The Earthshine Project

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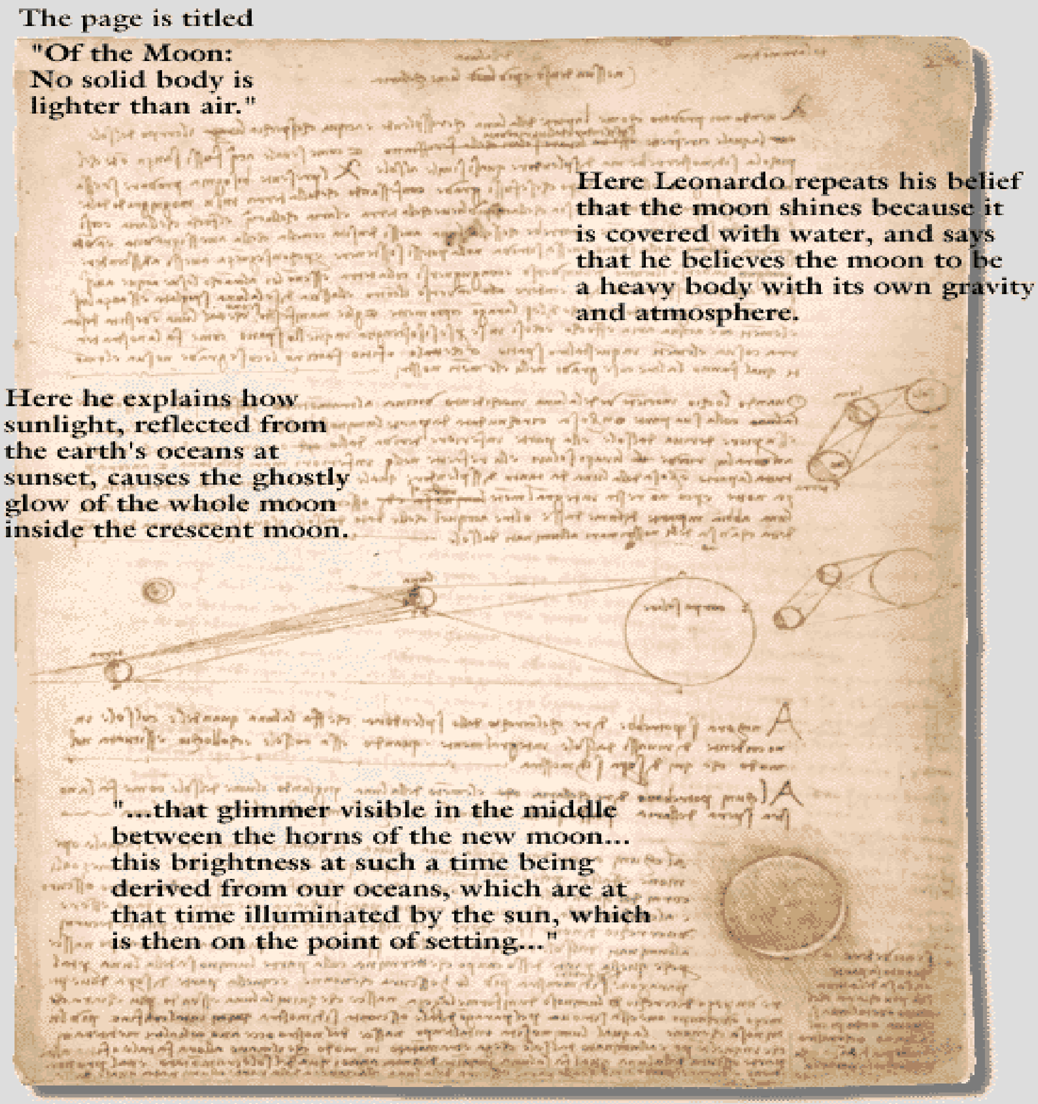
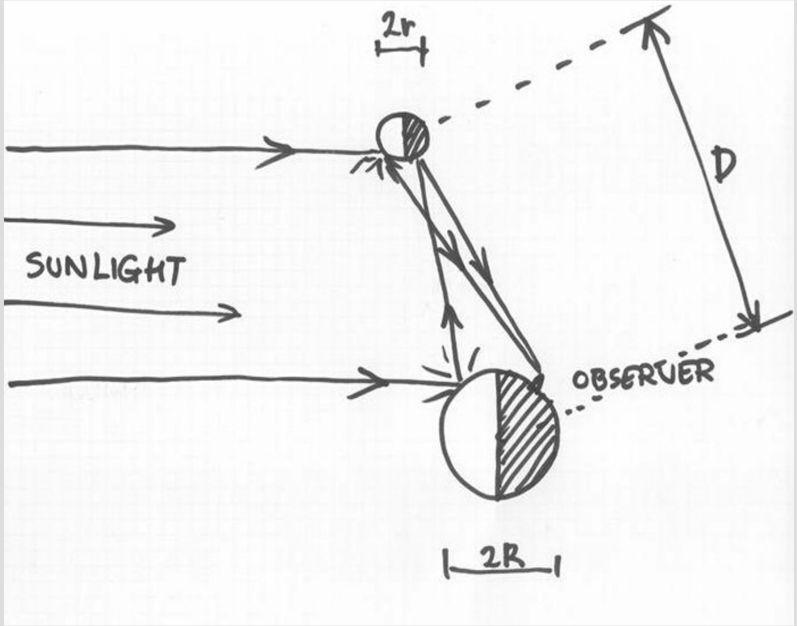
Leonardo da Vinci, c.1506

- da Vinci understood Earthshine as sunlight bouncing off Earth's oceans



Earthshine and Albedo

- Photometry of dark and bright side of the Moon
- The ratio is (more or less) Earth's albedo.
- Independent of solar irradiance, instrumental drift, atmospheric changes.

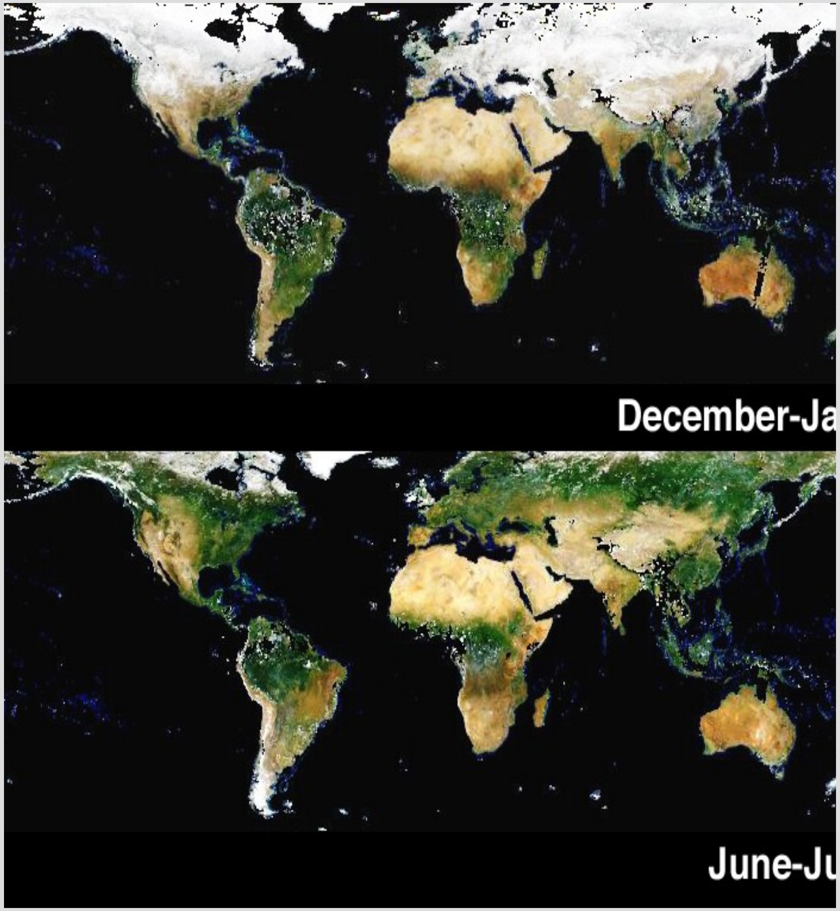


Albedo's influence

- A 1% change in albedo (e.g. from 0.300 to 0.303) forces climate by 2.4 W/m^2, which alters global mean T by 0.5 degrees C (BB case).

- Must therefore observe albedo better than to 1% - we hope to get to 0.1%.

Earth's albedo sans clouds



Lava: 0.04

Ocean: 0.05 (NOT 'specular reflection angle')

Swamps: 0.09-0.14

Leafy forest: 0.13

Bare soil: 0.05-0.4 (salt deserts brightest)

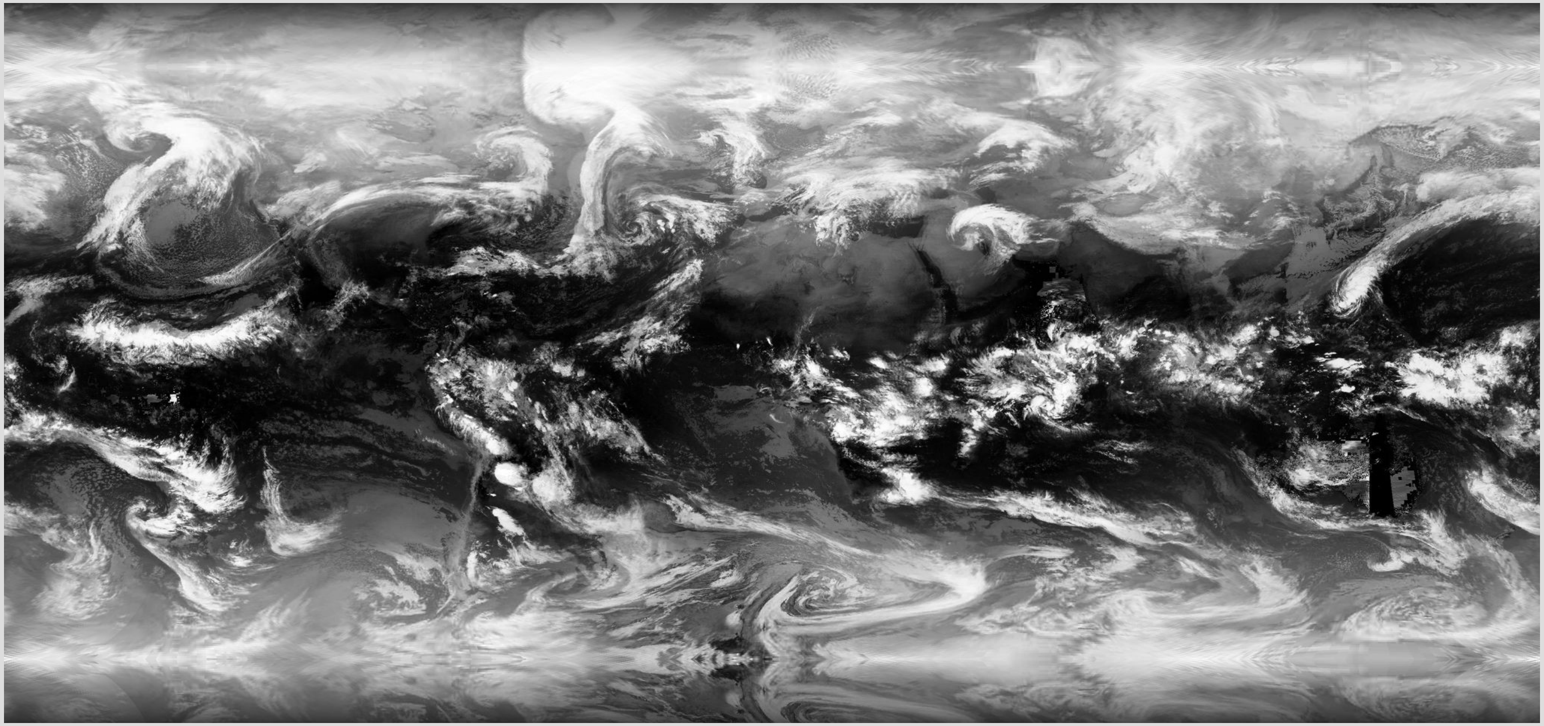
Grass: 0.2

Sand: 0.25-0.3

Ice: 0.3-0.8

Snow: up to 0.9

Albedo map with clouds



About half of Earth's albedo budget comes from cloud

thin cirrus : albedo < 0.01
thick fluffy clouds : up to 0.8 (like snow and ice)

Earthshine pioneers
Danjon and Dubois

- Danjon 1920s: cats-eye photometer various sites in France
- Dubois 1940s: also in France
- compared bright and dark sides to get a ratio (a good thing to do!)
- measured Earth's albedo with 5% accuracy (not so good!)

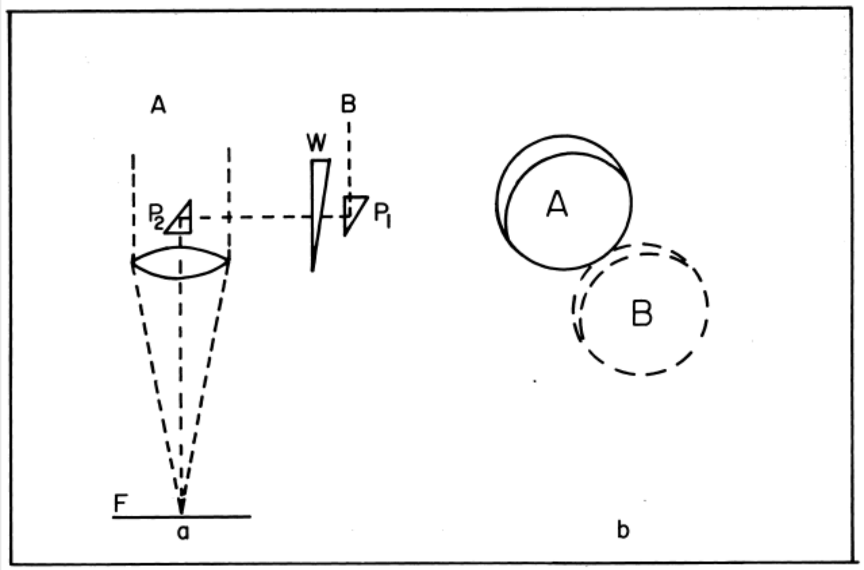
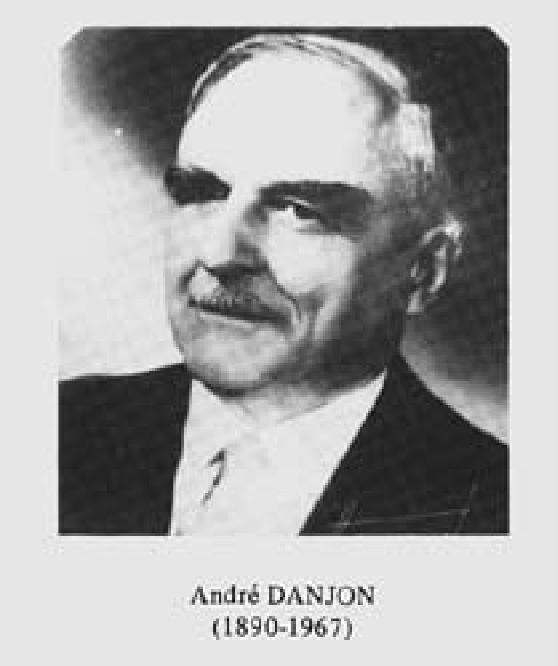


Figure 1.--Diagram of the Danjon-type photometer.

Pioneers - Danjon

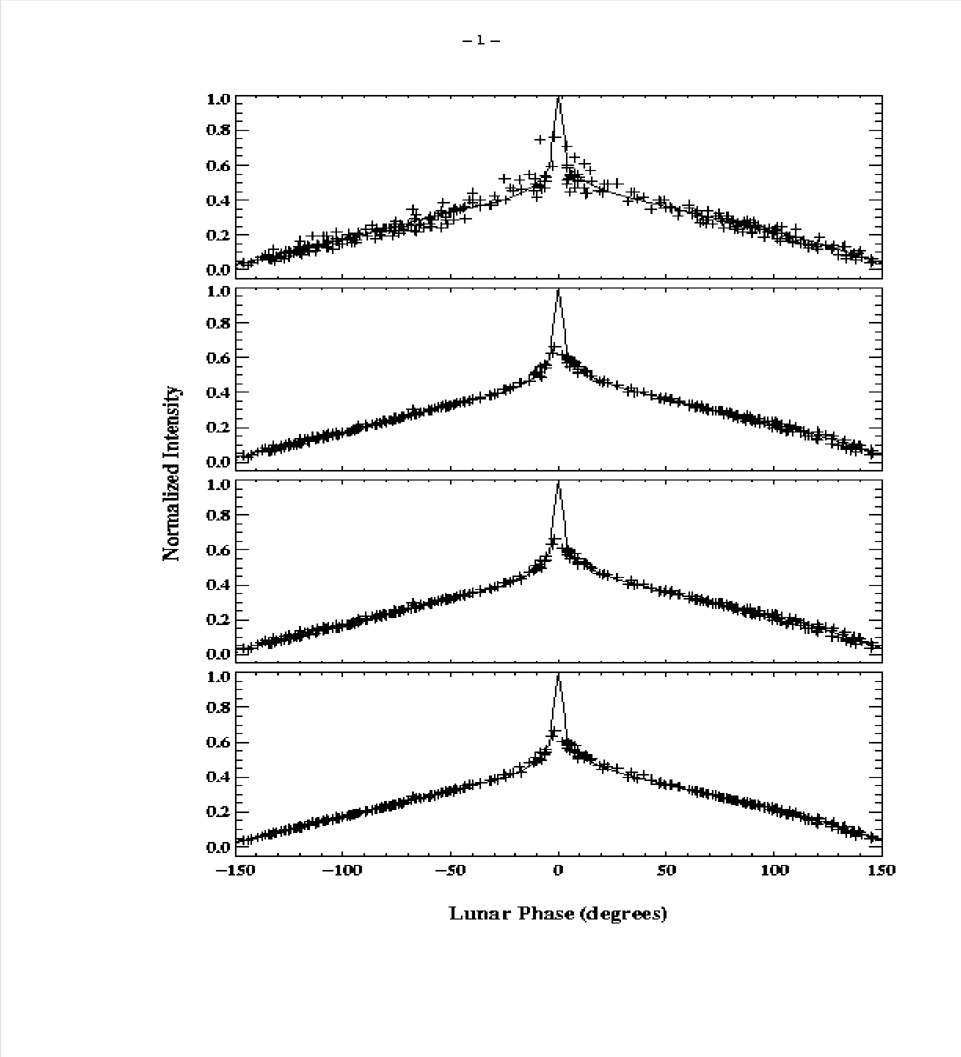
- Danjon showed that Earth's albedo *varies substantially* from night to night.
- He tried to correlate variation with cloud cover data, but was unable to do so,
- but did detect bright spot of specular reflection off oceans onto the Moon



Source: Observatoire de Paris

France is not enough

- Danjon/Dubois observed from France
- Earthshine seen from France is dominated by Eurasian landmass (which is bright compared to oceans
- obtained an albedo for Earth of 0.40,
- or 0.36 after correcting for Eurasia
- or 0.30 after 'opposition effect' removed



First global network

- Fred Whipple and Gustav Bakos, 1950s
- huge amount of work to do without computers
- 6 telescopes at satellite tracking stations
- Wisconsin, New Mexico, Hawaii, Australia, Peru, Iran
- Danjon cats-eye method
- confirmed 'Sun-glint'
- couldn't prove correlation of cloud cover with Earthshine

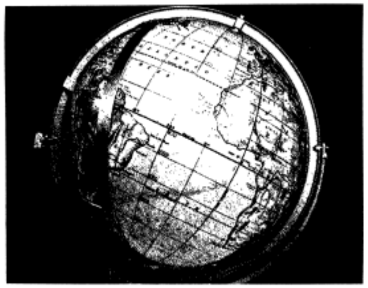


Figure 4.--A view of the earth from the moon as it would have been on May 2, 1959, at 09 31 UT, with a sublunar point of 21°W -4° and a subsolar point of 324°W $+15^\circ$. This photograph was made at the Yerkes Observatory.

Bakos, G. SAO Special Report #162 (1964)

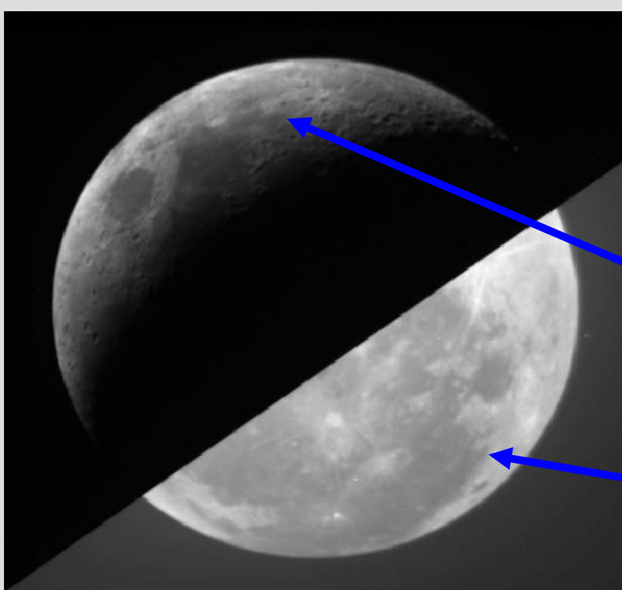
They slept on the Moon

- Further long term earthshine studies did not take place until after humans had looked at earthlight while standing on the moon

Big Bear Earthshine Project

Koonan, Goode and Palle made Earthshine measurements from Big Bear Solar Observatory during 1995-1996 and 1999-2003

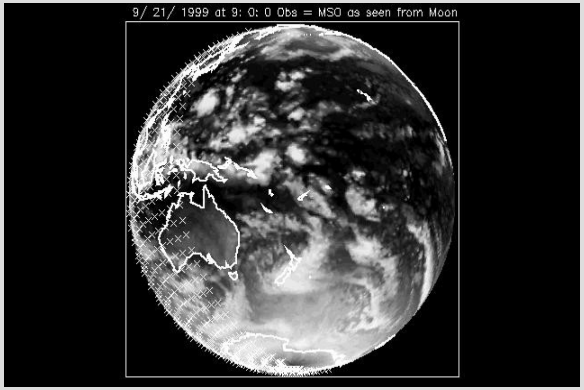
Small refractor, CCD, masks and accurately timed shutter

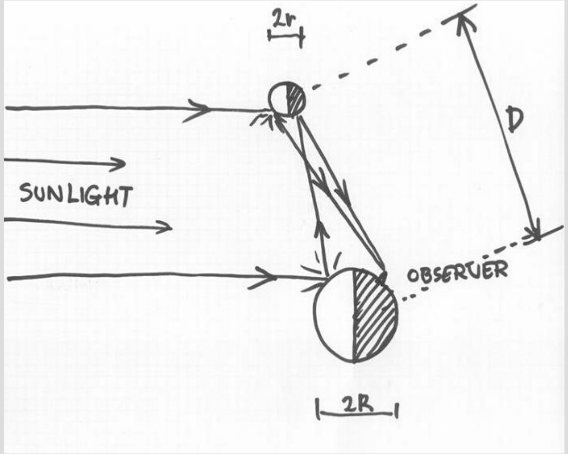


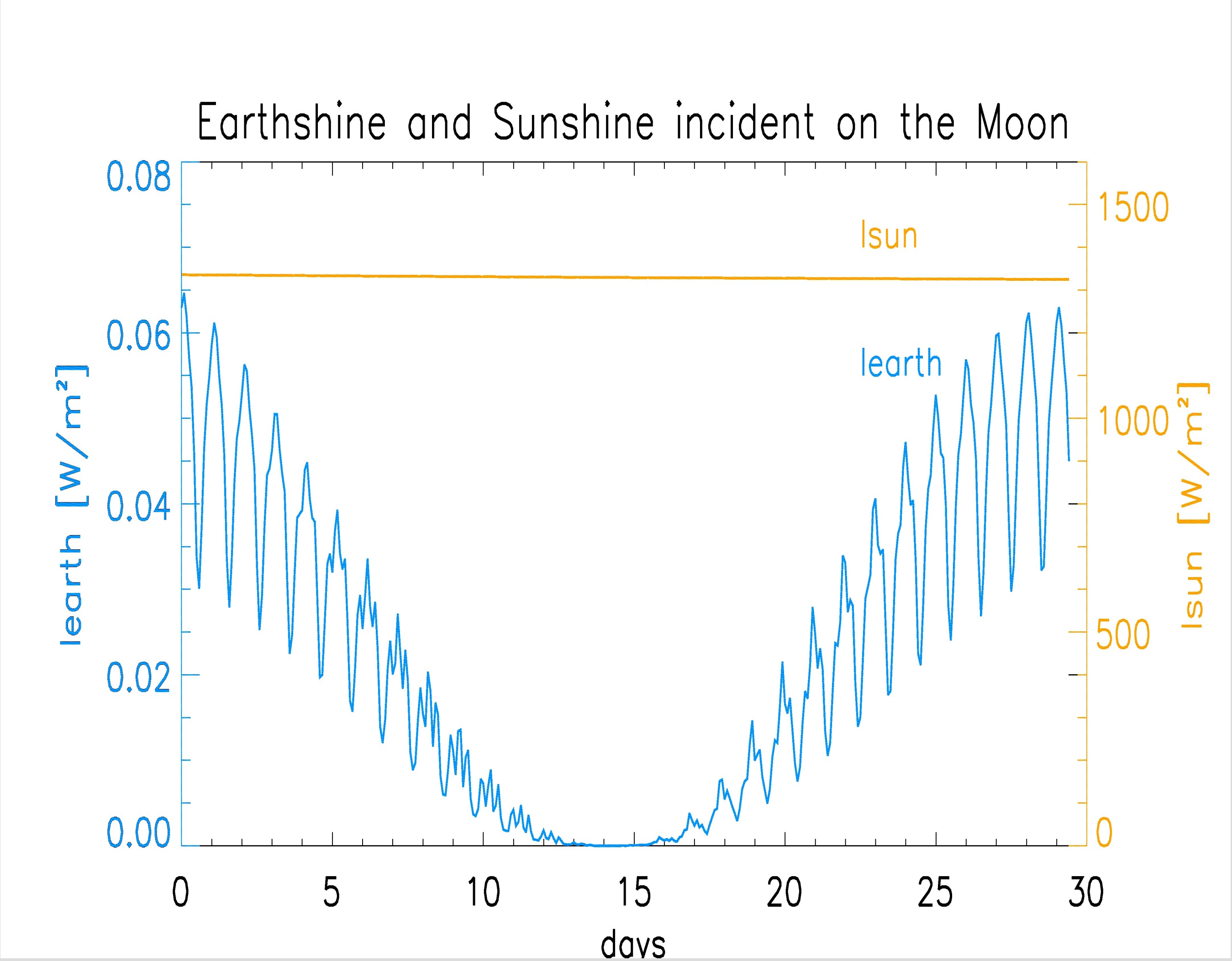
Bright side

Dark side

Simulated Earthshine







It works!

Each Earthshine observation gives information about the Earth's albedo from a particular part of the surface (shown as light areas)

Several telescopes, at different longitudes and latitudes are a must for global coverage

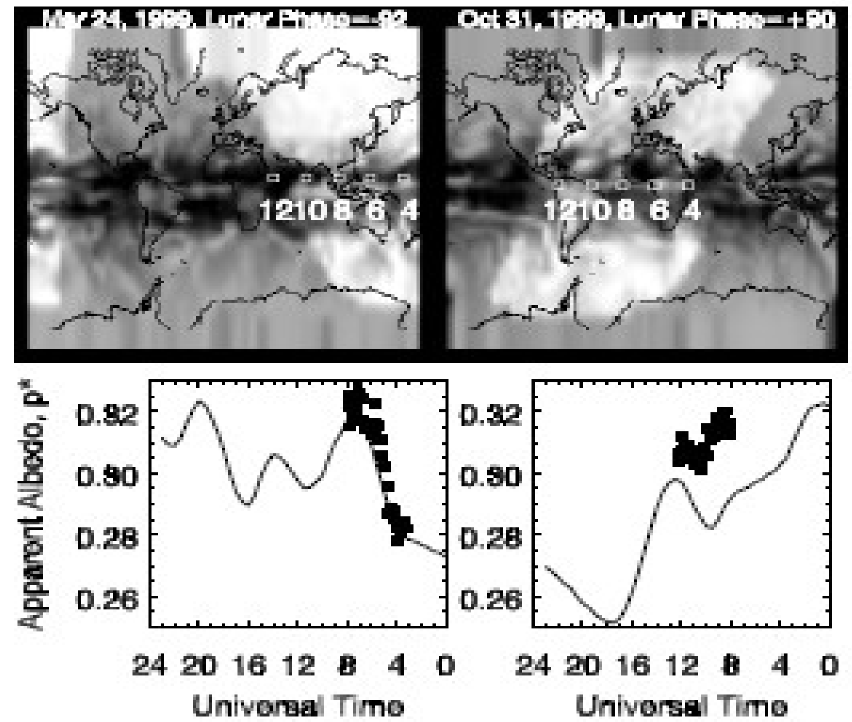
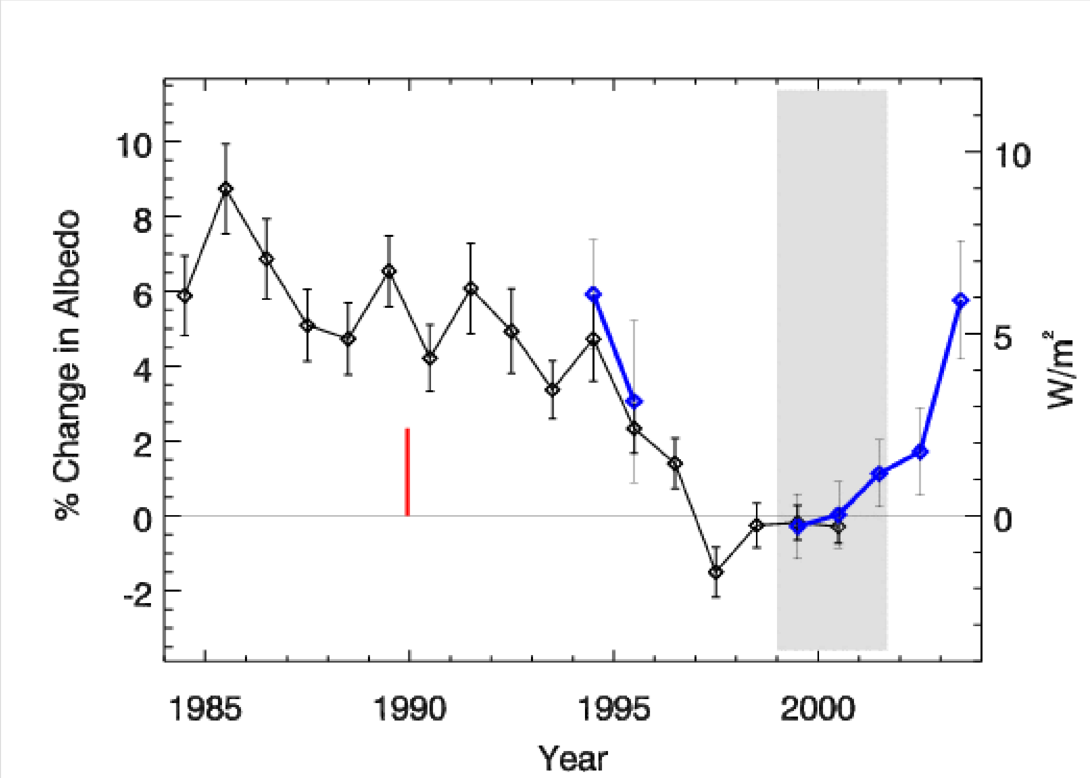


Figure 1. (top) Extended bright areas highlighting those parts of the Earth that are the source of the earthshine. The satellite-derived WSI cloud cover maps are shown in a secondary gray scale, with brighter areas indicating greater cloud cover. For 31 October 1999, note that the northernmost regions are not sunlit, and the southernmost regions do not contribute to earthshine because the Moon is fairly far north in the sky. The empty white boxes indicate the longitudes of maximal contribution to the earthshine at the UT shown. (bottom) Solid boxes show the observed apparent albedo as a function of time (note that the time axis is reversed), while the solid line indicates the simulated p^* values for the night.

Palle et al 2004, *Science, 304, 1299*

BBSO Earthshine match to satellite proxy

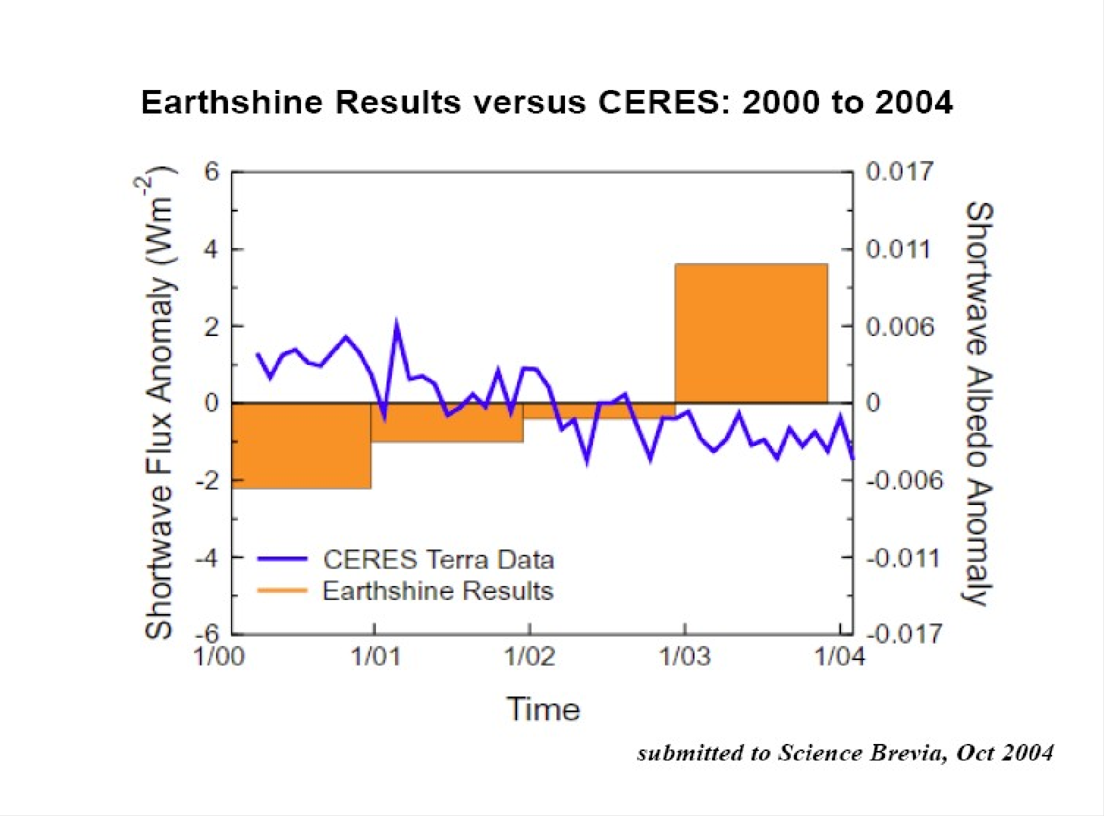


Big Bear Earthshine project results 1990s and 2000s

Follows satellite (ISCCP) reconstruction of Earth's reflectance

Could climate forcing have changed by 5 W/m^2 – it's an awfully large amount!

Conflict with satellite data



CERES – Cloud and Earth's Radiant Energy System
Satellite monitoring of Earth radiation budget (short and long wavelength = optical/IR and FIR)

Earthshine BBSO

Why do this from the ground?

- it's much cheaper than satellites
- one can monitor for decades with easily duplicated instrumentation – the Moon will be there 100 years from now
- independent of atmospheric changes, instrumental drift in satellites, solar irradiance

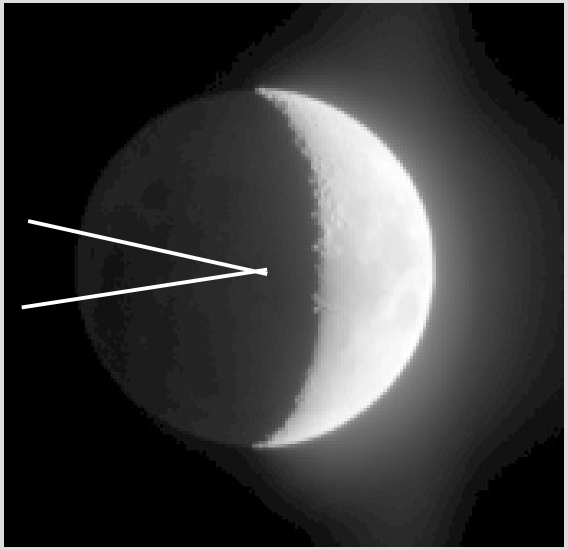
Grove Creek 2006

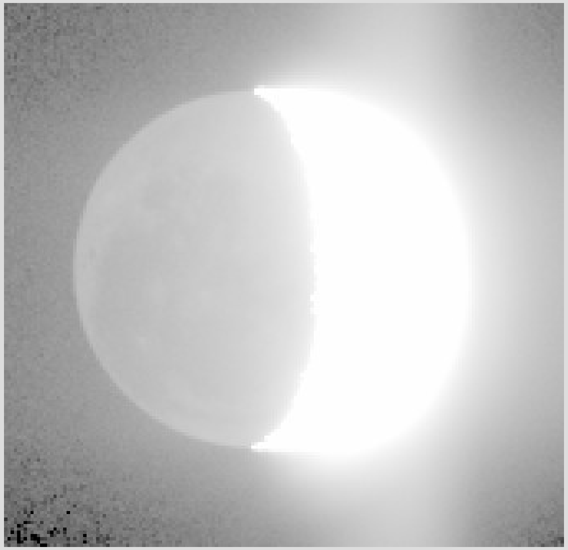
Andrew Mattingly working at Grove Creek near Sydney

- 100 mm reflector borrowed from local telescope shop
- 12" f/10 Meade LX200 + 0.5X focal reducer + ST8XME camera

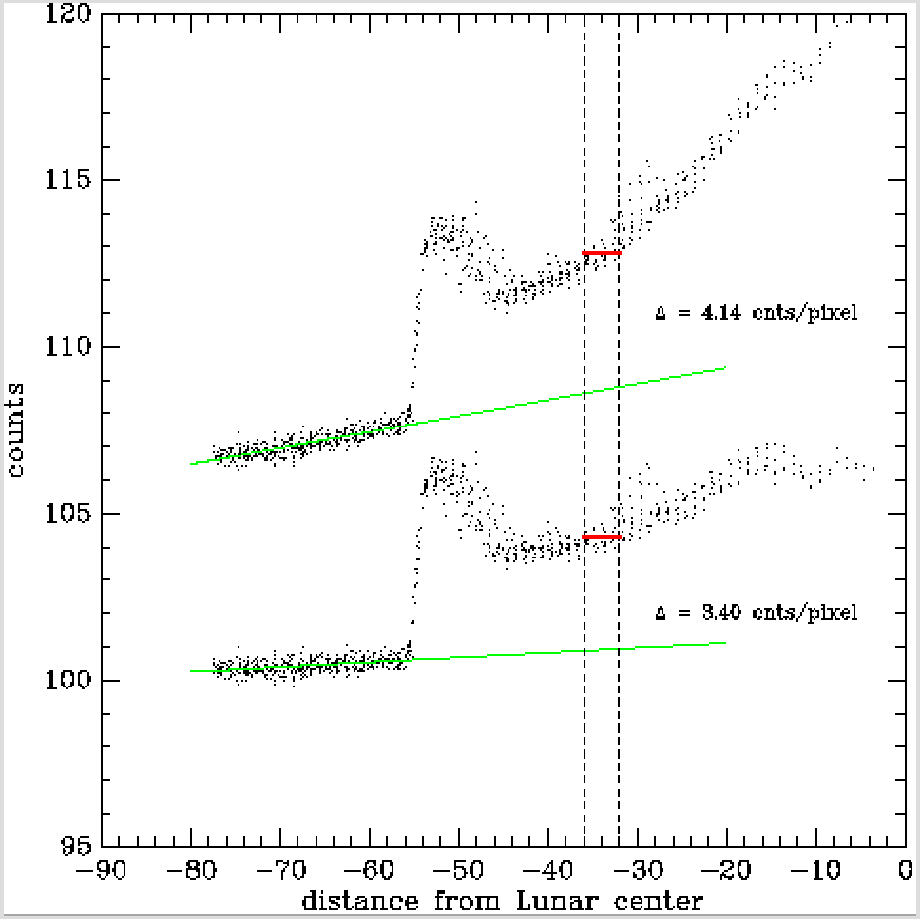
- choice of clear, Johnson B, V, R or BATC-9 filters

Grove Creek : 350 coadded short exposures





350 x 0.02 sec exposures

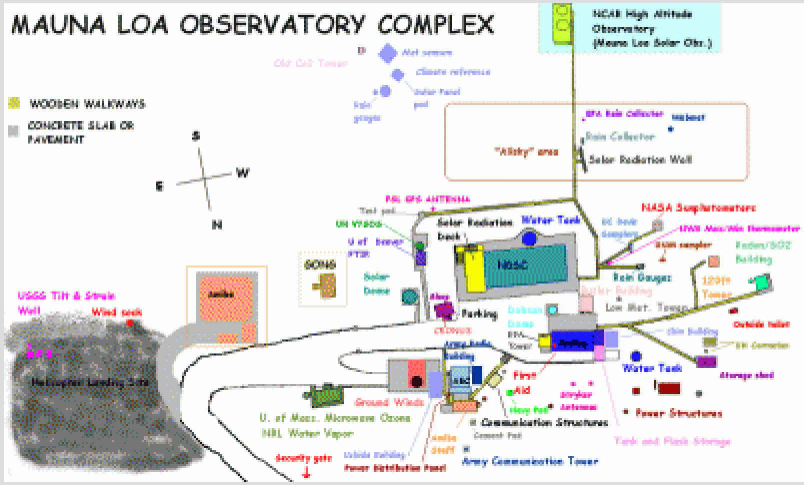


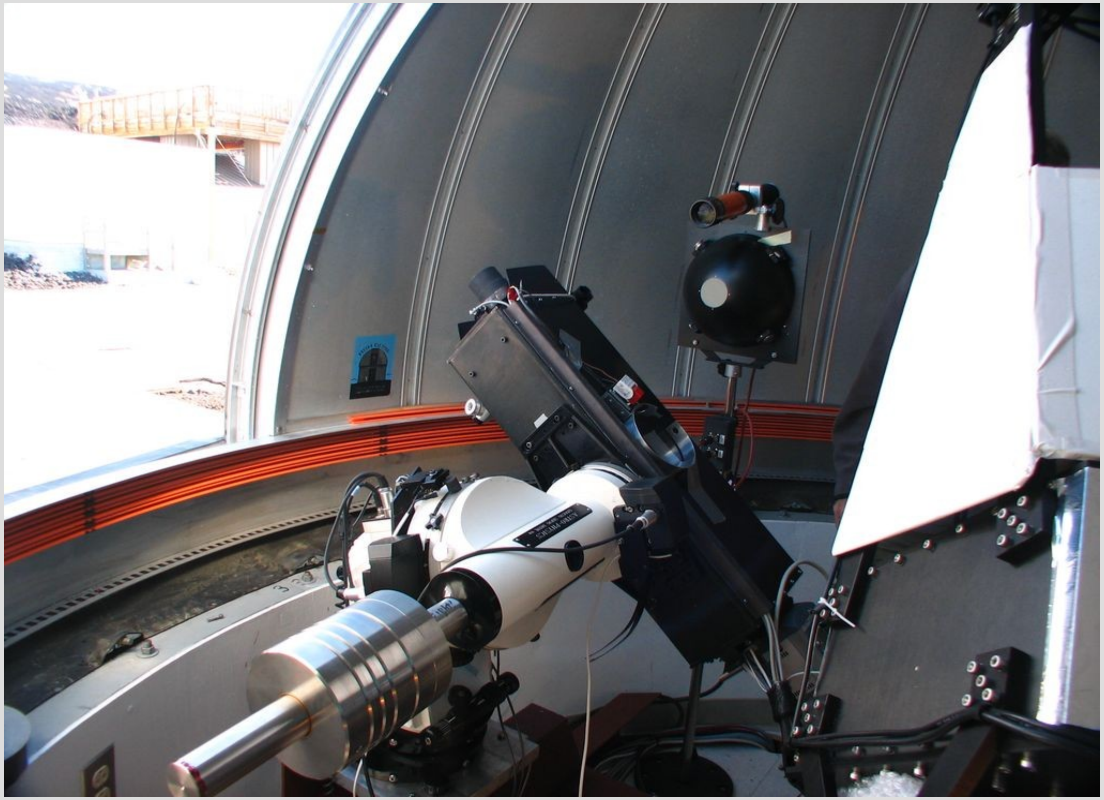
Background removal only good to 15%

Earthshine project overview

- 2003/2004: Pilot project, finished
- 2007-2010: Design and construct prototype automatic telescope(s) 500,000 euros funding (VINNOVA)
- May 2011 – telescope shipped to Mauna Loa, Hawaii
- September 2011-present : telescope and instrumentation calibration and observing earthshine
- Currently testing short, coadded exposures to measure ES

The Lund Earthshine Telescope





Optical layout

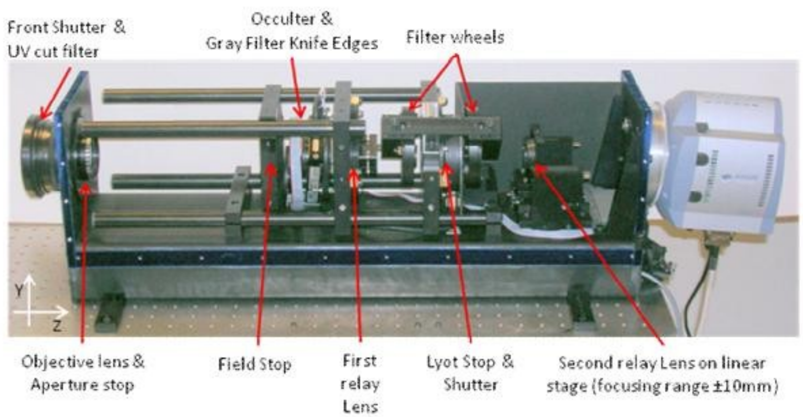


Figure 4. Photo of the Lund Earthshine telescope without cover.

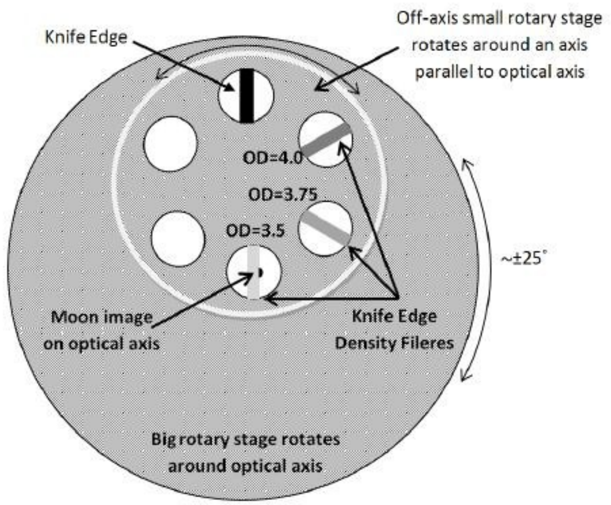


Figure 5. Diagram of the electro-mechanical system for selecting the knife edges using two rotary stages.

4 cm f12.5 refractor

0.9 degree Field-of-View

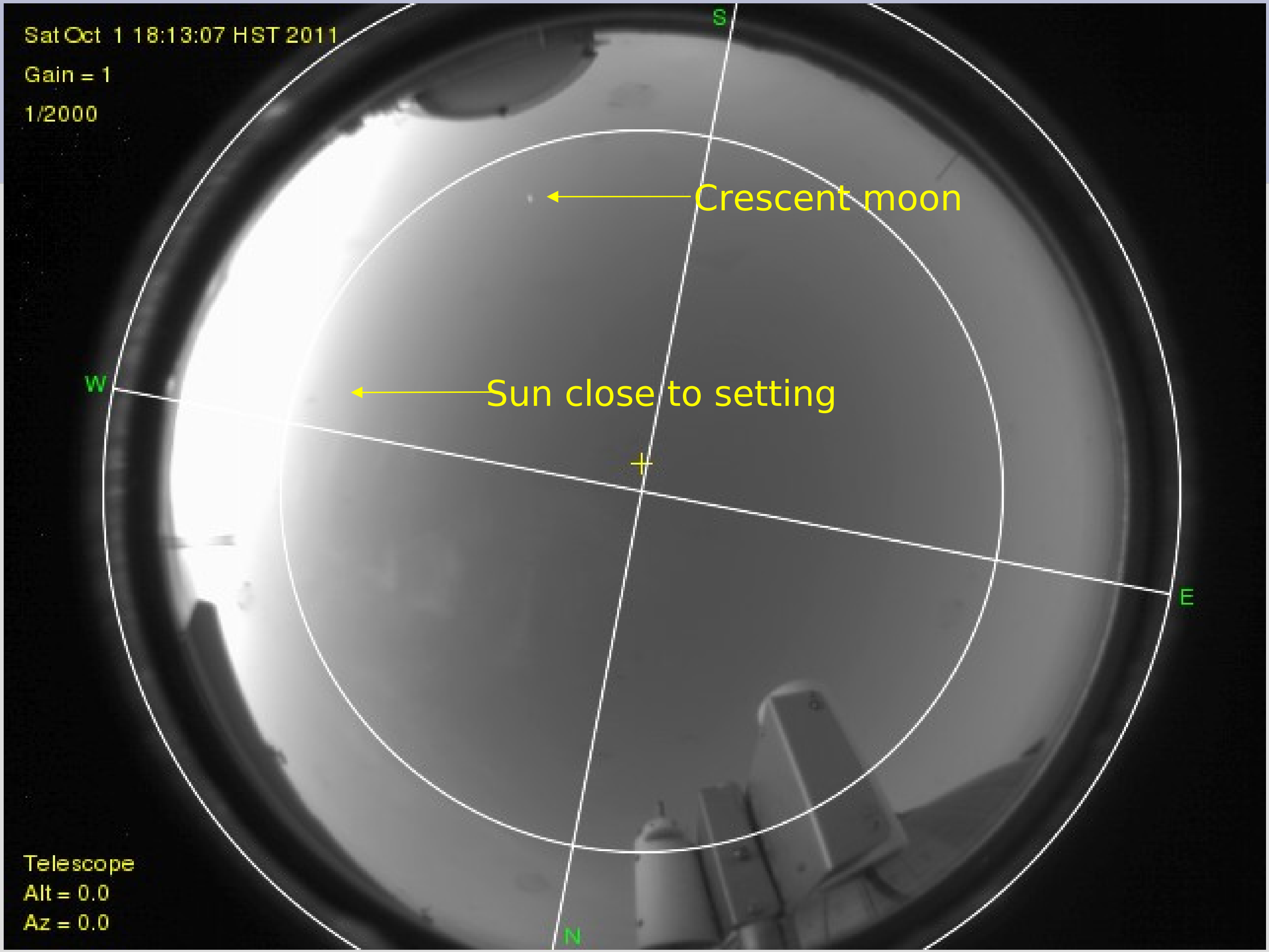
back-illuminated 512x512 CCD

7 arcsec / pixel

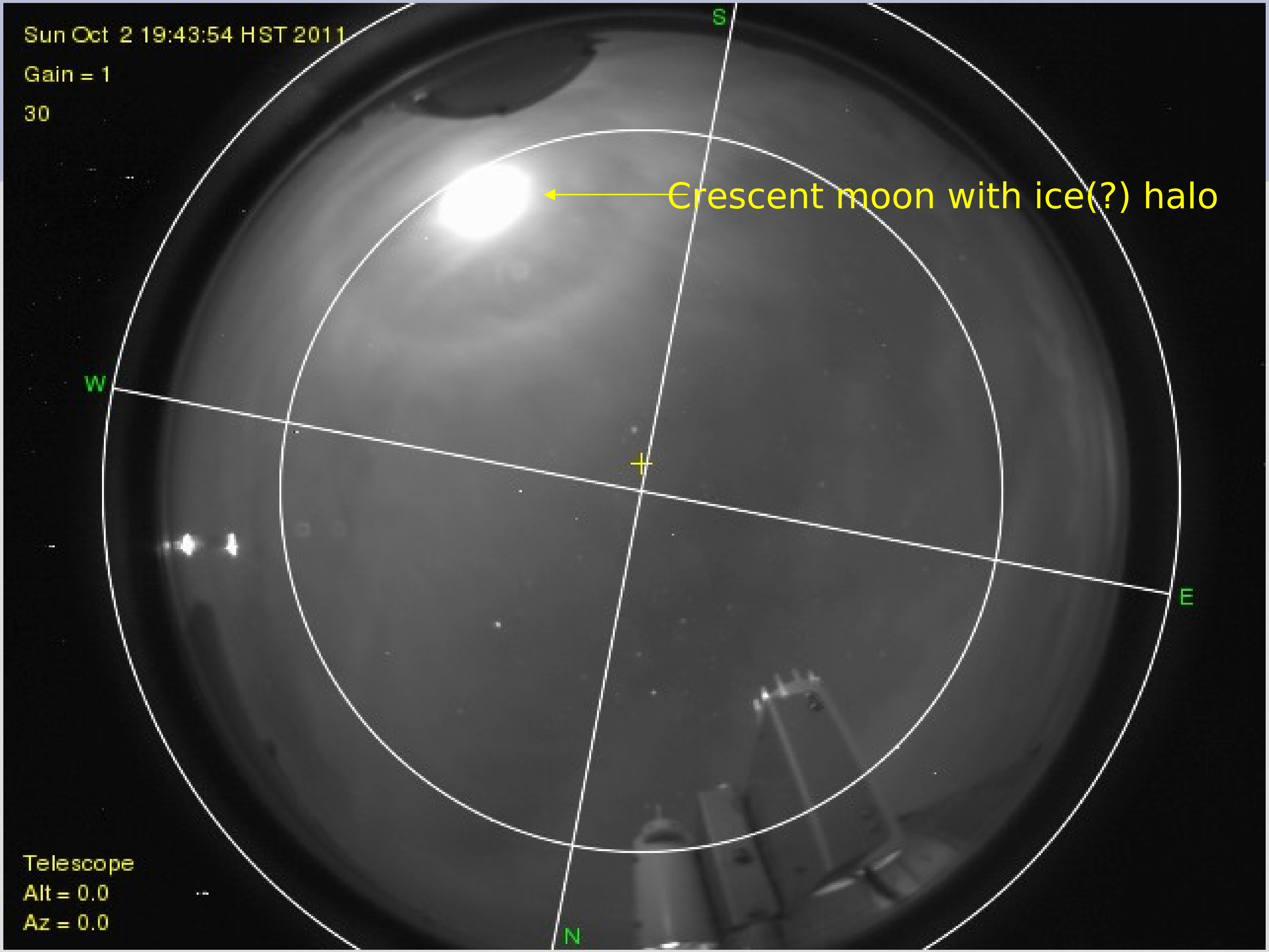
Filters: B, V, VE1, VE2, IRCUT

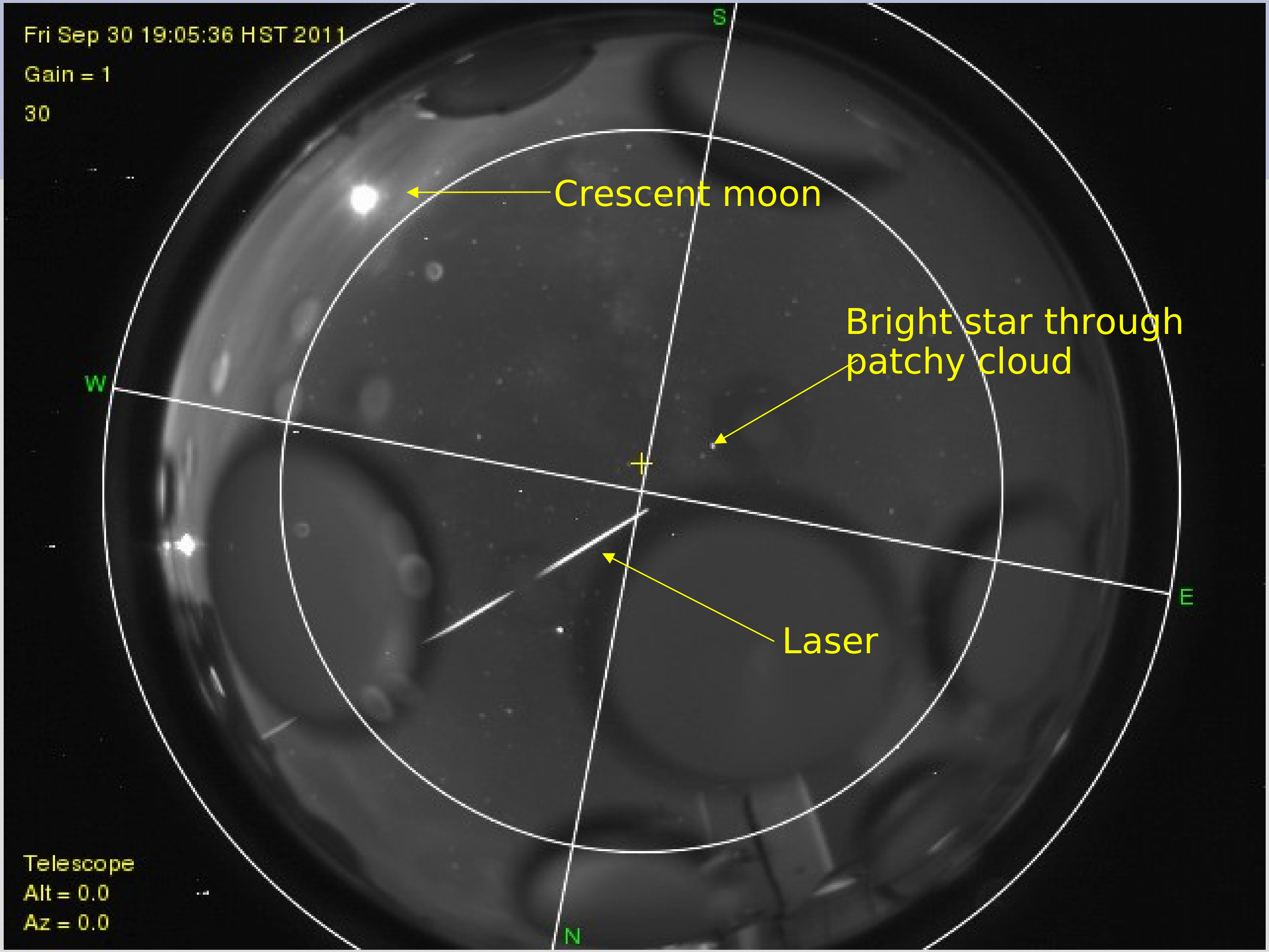
Knife edge

Neutral density filters

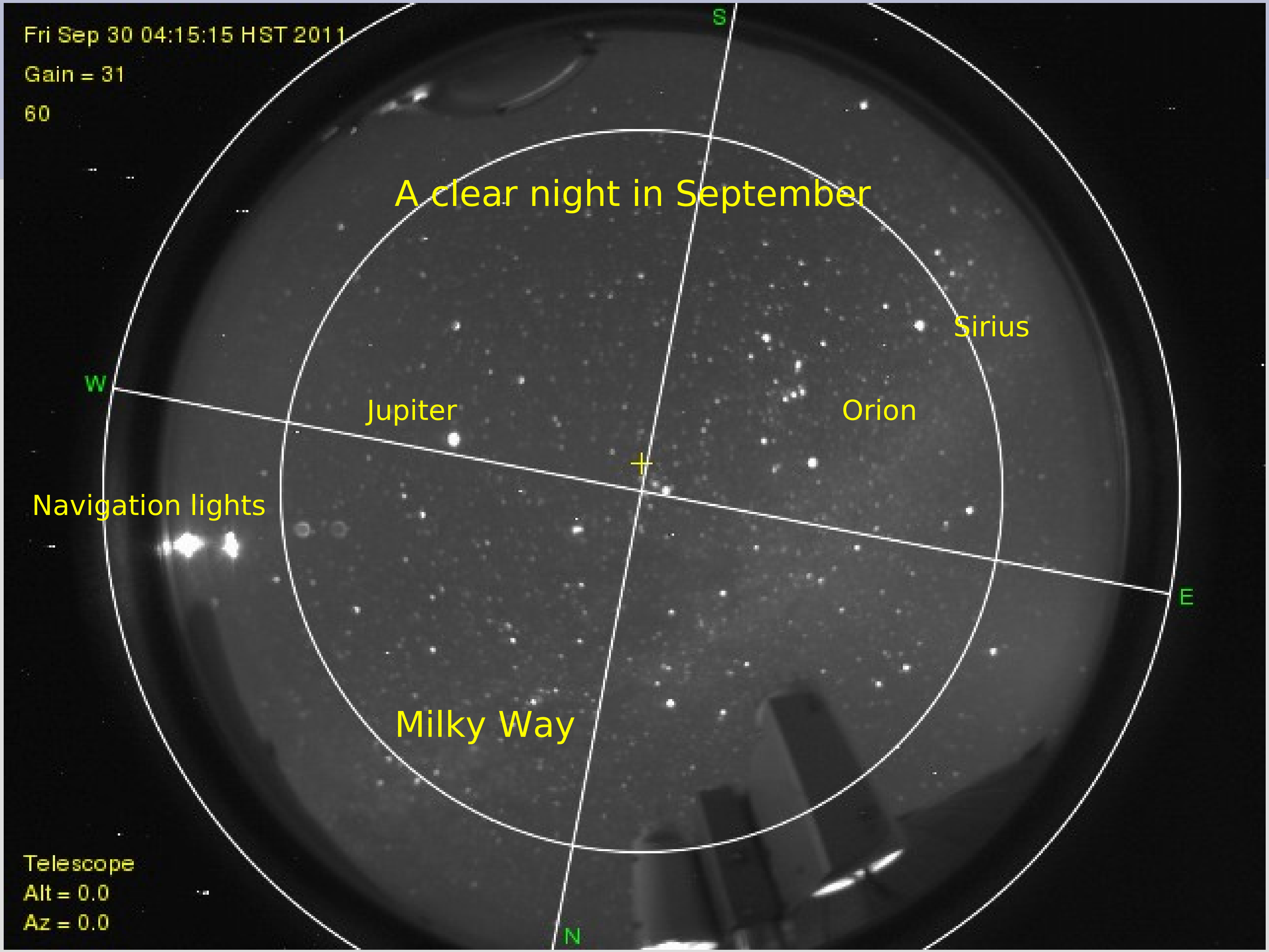

Sat Oct 1 18:13:07 HST 2011
Gain = 1
1/2000
S
W
E
N
Crescent moon
Sun close to setting
Telescope
Alt = 0.0
Az = 0.0

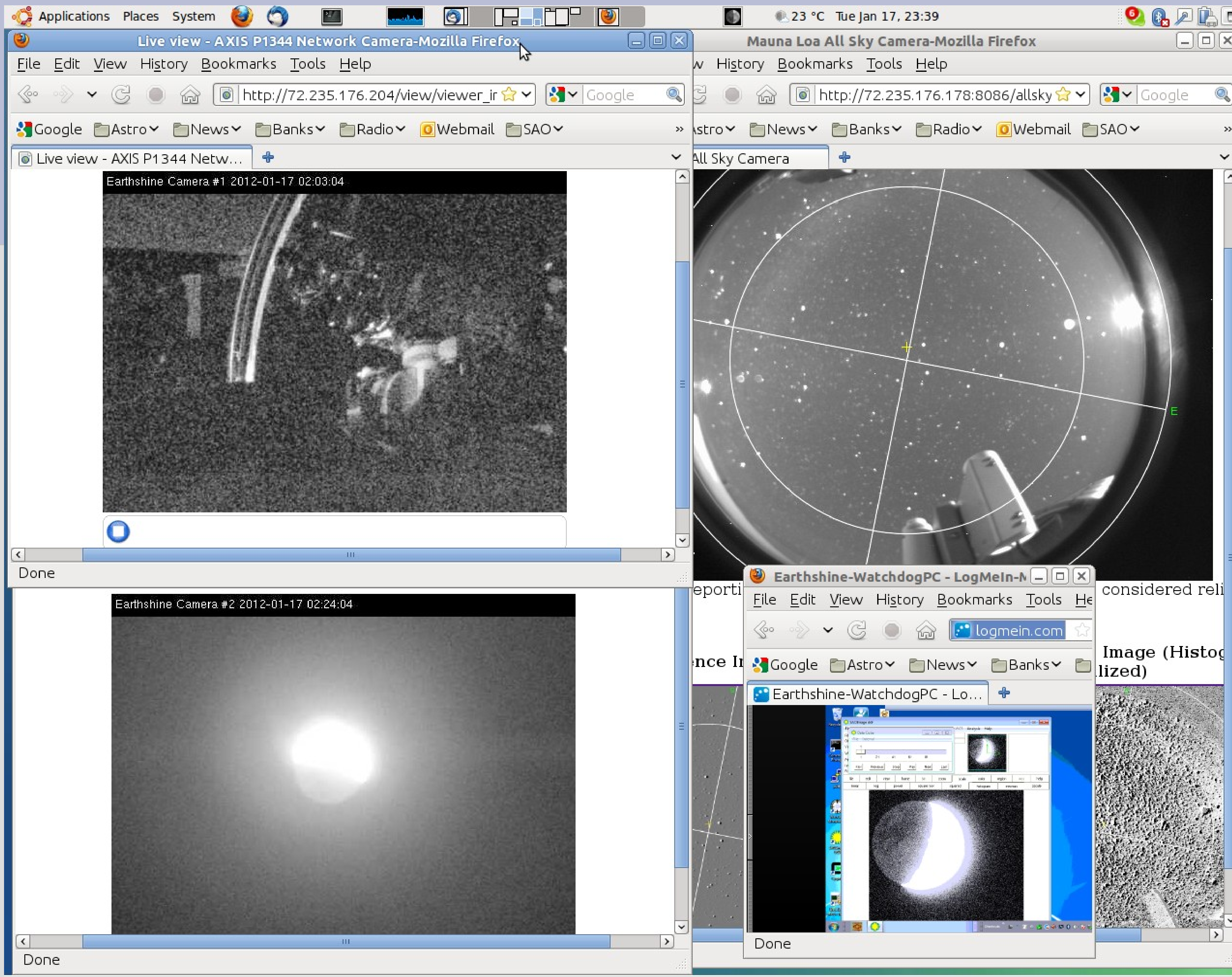

Fri Sep 30 16:38:56 HST 2011
Gain = 1
1/2000
A rainy day in September
S
W
E
N
Telescope
Alt = 0.0
Az = 0.0


Sun Oct 2 19:43:54 HST 2011
Gain = 1
30
S
W
E
N
Crescent moon with ice(?) halo
Telescope
Alt = 0.0
Az = 0.0



Fri Sep 30 19:05:36 HST 2011
Gain = 1
30
S
W
E
N
Crescent moon
Bright star through patchy cloud
Laser
Telescope
Alt = 0.0
Az = 0.0


Fri Sep 30 04:15:15 HST 2011
Gain = 31
60
S
A clear night in September
Sirius
W
Jupiter
Orion
Navigation lights
E
Milky Way
Telescope
Alt = 0.0
Az = 0.0
N


Applications Places System
23 °C Tue Jan 17, 23:39
Live view - AXIS P1344 Network Camera-Mozilla Firefox
File Edit View History Bookmarks Tools Help
http://72.235.176.204/view/viewer_ir
Google Astro News Banks Radio Webmail SAO
Live view - AXIS P1344 Netw...
Earthshine Camera #1 2012-01-17 02:03:04
Done
Earthshine Camera #2 2012-01-17 02:24:04
Done
Mauna Loa All Sky Camera-Mozilla Firefox
History Bookmarks Tools Help
http://72.235.176.178:8086/allsky
All Sky Camera
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Earthshine-WatchdogPC - LogMeIn-M
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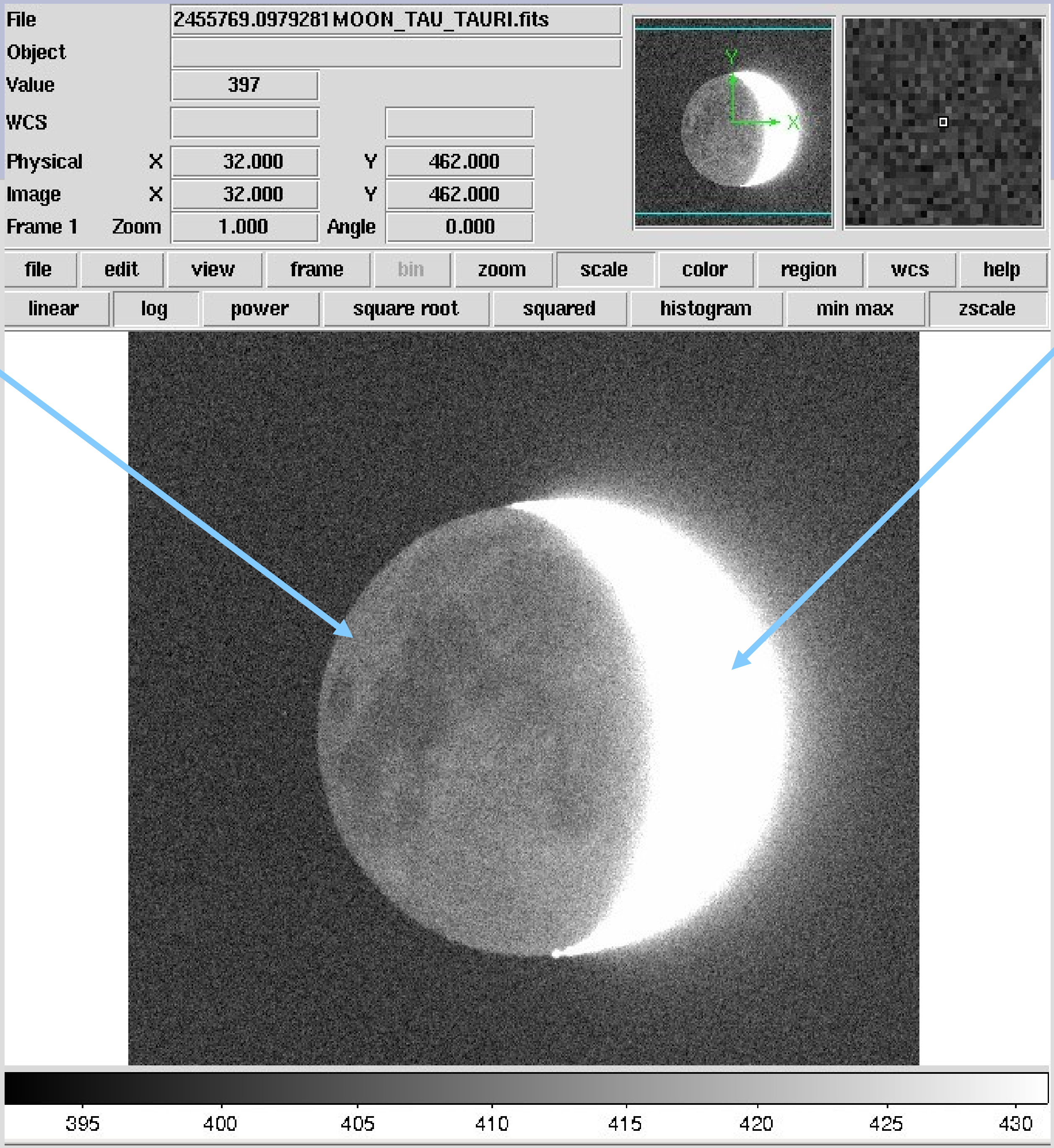
logmein.com
Google Astro News Banks
Earthshine-WatchdogPC - Lo...
Done

Data!

Earthshine

~10 counts per pixel



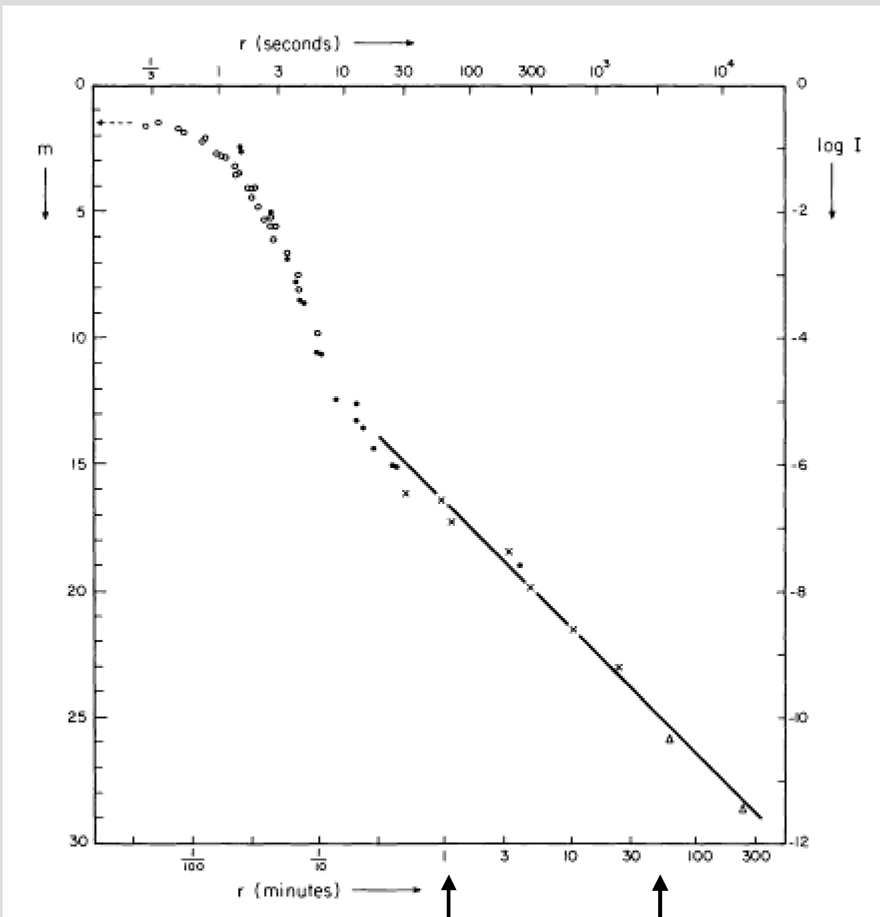
Bright side

~50,000 photons per pixel

30 millisec exposure in V

Stellar PSF at very large angle

Palomar Schmidt, King (1971)



1 minute **1 degree**

$PSF \sim r^{-\alpha}$

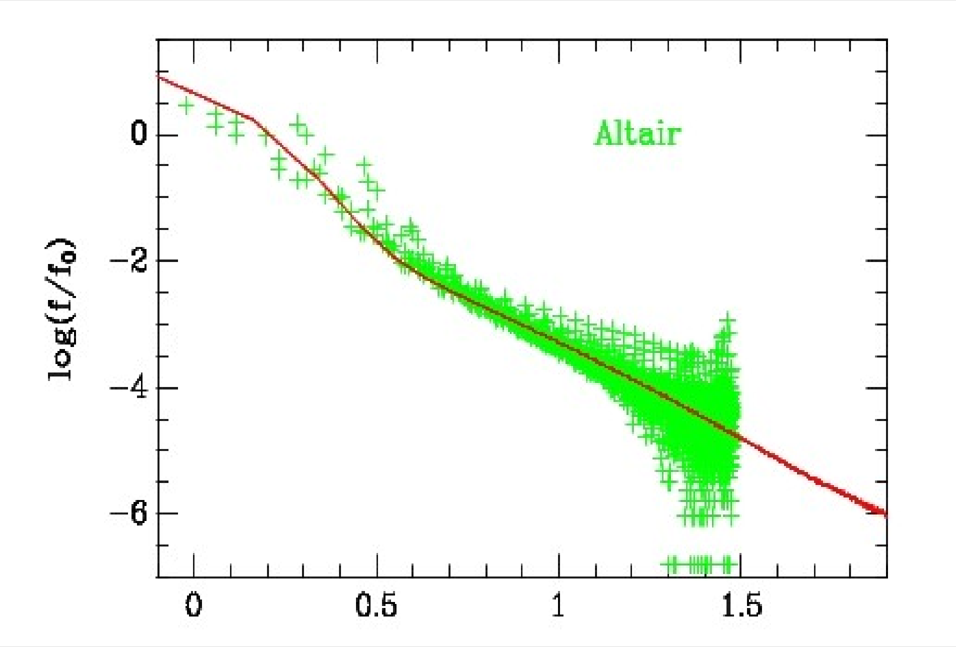
Typical values for the power-law fall off of the PSF are on a wide range of telescopes are

Telescope	α
Palomar 48” Schmidt	-2
McDonald 0.9m	-1.7
La Palma 2.5m	-3.5
Calar Alto 1.23m	-1.6
KPNO 0.9m	-2
KPNO 0.6m	-2
LCO 2.5m	-2.7

Source Bernstein (2007)

Scattered light and the telescope PSF

Altair (hundreds of coadded frames)

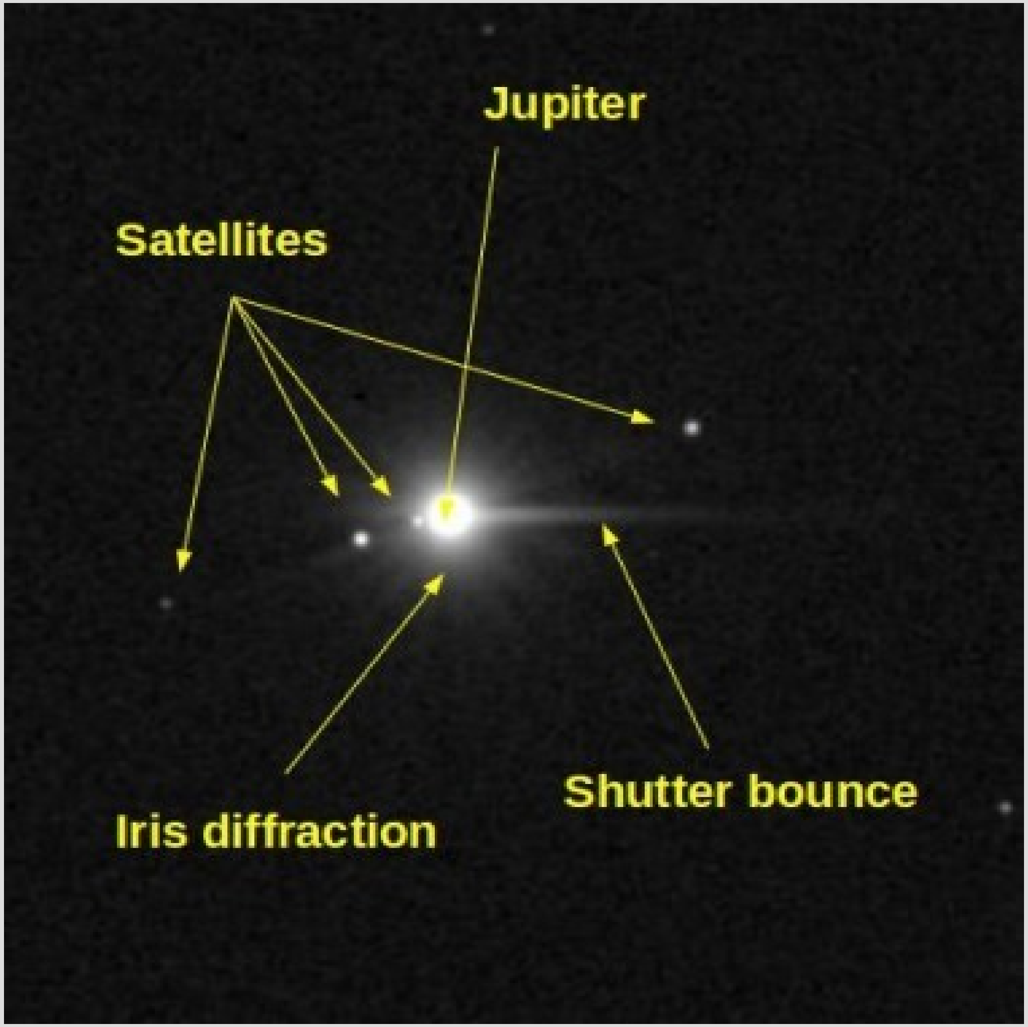


Log (r/pixels)

Almost full moon (dozens of coadded frames)

$\boldsymbol{PSF \sim r^{-2.8}}$

Jupiter and the PSF

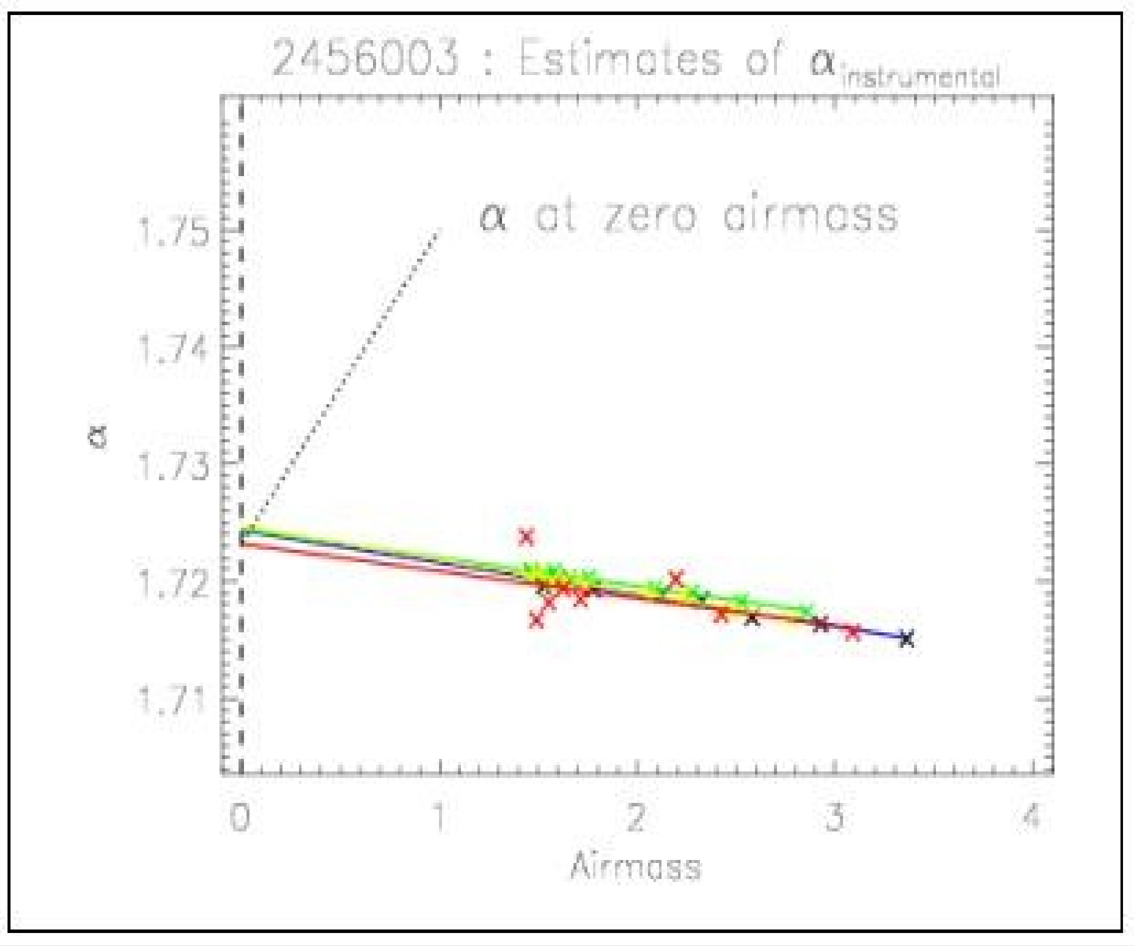


Jupiter is very bright, making the PSF at large distances easier to measure than with stars

But it's not a point source so it gets complicated!

But observations with Jupiter confirm the power law fall off at large angle

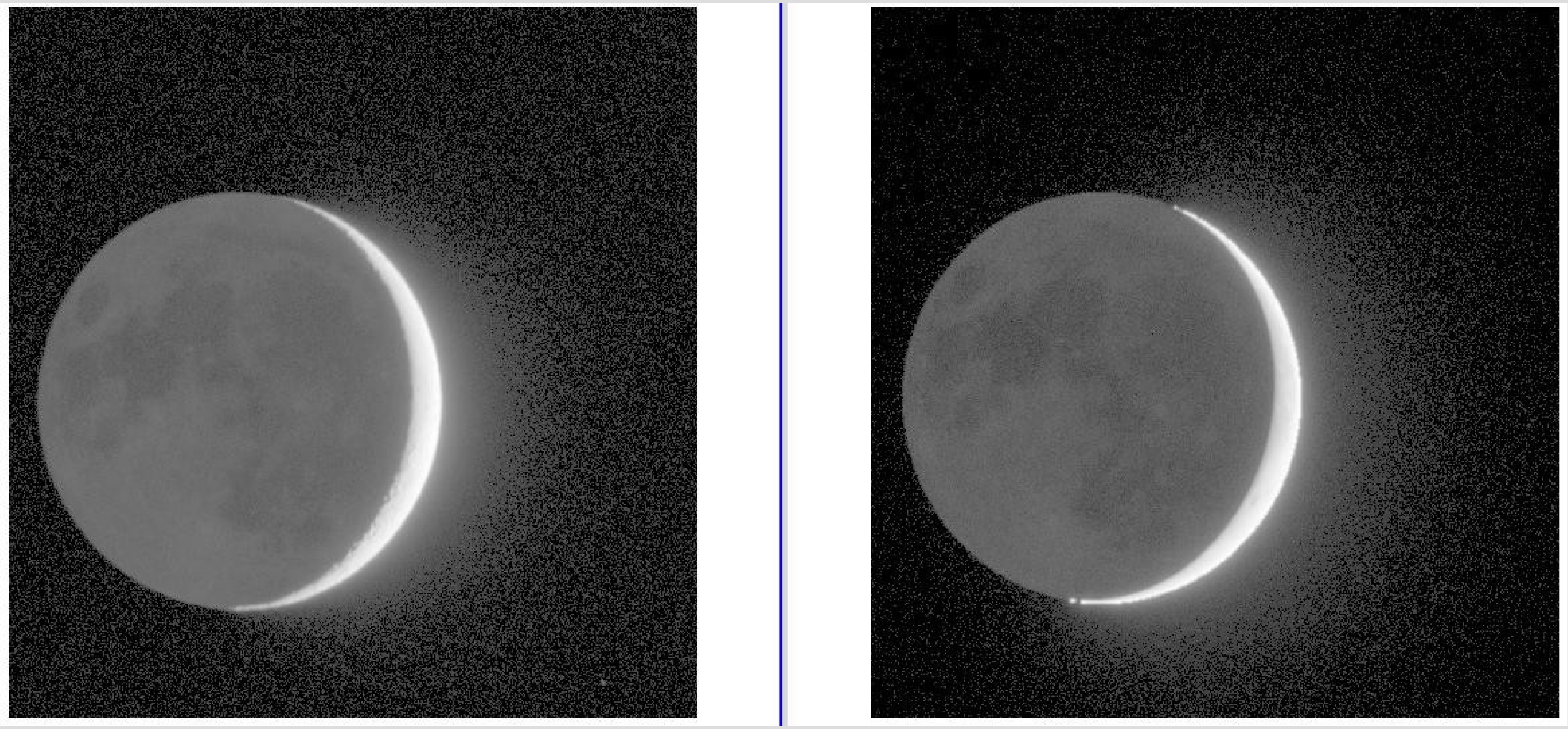
PSF power law and airmass



Scattering in the PSF depends slightly on the airmass

Scattering in the PSF has something to do with both air and the telescope optics

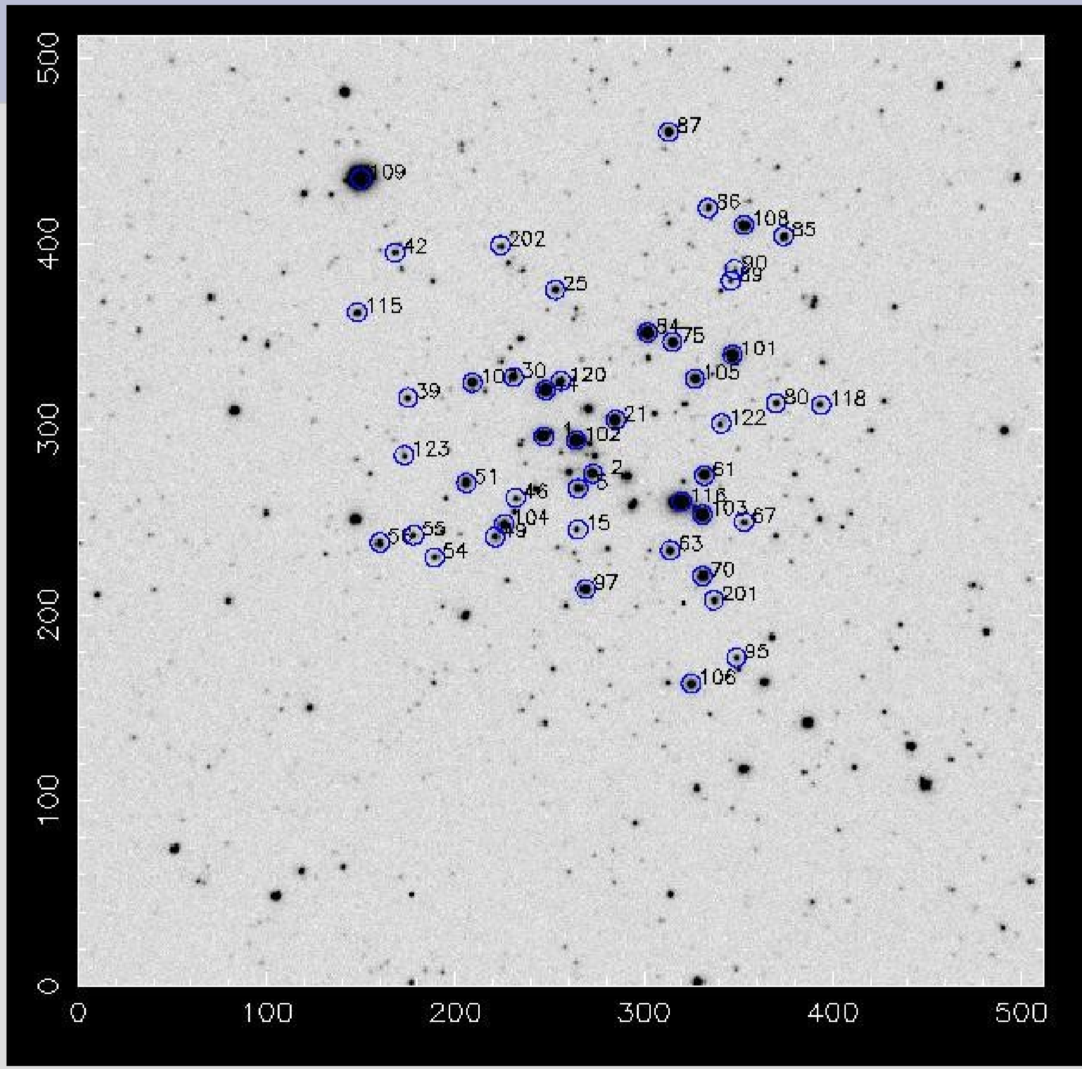
Real versus simulated data



Synthetic lunar images with sunlight and earthshine can be convolved with PSF – and noise added – to simulate our data

Useful for testing the **pipeline** with known earthshine flux determinations

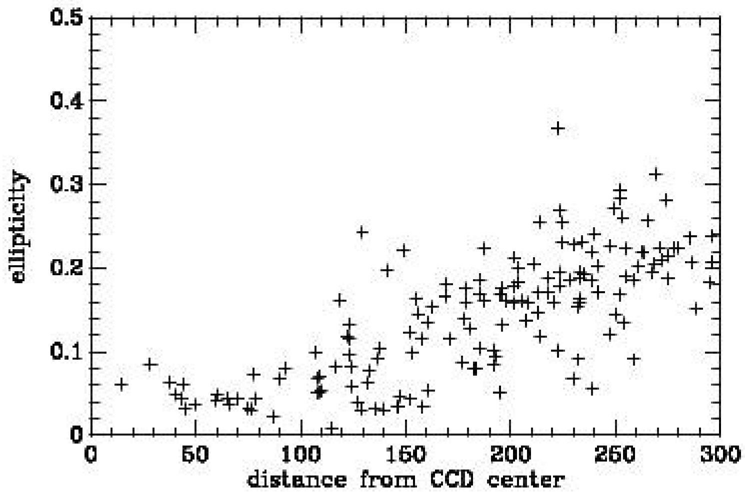
Photometric calibration

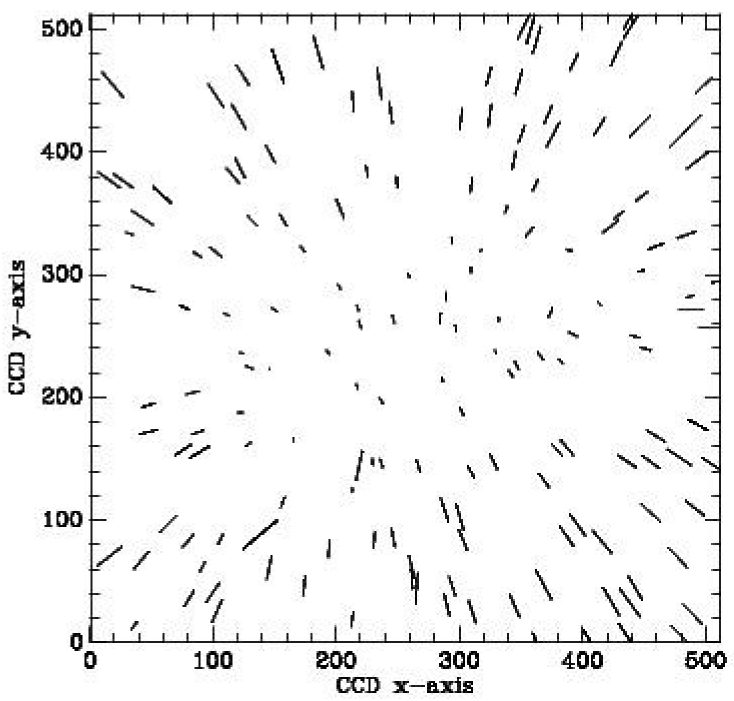


M41 – an open cluster in the Milky Way plane

Our V and B filters are much like their Johnson counterparts – we are still working on the calibration of the IRCUT, VE1 and VE2 filters...

Astigmatism



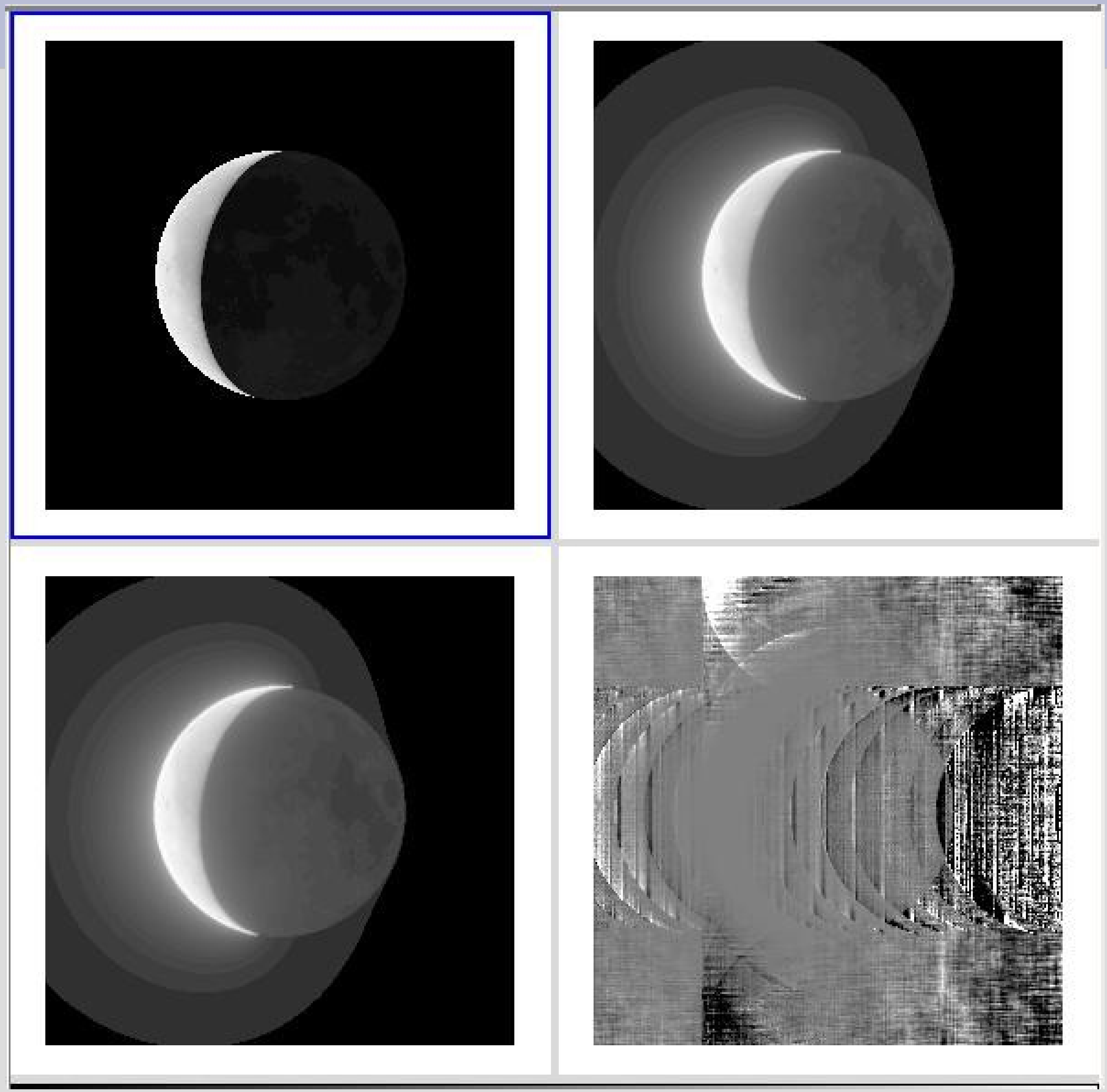


Astigmatism in the field of view has been measured

We have yet to evaluate to what extent this must be accounted for in the earthshine measurement

CPU versus GPU

Synthetic crescent moon with earthshine



Standard (CPU) FFT (fftw3) convolution with the PSF

GPU convolution with the PSF (thanks to Ben Barsdell!)

Ratio of GPU to CPU solution

Plans for 2012

Finish commissioning the telescope

Test three other observing modes
- neutral density filters
- knife edge
- accurately timed shutter

Which measures albedo routinely and best?

Demonstrate we can measure hourly, nightly and seasonal albedo changes on Earth