec
2008/06/14 03:23:48 [Camera::Background] Background 1550.6 +/- 3.3
2008/06/14 03:23:48 [Camera::Expose] time to compute background 80 msec
2008/06/14 03:23:48 [Camera::MinMax] Image min=1534, Maximum at (1125,1046)=65535
2008/06/14 03:23:48 [Camera::Expose] time to find min/max 213 msec
2008/06/14 03:23:48 [Camera::Photometry] Instrumental magnitude @ (1124.2,1046.7) = 4.598 +/- 0.000
2008/06/14 03:23:48 [Camera::Expose] time to do photometry 80 msec
2008/06/14 03:23:48 [Camera::FWHM] Seeing(FWHM) 6.2 pixels, 2.8 arcsec
2008/06/14 03:23:48 [Camera::Expose] time to find fwhm 81 msec
2008/06/14 03:23:48 [Camera::Expose] Image saved to /xena/rdata/robotic/080614/080614.000
2008/06/14 03:23:48 [Camera::Expose] time to update header 306 msec
2008/06/14 03:23:49 [Camera::Expose] total time to take image 9237 msec
2008/06/14 03:23:49 Requested observations completed.
2008/06/14 03:23:49 1 frames taken.
2008/06/14 03:23:49 Autofile off
2008/06/14 03:23:49 Offset to bring Max to Lock point 9.7 46.1
2008/06/14 03:23:53 previous subframe params: xcen 0 xsize 0 ycen 0 ysize 0
2008/06/14 03:23:53 SSS command full frame!
2008/06/14 03:29:14 Filter::GoTo: 1174 msec to move 1:(0->0) 2:(2->3)
2008/06/14 03:29:14 Tubetemp=74.02, Mirror=69.22, setting focus to 5560
```

move log

2008/06/14 02:36:49 WK
2008/06/14 02:36:51 ST "19:36:51"
2008/06/14 02:36:51 LI 0
2008/06/14 02:36:52 PP
2008/06/14 02:36:59 OS 180
2008/06/14 02:40:08 CS 3
2008/06/14 02:40:15 DM 1
2008/06/14 02:40:15 TC 1
2008/06/14 02:40:16 FT 0
2008/06/14 02:40:16 DS 120
2008/06/14 02:40:17 DE
2008/06/14 02:40:18 EE "E:\PLUTO08.MOV"
2008/06/14 02:40:23 FG 5510
2008/06/14 03:23:10 CO 13:54:40.99 +18:23:48.4
2008/06/14 03:23:39 NU
2008/06/14 03:23:49 RM 97 461
2008/06/14 03:23:52 UC
2008/06/14 03:29:15 CO 13:58:54.15 +24:41:30.6
2008/06/14 03:29:27 NU
2008/06/14 03:29:30 RM -8 -123
2008/06/14 03:29:32 UC
2008/06/14 03:29:34 FG 5420
2008/06/14 03:29:36 NU
2008/06/14 03:29:38 FG 5430
2008/06/14 03:29:39 NU

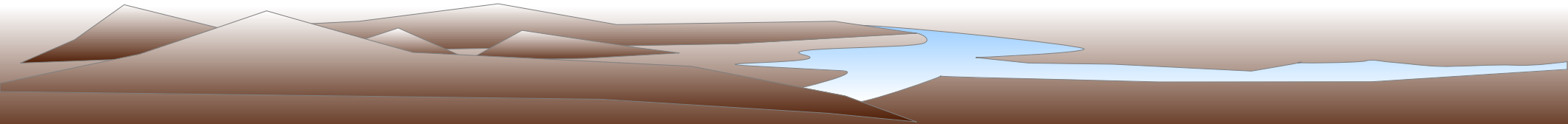
cmdr log

```
2008/06/14 02:11:15 572 pending, busy=1
2008/06/14 02:21:15 572 pending, busy=1
2008/06/14 02:31:15 572 pending, busy=1
2008/06/14 02:36:49 080614.000
2008/06/14 02:40:16 080614.000
2008/06/14 02:41:15 549 pending, busy=1
2008/06/14 02:51:15 549 pending, busy=1
2008/06/14 03:01:15 549 pending, busy=1
2008/06/14 03:11:15 549 pending, busy=1
2008/06/14 03:21:15 549 pending, busy=1
2008/06/14 03:23:49 /xena/rdata/robotic/080614/080614.000
2008/06/14 03:29:30 /xena/rdata/robotic/080614/080614.000
2008/06/14 03:29:38 focus= 5420 fwhm=8.8 peak=8888.0 flux=1.20026e+06 fom=0.0074
2008/06/14 03:29:42 focus= 5430 fwhm=8.7 peak=8143.4 flux=1.17482e+06 fom=0.0069
2008/06/14 03:29:46 focus= 5440 fwhm=8.5 peak=9882.8 flux=1.1782e+06 fom=0.0084
2008/06/14 03:29:49 focus= 5450 fwhm=8.2 peak=8508.6 flux=1.22149e+06 fom=0.0070
2008/06/14 03:29:53 focus= 5460 fwhm=7.5 peak=11186.6 flux=1.21806e+06 fom=0.0092
2008/06/14 03:29:58 focus= 5470 fwhm=6.4 peak=13754.3 flux=1.22161e+06 fom=0.0113
2008/06/14 03:30:01 focus= 5480 fwhm=6.4 peak=14870.1 flux=1.23581e+06 fom=0.0120
```



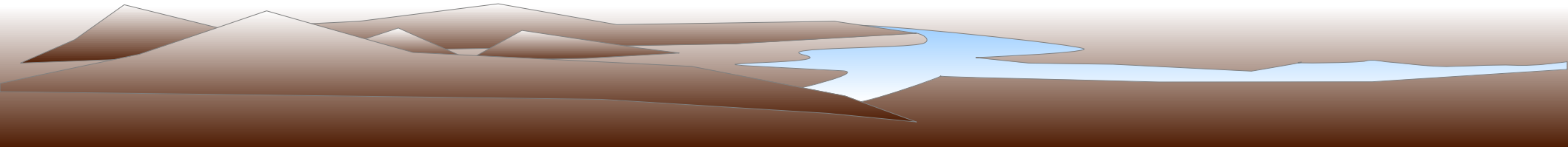
Interesting Lessons Learned, cont'd

- ☪ Good log files are critically important
 - ☪ Balance required between too much and too little
 - ☪ Use good search string markers for use with grep
 - ☪ Time-tag *everything*
 - ☪ *All* machines involved need good time, use ntp
- ☪ Standard star scheduling
 - ☪ Magic time when standard field at $X=2.5$
 - ☪ Work science data around standards



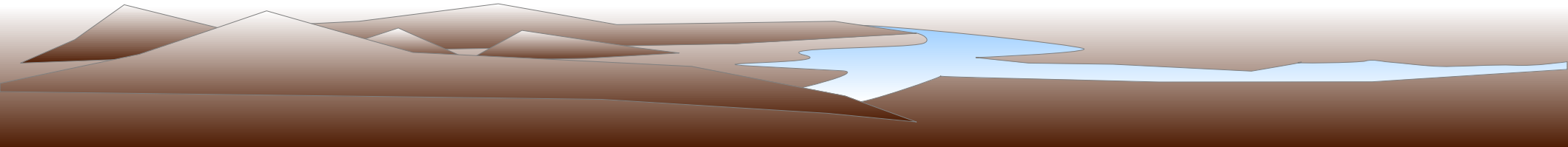
Standard Star Scheduling

- ☉ 15 fields from Landolt standards
 - ☉ Each field has at least two stars
- ☉ Each field can be at 2.5 airmasses at two times, each of these times is an LST when standards can be done well
- ☉ At the correct time for one field, others are available at different air masses, chose the one nearest the meridian and sometimes one more in between (as long as none are too near the Moon)
- ☉ Standard star observations roughly every 2 hours

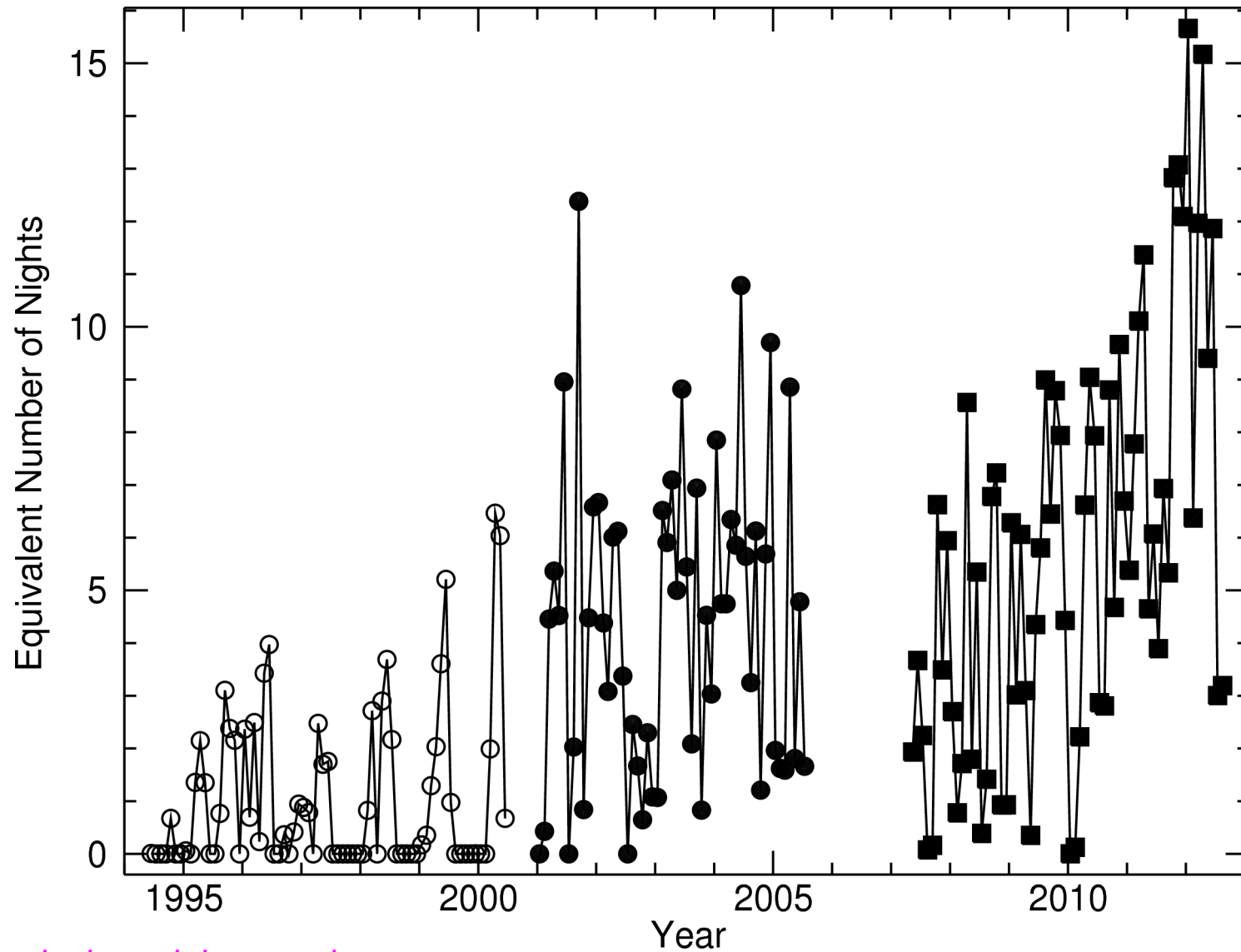


Interesting Lessons Learned, cont'd

- ☪ Demand for this system has been low at Lowell but interest is growing
 - ☪ Inertia, mysterious but consistent with most professional observatories I've worked at
 - ☪ Non full-time use excludes some projects
- ☪ Maintenance(non-observing) costs appear to be independent of classical/robotic usage
- ☪ Response time for responding to failures is slower than for classical observing → less “value” given to robotic time

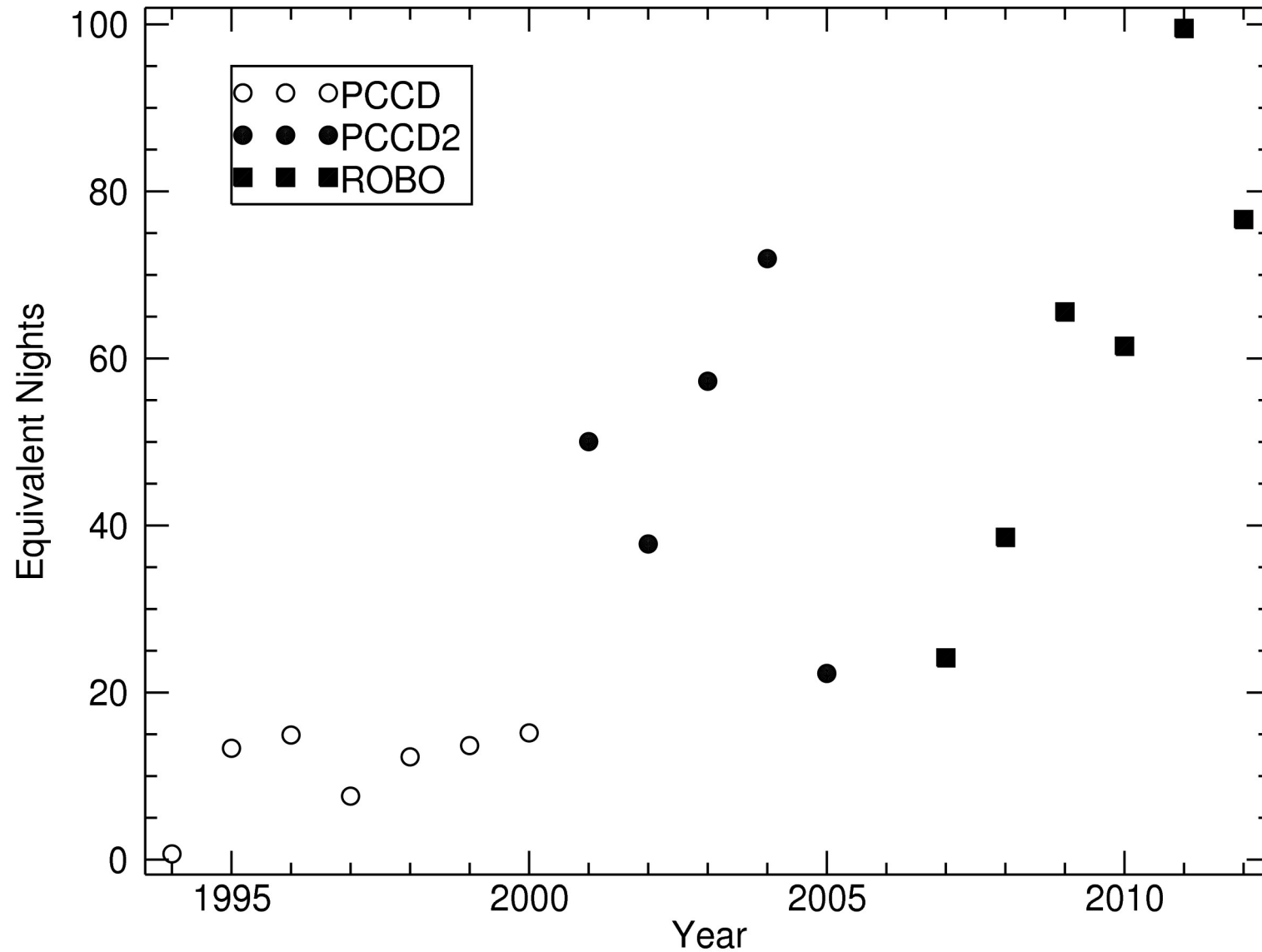


Usage Comparison



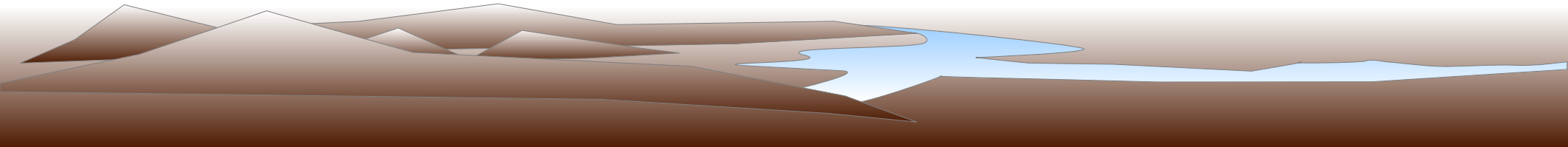
*Equivalent night = total
exposure time [days] / 10*

Usage Comparison Summary








Upgrades never happen when the system is “good enough”

- ☛ More flexible and general scheduling system
 - ☛ Development limited by funding opportunities
 - ☛ Ideal tool is a just-in time scheduler based on a fuzzy-logic based system (→ CFHT).
- ☛ Off-axis guider
 - ☛ System completed after 10+ years of effort
 - ☛ Classical modes work now, marginally
 - ☛ Robotic modes require new control methodology that is on the “to-do list”

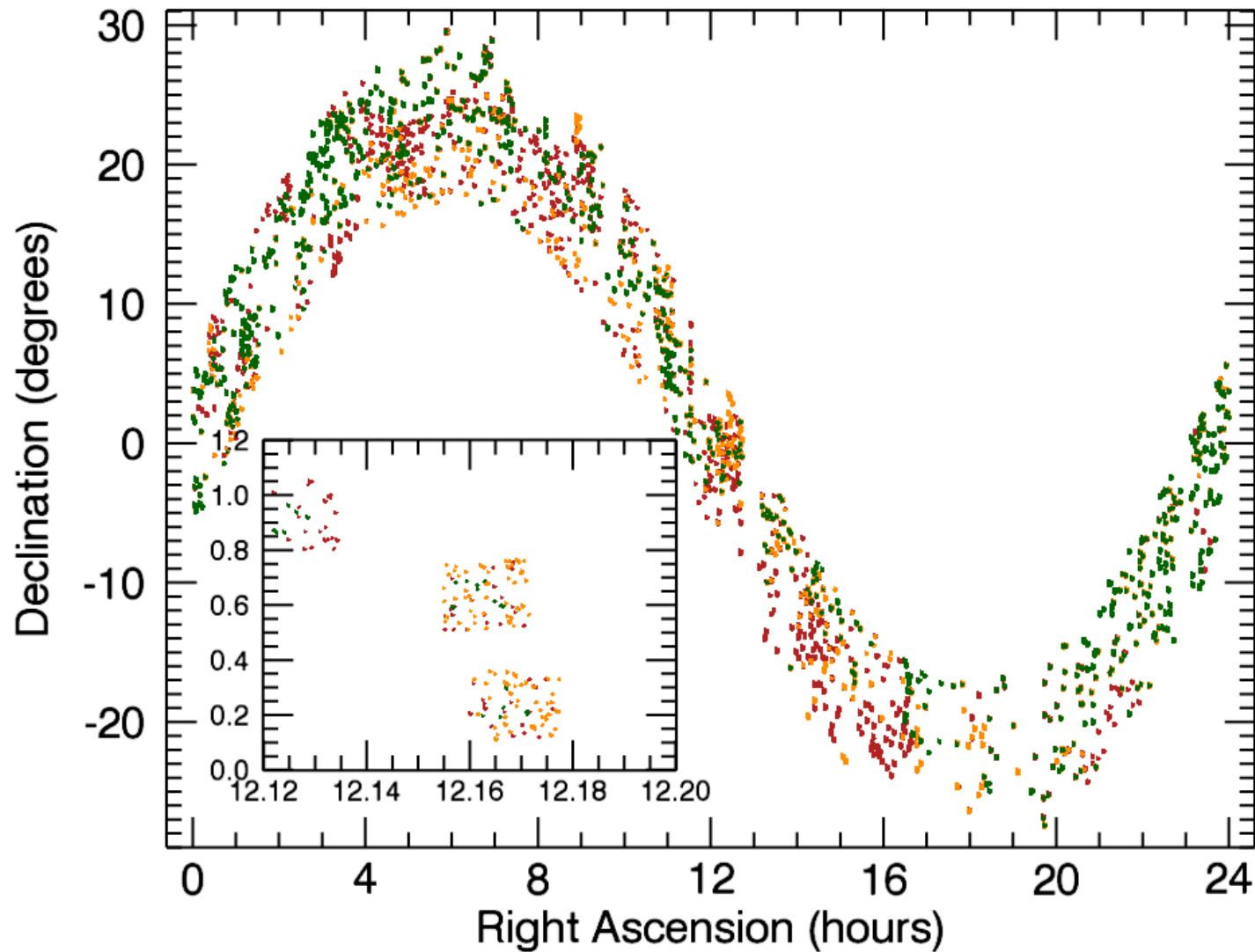


Results

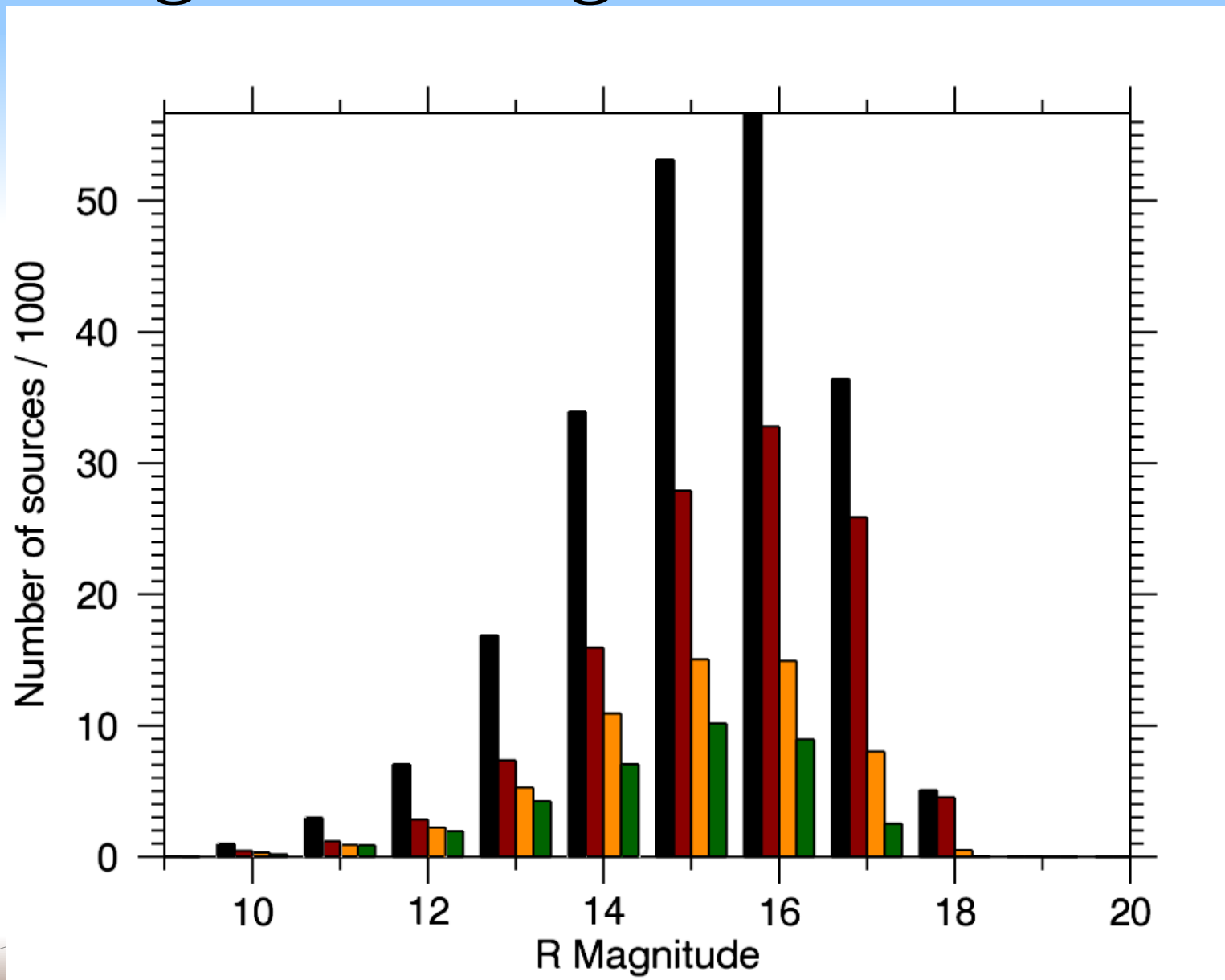
Deep Ecliptic Survey

-  NOAO Survey Program to search for Kuiper Belt objects along the ecliptic
-  Search data using Mosaic camera at Cerro Tololo and Kitt Peak on the 4-m telescopes
-  Photometric zero-point calibration relegated to smaller facilities
-  Calibration observations began in 2001, completed in 2010, on robotic system
-  213,272 sources calibrated in V and R; 35,427 sources measured on three or more nights.

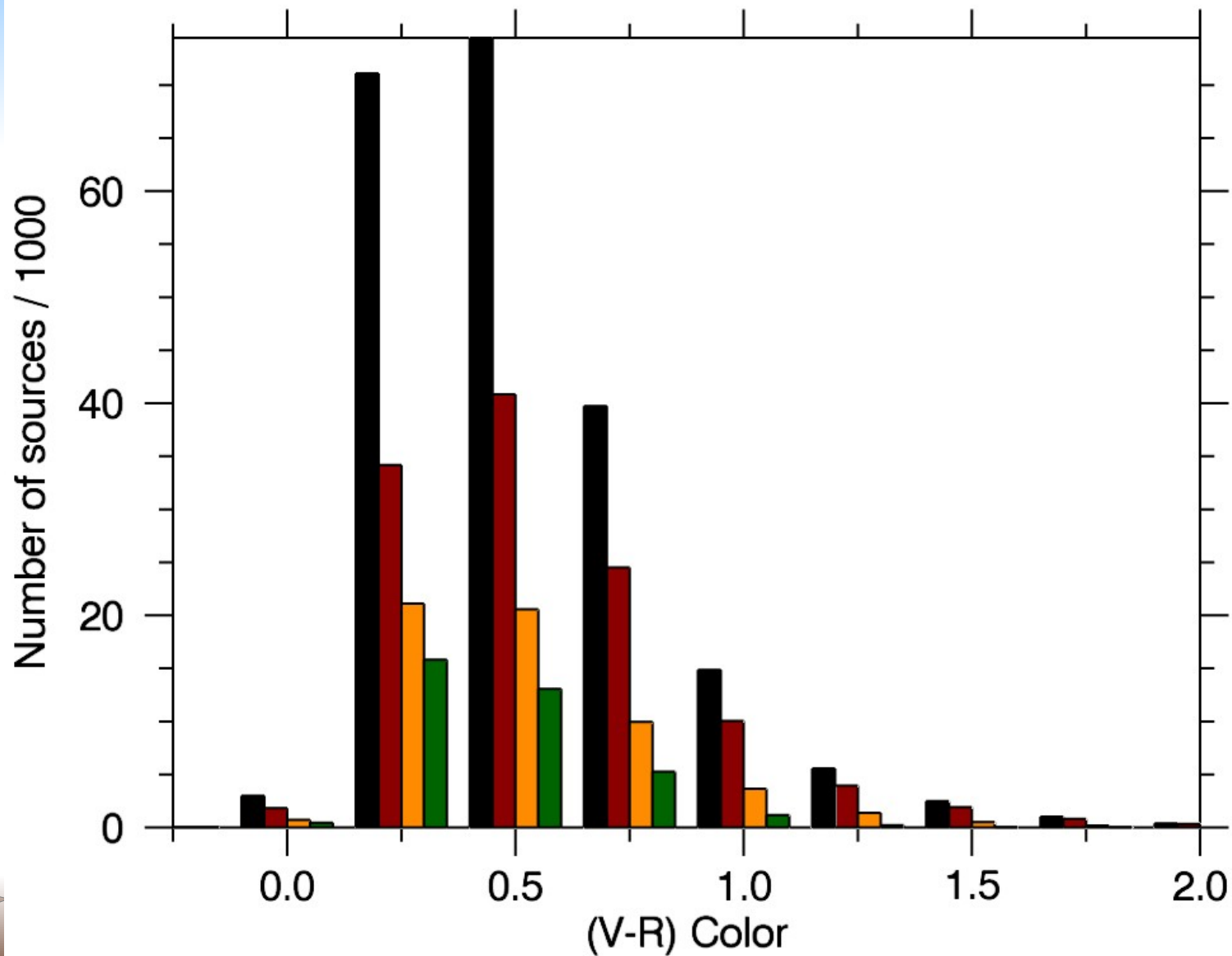
Positions of Sources Observed



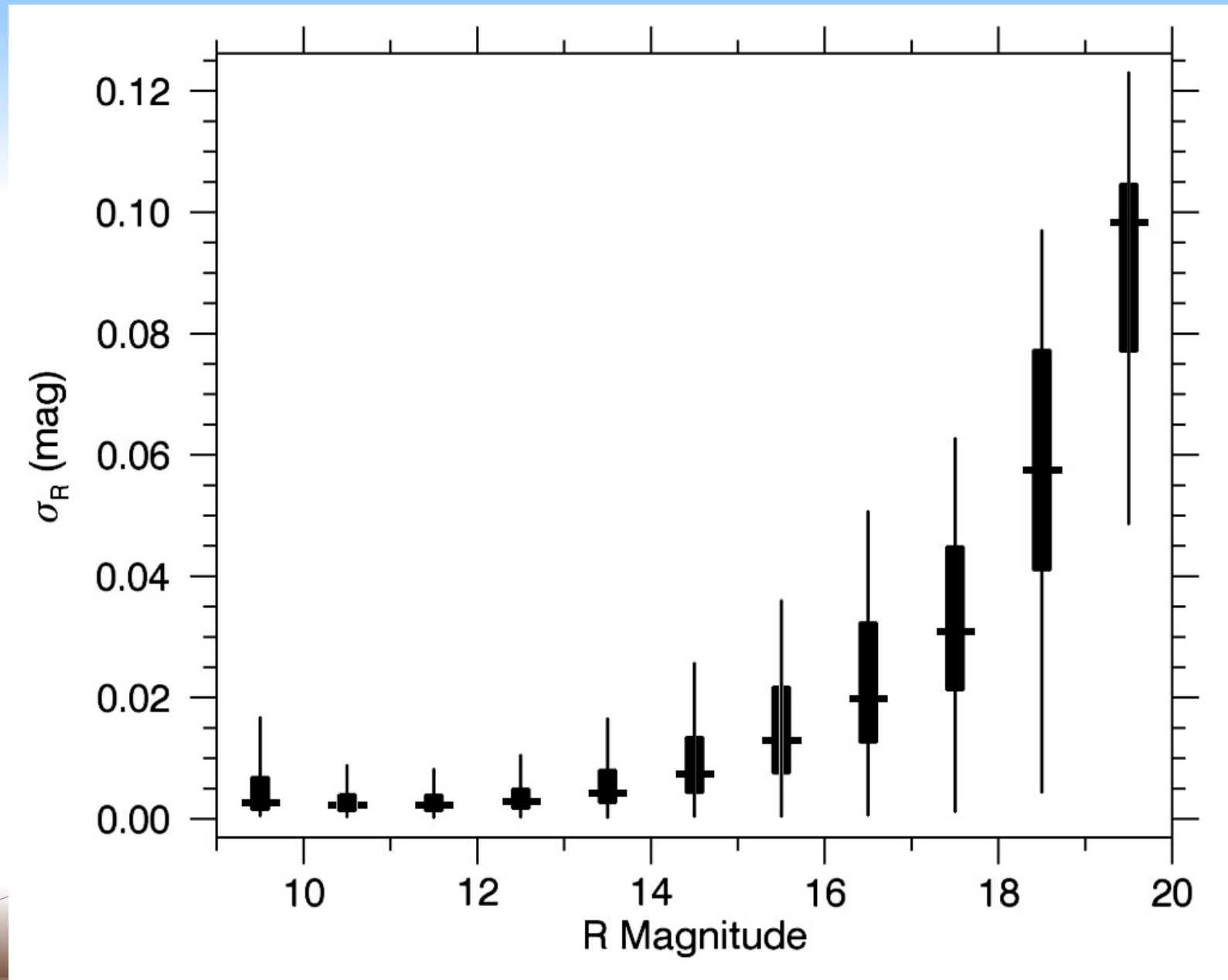
Range of R magnitude covered



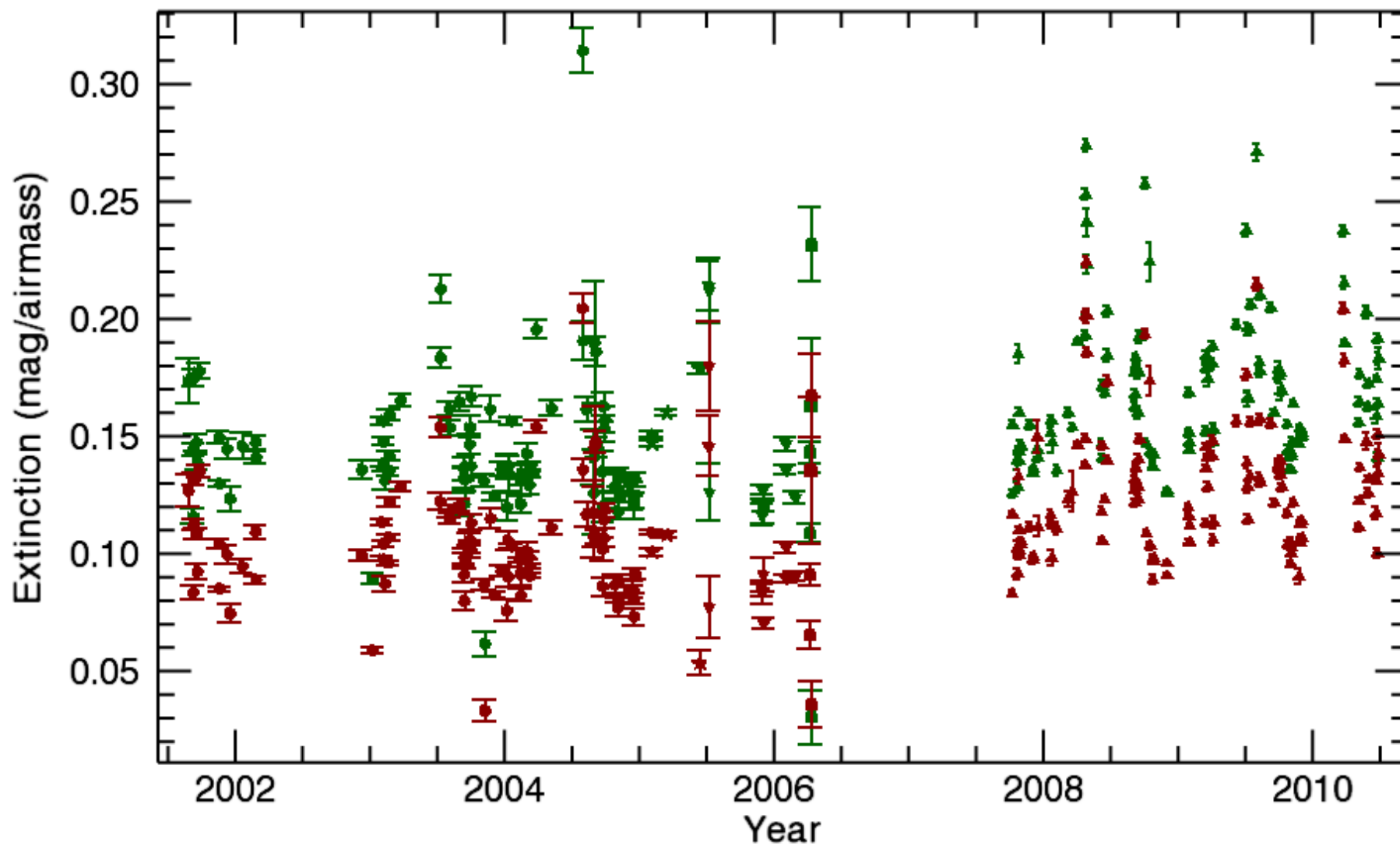
Distribution of V-R in Catalog



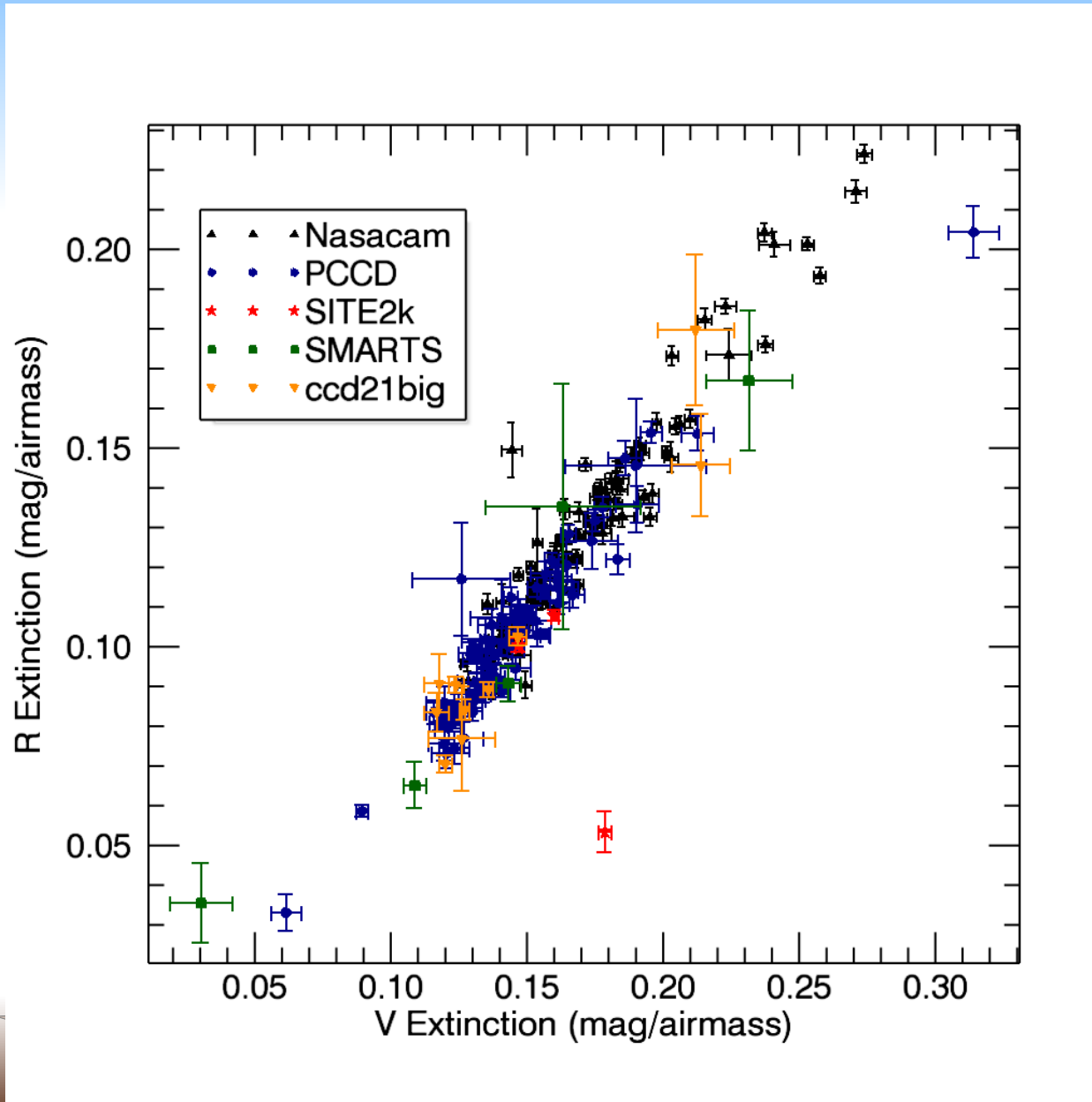
Distribution of Uncertainties in Catalog



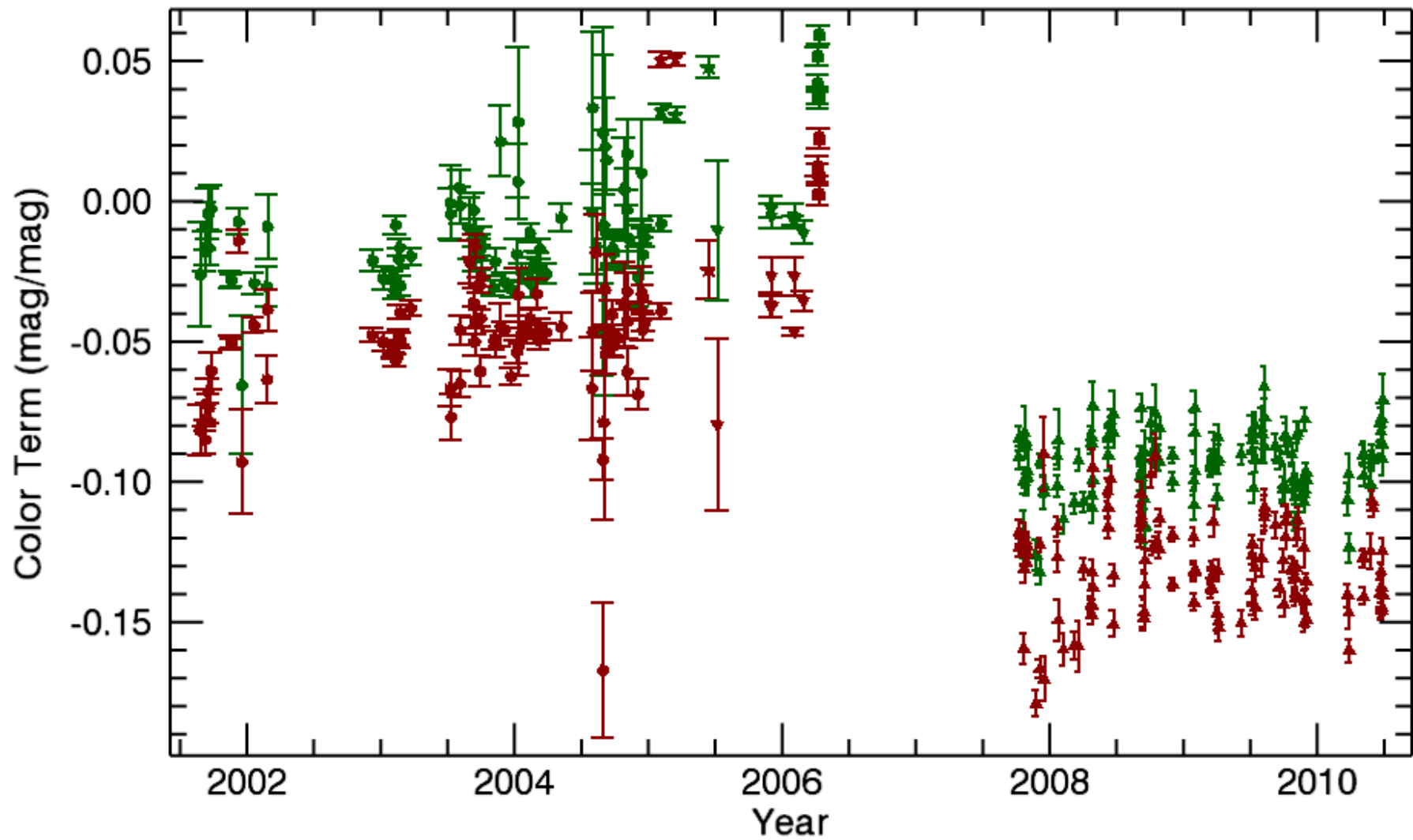
Extinction History



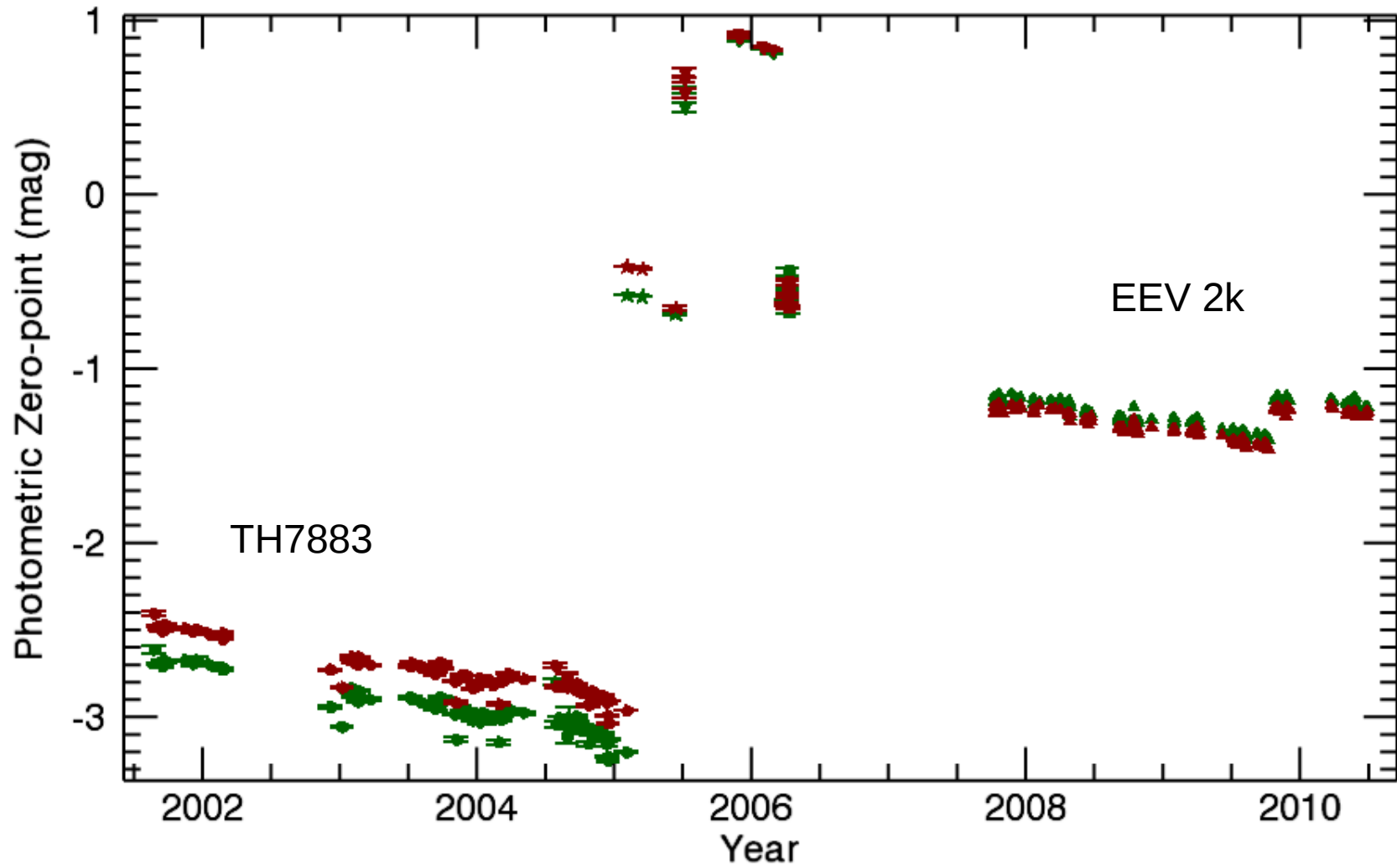
V and R extinction comparison



Color term history

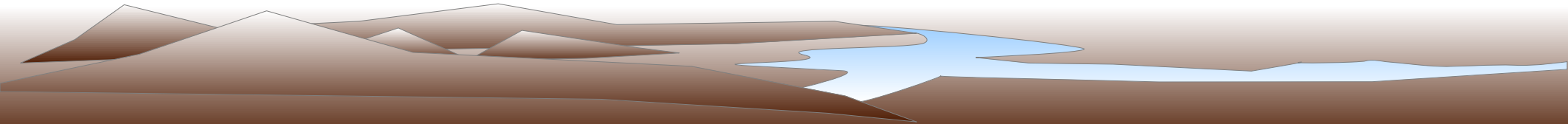


Zero-point history



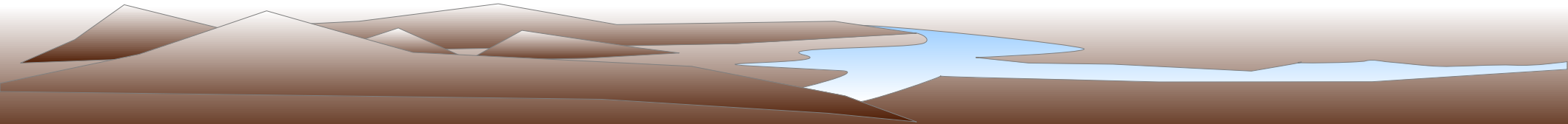
Pluto Monitoring

- ☪ Long-term photometric monitoring of the brightness and color of Pluto.
- ☪ B , V , and $B-V$ is most diagnostic in standard filters and observation record extends back to discovery
- ☪ 1935-2000 the $B-V$ color was constant
- ☪ In 2002 the color jumped from 0.87 to 0.96
- ☪ These observations provide crucial constraints on volatile migration on the surface of Pluto

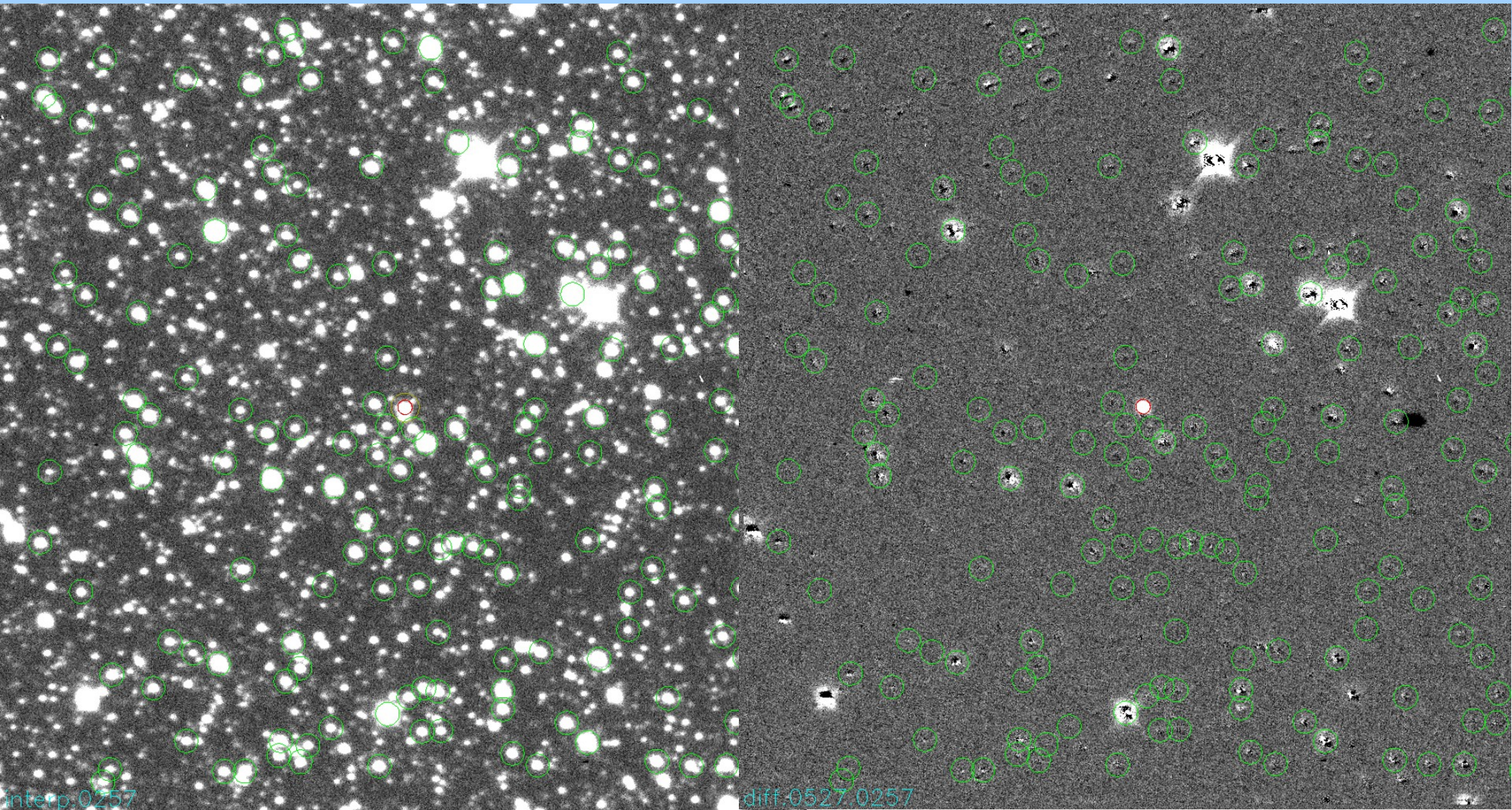


Pluto Monitoring, continued

- ☉ Rotation period 6.4 days
- ☉ Lightcurve affected by solar phase angle
- ☉ Orbital period is 240 year, this is a long-term project
- ☉ Current epoch is post-perihelion and the start of spring in the northern hemisphere. → epoch of maximum change
- ☉ Unfortunately, the galactic latitude of Pluto is very low and photometry is difficult



Sample Pluto Field (2010-05-25)



Pluto Monitoring, continued

- ☉ Each night is just one snippet of the lightcurve
- ☉ The best data come from a large number of nights over the course of one observing season
- ☉ Ideal project for robotic facilities, small amount of time each night.
- ☉ Lowell Observatory used for building a catalog of photometric calibrators
- ☉ Pluto observations at Lowell Obs. and Las Cumbres (FTS) with some help from NMSU 1m

