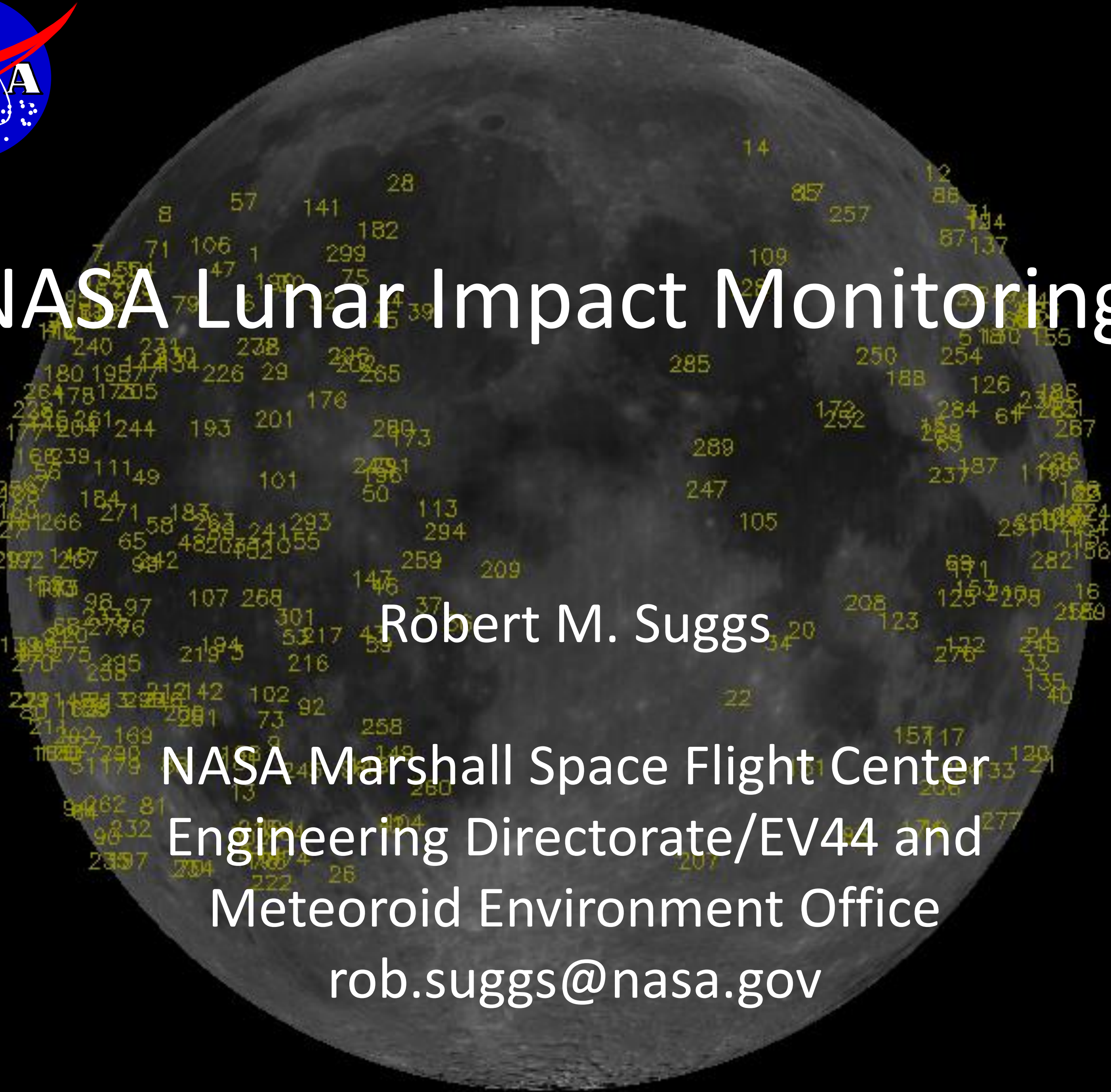
NASA Lunar Impact Monitoring



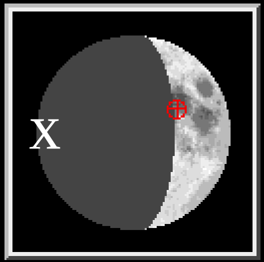
Robert M. Suggs

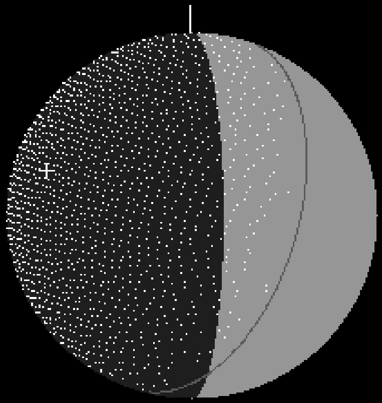
NASA Marshall Space Flight Center
Engineering Directorate/EV44 and
Meteoroid Environment Office
rob.suggs@nasa.gov

9 Years of Observations

- The MSFC lunar impact monitoring program began in 2006 in support of environment definition for the Constellation (return to Moon) program
- Work continued by the Meteoroid Environment Office after Constellation cancellation
- Over 330 impacts have been recorded
- A paper published in Icarus reported on the first 5 years of observations and 126 calibrated flashes
  - **Icarus:** http://www.sciencedirect.com/science/article/pii/S0019103514002243
  - **ArXiv:** http://arxiv.org/abs/1404.6458
- A NASA Technical Memorandum on flash locations is in press

Jack Schmitt/Apollo 17 observation of lunar impact





Geminid visiblity

"NASA Apollo 17 transcript" discussion is given below (before descent to lunar surfac
----
03 15 38 09 (mission elapsed time)
(10 Dec 1972, 21:16:09 UT – possible Geminid)

LMP Hey, I just saw a flash on the lunar surface!

CC Oh, yes?

LMP It was just out there north of Grimaldi [mare]. Just north of Grimaldi. You might see if you got anything on your seismometers, although a small impact probably would give a fair amount of visible light.

CC Okay. We'll check.

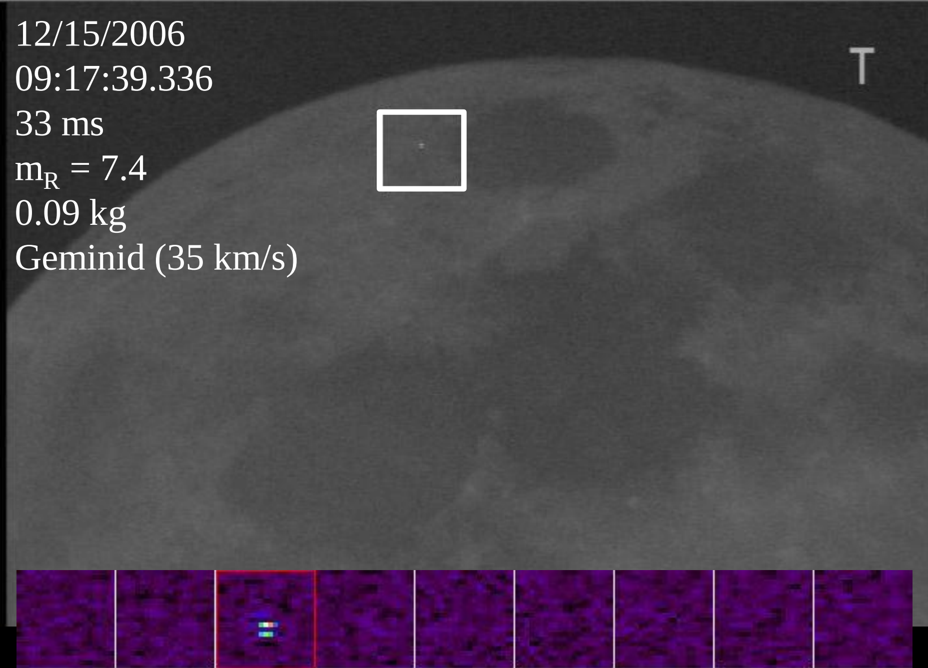
LMP It was a bright little flash right out there near that crater. See the [sharp rimed] crater right at the [north] edge of [the] Grimaldi [mare]? Then there is another one [i.e., sharp rimed crater] [directly] north of it [about 50km]- fairly sharp one north of it. [That] is where there was just a thin streak [pin prick] [flash?] of light.

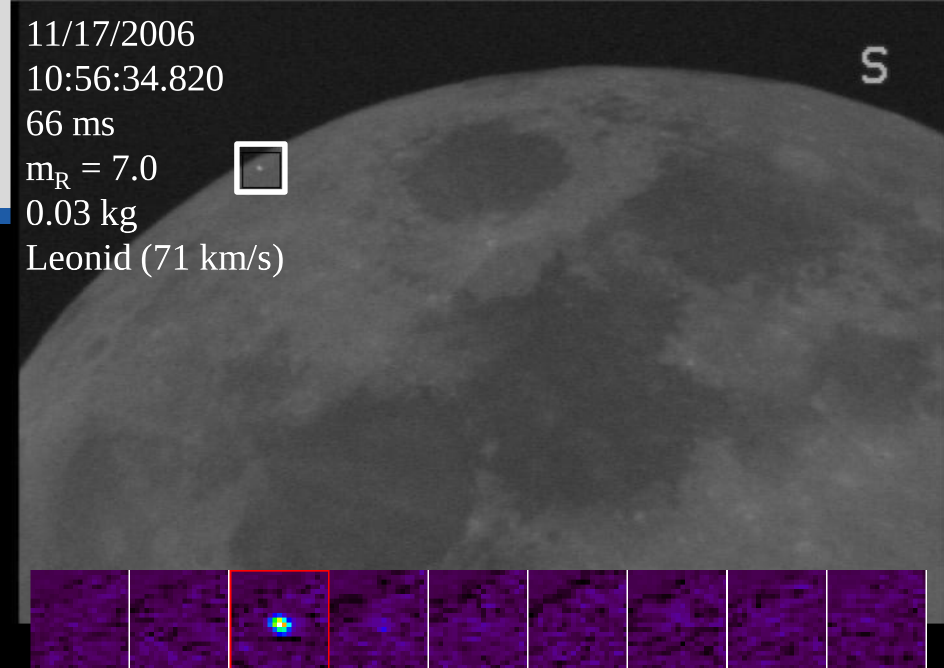
CC How about putting an X on the map where you saw it?

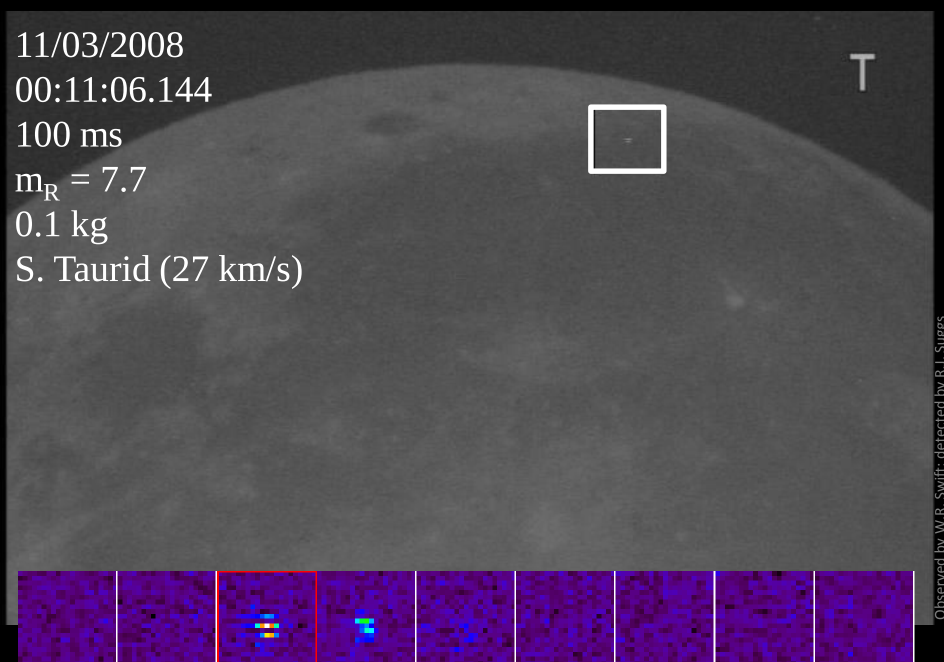
Instrumentation and Photometric Calibration

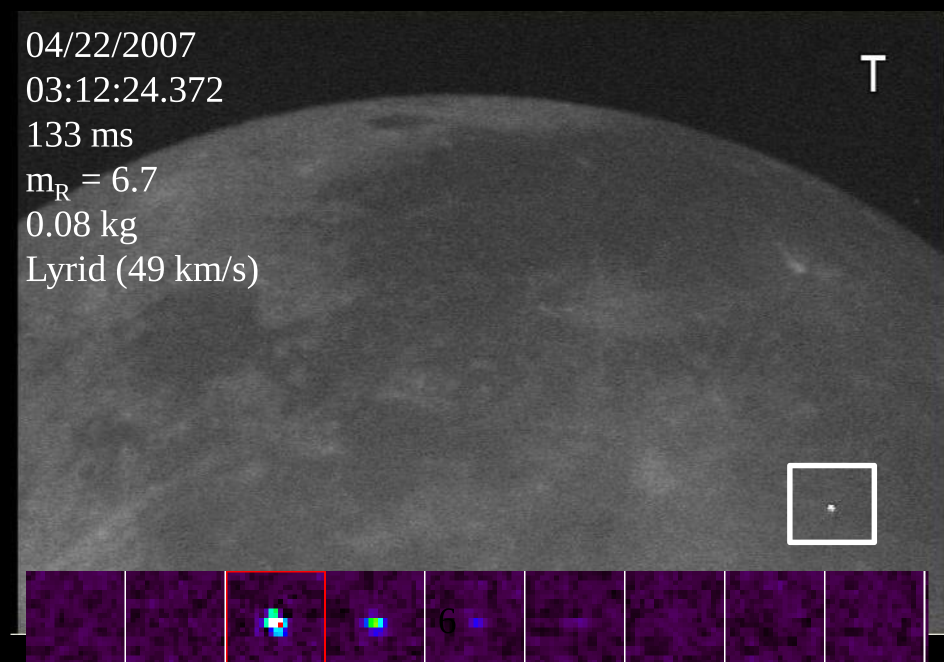
Outline

- How we observe
  - Equipment, camera settings, software
  - Issues: glare, noise, number of cameras
- How we calibrate
  - Date/time, location (Danielle will cover), magnitude (energy)
- Implications for the flux of meteoroids at Earth


12/15/2006
09:17:39.336
33 ms
m_R = 7.4
0.09 kg
Geminid (35 km/s)
T
Observed by D.E. Moser & W.R. Swift; detected by R.J. Suggs


11/17/2006
10:56:34.820
66 ms
m_R = 7.0
0.03 kg
Leonid (71 km/s)
S
Observed by V. Coffey, D.E. Moser & W.R. Swift; detected by R.J. Suggs


11/03/2008
00:11:06.144
100 ms
m_R = 7.7
0.1 kg
S. Taurid (27 km/s)
T
Observed by W.R. Swift; detected by R.J. Suggs


04/22/2007
03:12:24.372
133 ms
m_R = 6.7
0.08 kg
Lyrid (49 km/s)
T
Observed by R.M. Suggs; detected by R.J. Suggs

Camera Field of View and Tracking

Approximately 20 arcmin horizontal

Approximately 1m effective focal length with ½ inch CCD

Good compromise between collecting area and glare

Telescope mount with lunar rate (in RA and Dec) is helpful although manual corrections are needed

Aristarchus and Proclus are easy to see and use as tracking targets

Videos

When we Observe

- Initially it was anytime the glare from the sunlit face did not completely wash out the earthshine face
  - Typically between 10% illuminated (crescent) and 50% (quarter)
- Impact rate is higher during meteor showers and we are focusing on those now after 7 years of observing anytime
- Observe from nautical twilight to moonset – evening
- Observe from moonrise to nautical twilight – morning
- Generate a schedule each year with dates, times, and shower visibilities

Equipment

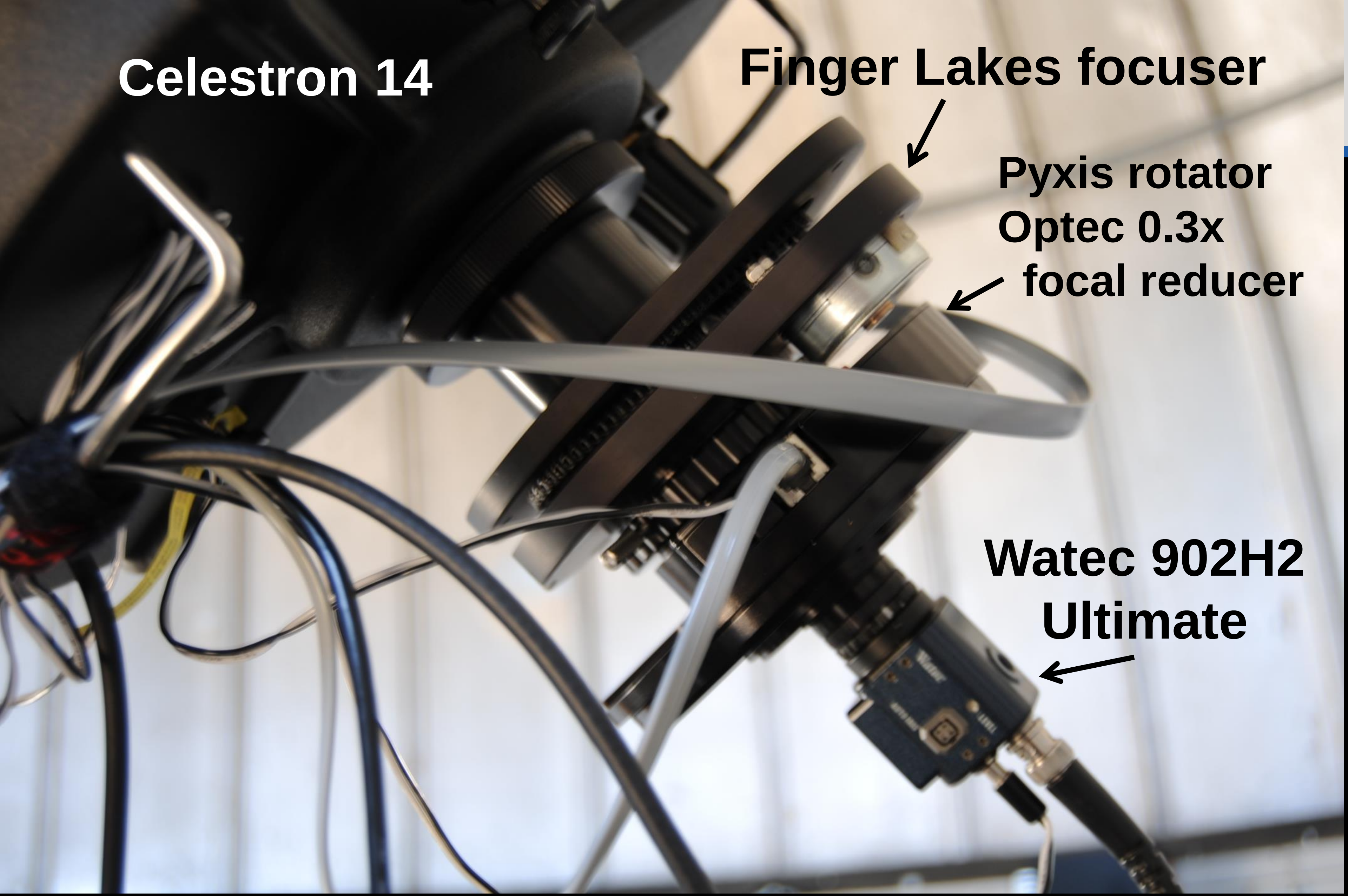
- Telescopes – 14 inch (0.35m), have also used 0.5m
- Camera – B&W video 1/2inch Sony HAD EX chip (Watec 902H2 Ultimate is the most sensitive we have found)
- Digitizer – preferably delivering Sony CODEC .AVI files if using LunarScan (Sony GV-D800, many Sony digital 8 camcorders, Canopus ADVC-110)
  - This gives 720x480 pixels x8 bits
- Time encoder – GPS (Kiwi or Iota)
  - Initially used WWV on audio channel with reduced accuracy
- Windows PC with ~500Gb fast harddrive (to avoid dropped frames)
  - Firewire card for Sony or Canopus digitizers

Camera Settings

- Manual gain control to do reliable photometry
- Turn off automatic shutter control (ELC on Watec cameras)
- No integration (Sense Up = off for StellaCam or MallinCams)
- Best to use gamma = 0.45 to extend dynamic range at the expense of an extra calculation in the analysis (Gamma Lo for Watecs)

Automated Lunar and Meteor Observatory (MPC H58)

- Telescopes
  - 14” (0.35m)
    Meade, Celestron
    Paramount (ME, MX)
- Detectors
  - Watec 902H2 Ultimate
  - Gamma=0.45, man.gain, shutter off


Celestron 14
Finger Lakes focuser
Pyxis rotator
Optec 0.3x
focal reducer
Watec 902H2
Ultimate

Operator position

Glare is a huge challenge

- We are trying to detect a 9^{th} – 10^{th} magnitude flash a few arcminutes from the sunlit Moon
- Glare sources and their mitigation
  - cirrus clouds and contrails – wait for them to pass
  - dirty optics – keep them clean
  - inadequate baffles – telescope design
  - internal reflections in the optics – use flocking paper, especially in focal reducer

2 Cameras Needed

- Cosmic ray flashes in the CCD can look like impact flashes. 2 cameras help reject those.
  - Cosmic rays are single frame so any multiframe flash is possibly real
- Orbital debris flashes can look like impact flashes. 2 widely separated (10s of km) telescopes can reject those
  - We ran a telescope 100km from our primary observatory for 4 years and only saw one flash that would have fooled us, and it showed motion on close examination.
  - LEO debris moves very fast so multiframe flashes would show motion GEO is slower but still moving. Check many frames (2 or 3 seconds) either side of the flash all over the FOV
- Multi-frame flashes with no motion are likely real

Possible solution for 2 cameras with one telescope: Dichroic beamsplitter

- Dichroic passes 90% of near infrared light to SU640 NIR camera and reflects 90% of visible light to Watec
- This also gives “2 color” data if cameras are gen-locked (exposures at exactly same time)
- Main problem is different chip sizes and the need for focal reduction optics for the Watec
- *Beware of persistence in NIR camera pixels*
  - May still be useful for peak magnitude


From telescope
Goodrich SU 640 NIR camera
Dichroic beamsplitter
Visible light camera
Diagonal prism
Relay/focal reduction optics

Example of Persistence

Photometric Calibration

- Use "all sky" photometry
  - Require standard stars with various colors at various airmasses
- Calibration using earthshine is a bad idea
  - Brightness changes with terrestrial weather
  - Color changes with terrestrial weather
  - Extended source vs point source difficulties
- Color correction between filtered magnitude of standards and color of flash is important

Magnitude Equation

see Brian Warner's book "A Practical Guide to Lightcurve Photometry and Analysis"

$$R = -2.5 \log_{10}(S) - k' X + T\,(B-V) + ZP$$

R = Johnson-Cousins R magnitude

k' = extinction coefficient

X = airmass (zenith = 1.0)

T = color response correction term

$(B-V)$ = color index

ZP = zero point for the night

$S = DN^{1/0.45}$ if camera gamma set to 0.45 which extends dynamic range (faintest flash to saturation)

DN = pixel value 0 – 255

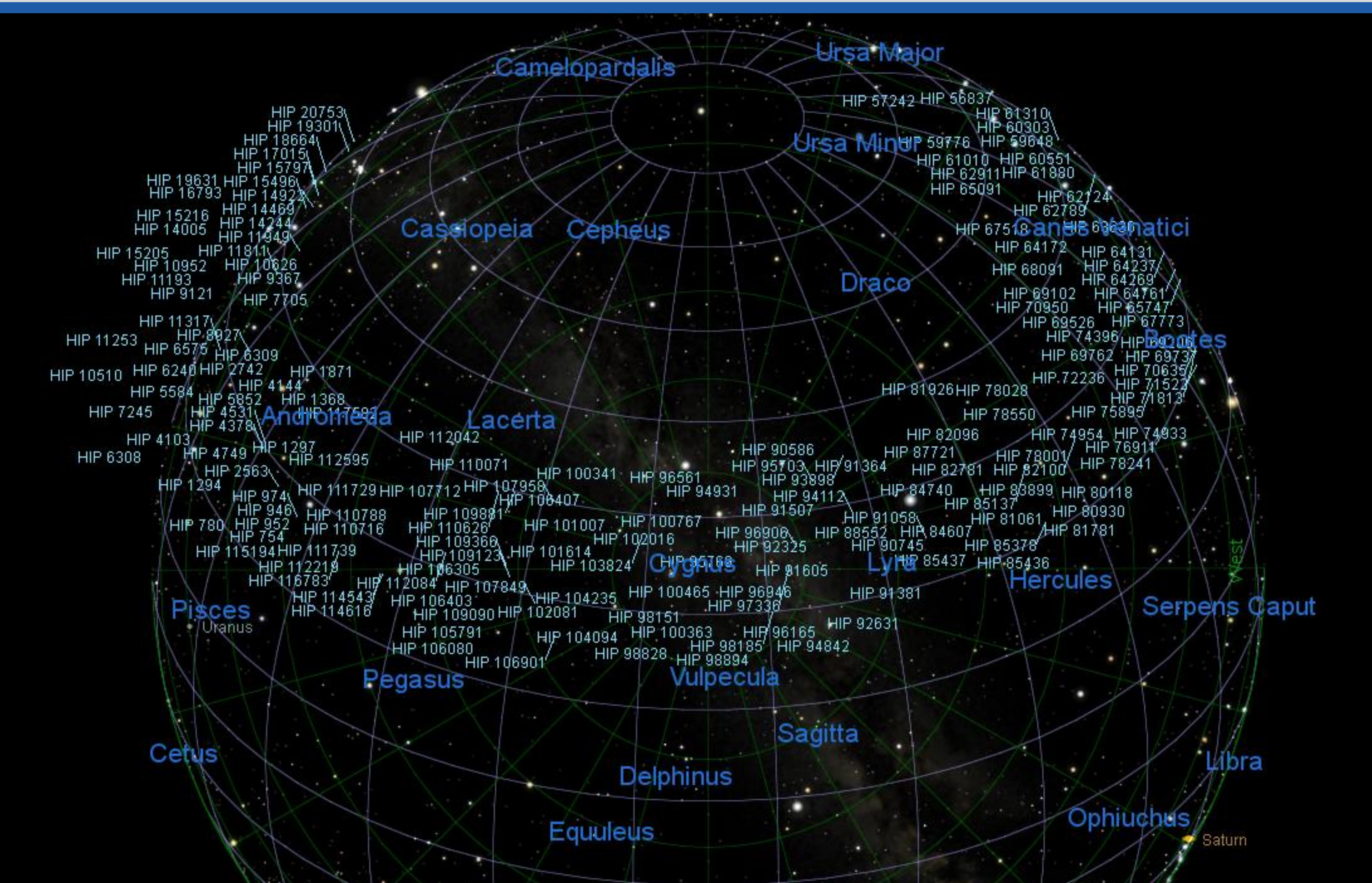
Must use Manual Gain Control (no AGC), no ELC (rightmost switch on the side of the Watec down) and adjust gain to balance sensitivity and glare/earthshine

Comparison Stars

- Stars will pass through the field of view during observations, but
  - you don't typically know the R magnitude
  - they are seldom in the FOV at the time of the flash
  - this means you **must** do "all sky" photometry rather than "differential" (i.e. must account for extinction as a function of airmass as well as zero point)
  - flat field must be very good because vignetting is worse near the edge of the FOV where the field stars will be seen, especially with focal reduction
- Observe some "standards" at various airmasses (1 and 2 - 3) after evening observations and before morning ones
- Build a standards list using SIMBAD for stars that are bright enough but don't saturate the system (8 – 9 R mag for 14in) that pass through the zenith simbad.u-strasbg.fr/simbad/
  - Must have published R and B-V mag and not be a variable

$$R = -2.5 \log(S) - k' X + T\,(B-V) + ZP$$

Comparison Stars

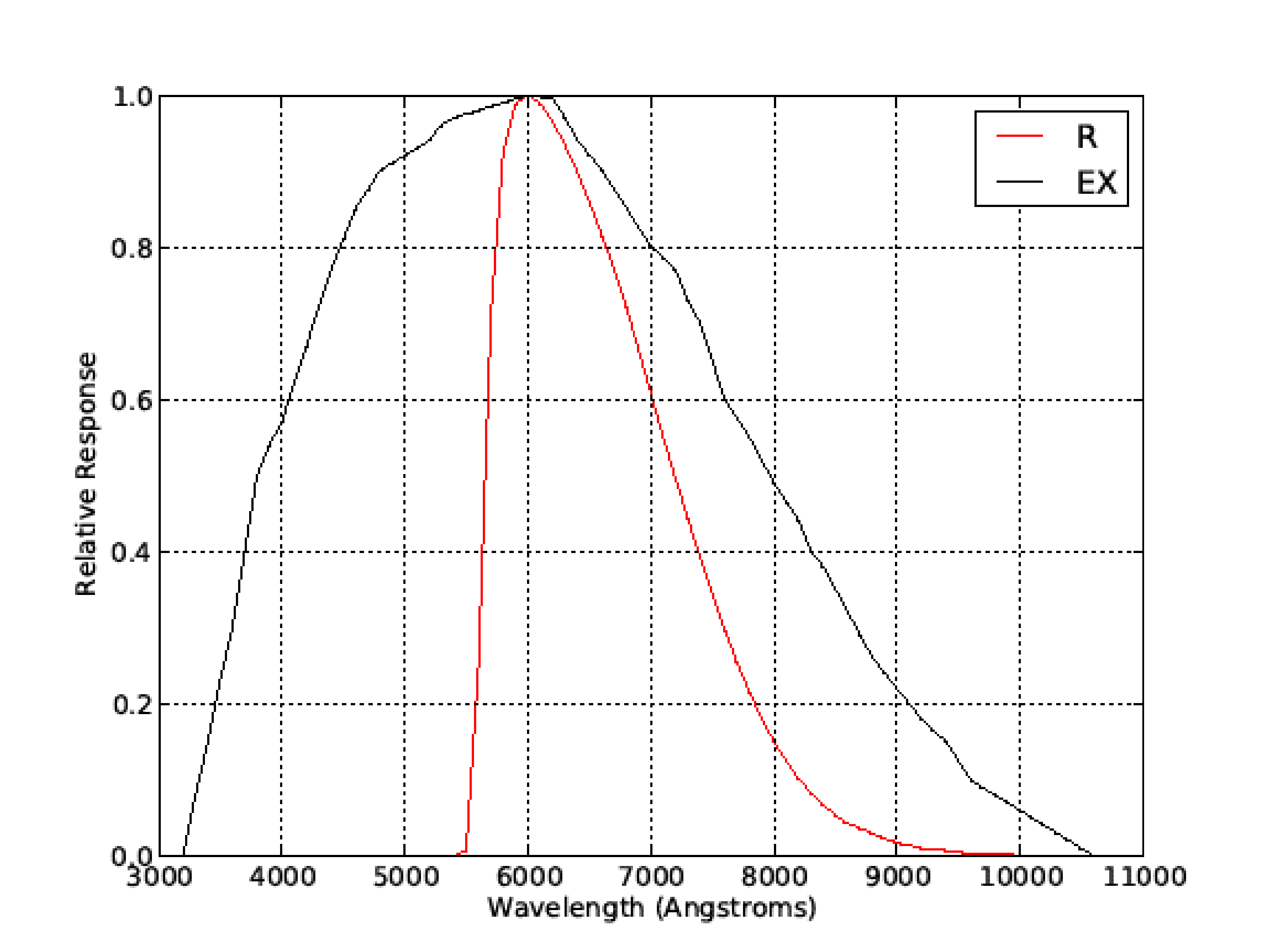


Filters and Photometric Calibration

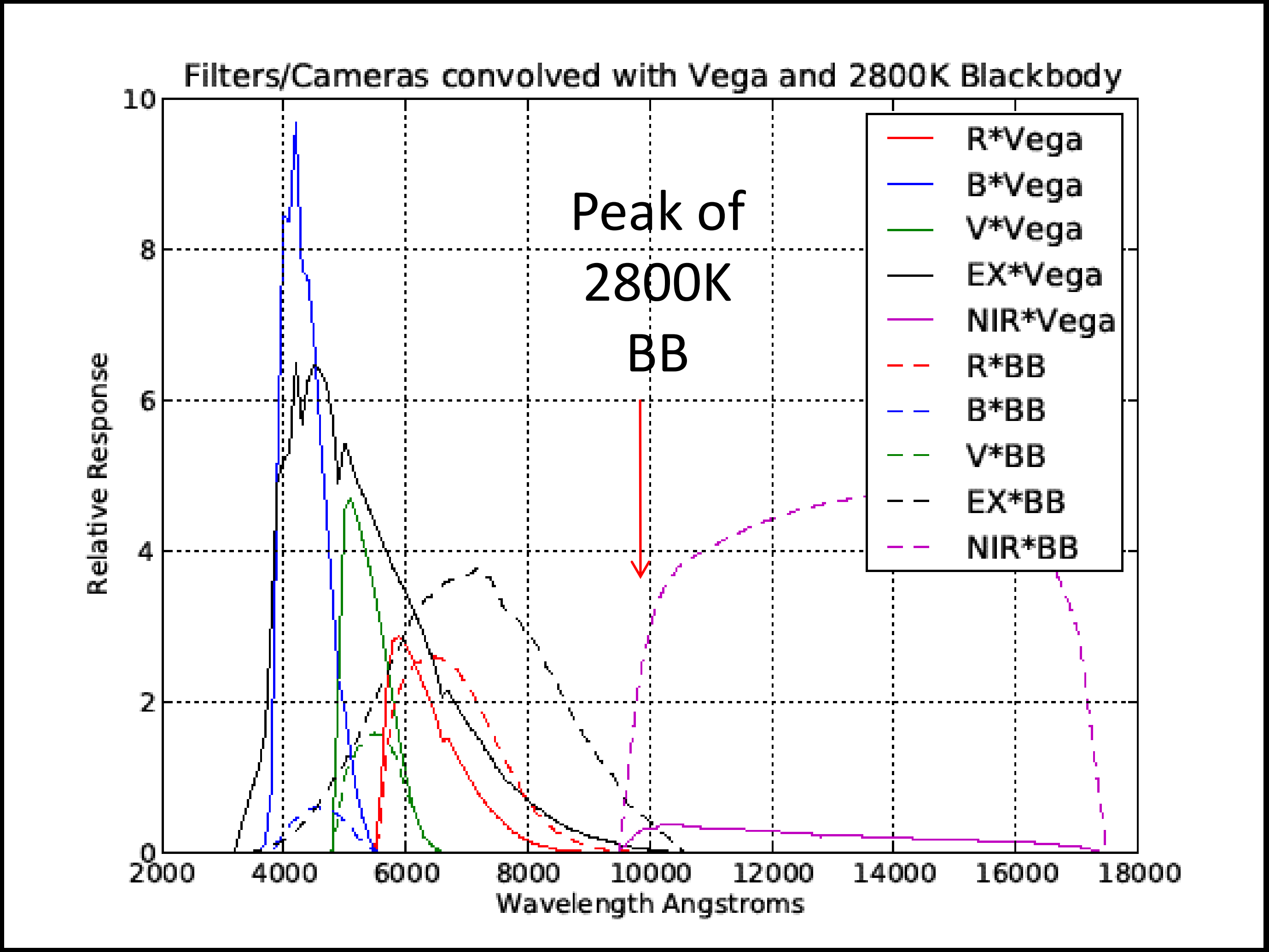
- Use the camera unfiltered to give maximum sensitivity
  - Wider spectral response
    - near infrared where the flash is brightest
    - blue and green where earthshine is brightest (to see features)
- Calibration should be done with R magnitudes of comparison stars
  - Peak sensitivity of HAD EX and R filter is at the same wavelength but width is very different
  - Need the color term T (B-V) = EX-R in the magnitude equation

$$R = -2.5 \log(S) - k' X + T\,(B-V) + ZP$$

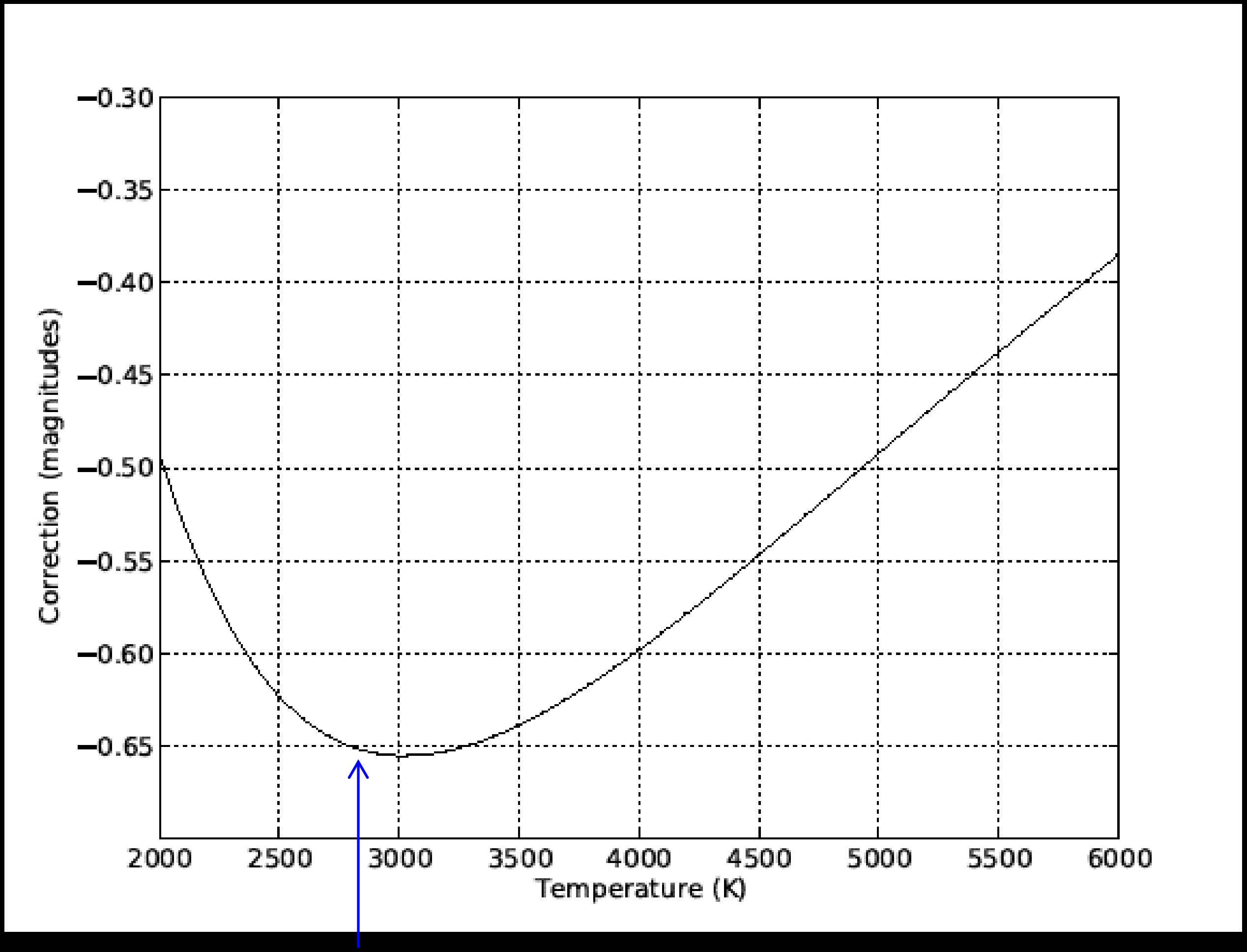
Sony HAD EX response compared to Johnson-Cousins R filter



Filter and camera responses depend on color of object



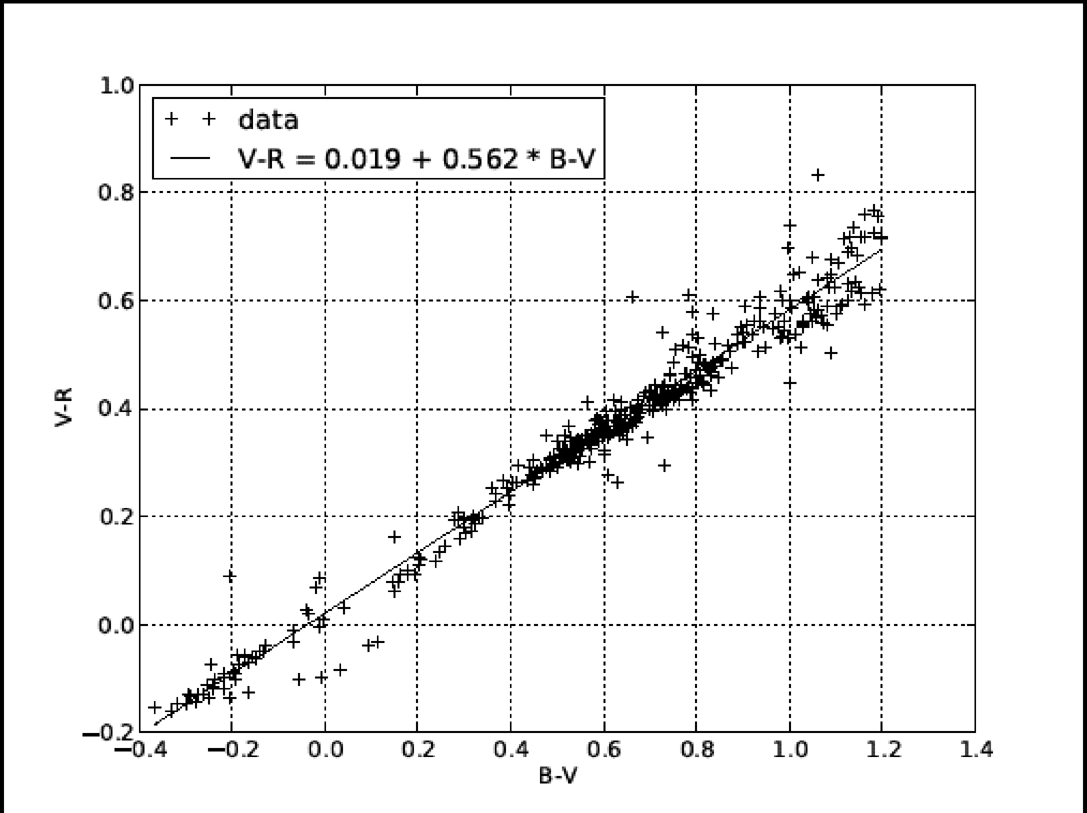
Correction from HAD EX to R filter vs blackbody temperature
R-EX replaces T(B-V)



Theoretical peak flash temperature 2800K Nemtchinov et al.

Johnson R from B and V

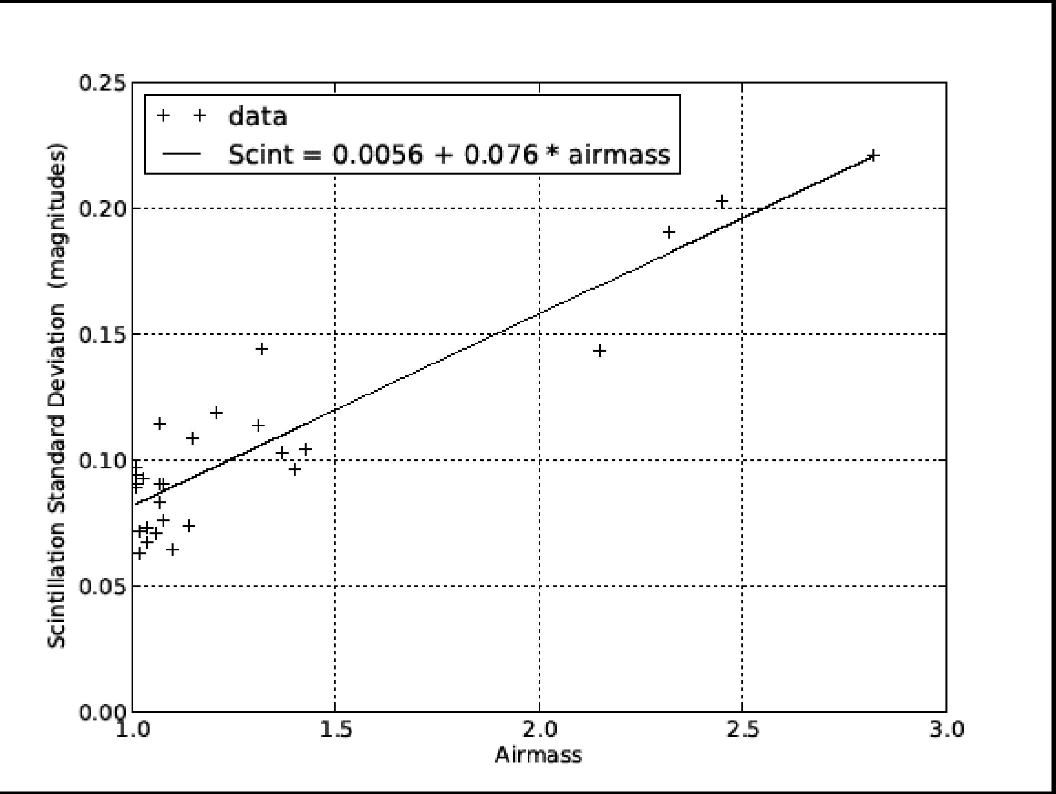
If you don't have an R magnitude but do have B and V use this correlation between V-R and B-V determined from Landolt Standards



$R = V - 0.019 - 0.562\ (B\text{-}V)$ *Only for stars bluer than B-V = 1.2*

Uncertainty due to atmospheric scintillation

Error due to atmospheric scintillation is a function of airmass X
Determine this for your site by measuring field-to-field instrumental magnitude deviation at various airmasses



$$\sigma_{scint} = 0.0056 + 0.076\,X \qquad \sigma^2 = \sigma_{scint}^2 + \sigma_{fit}^2$$

Mass of the impactor assuming impact speed (from shower association)

Luminous efficiency

$$\eta = 1.5\times10^{-3} \exp\left(-9.3^2/v^2\right)$$

v = impact speed in km/s

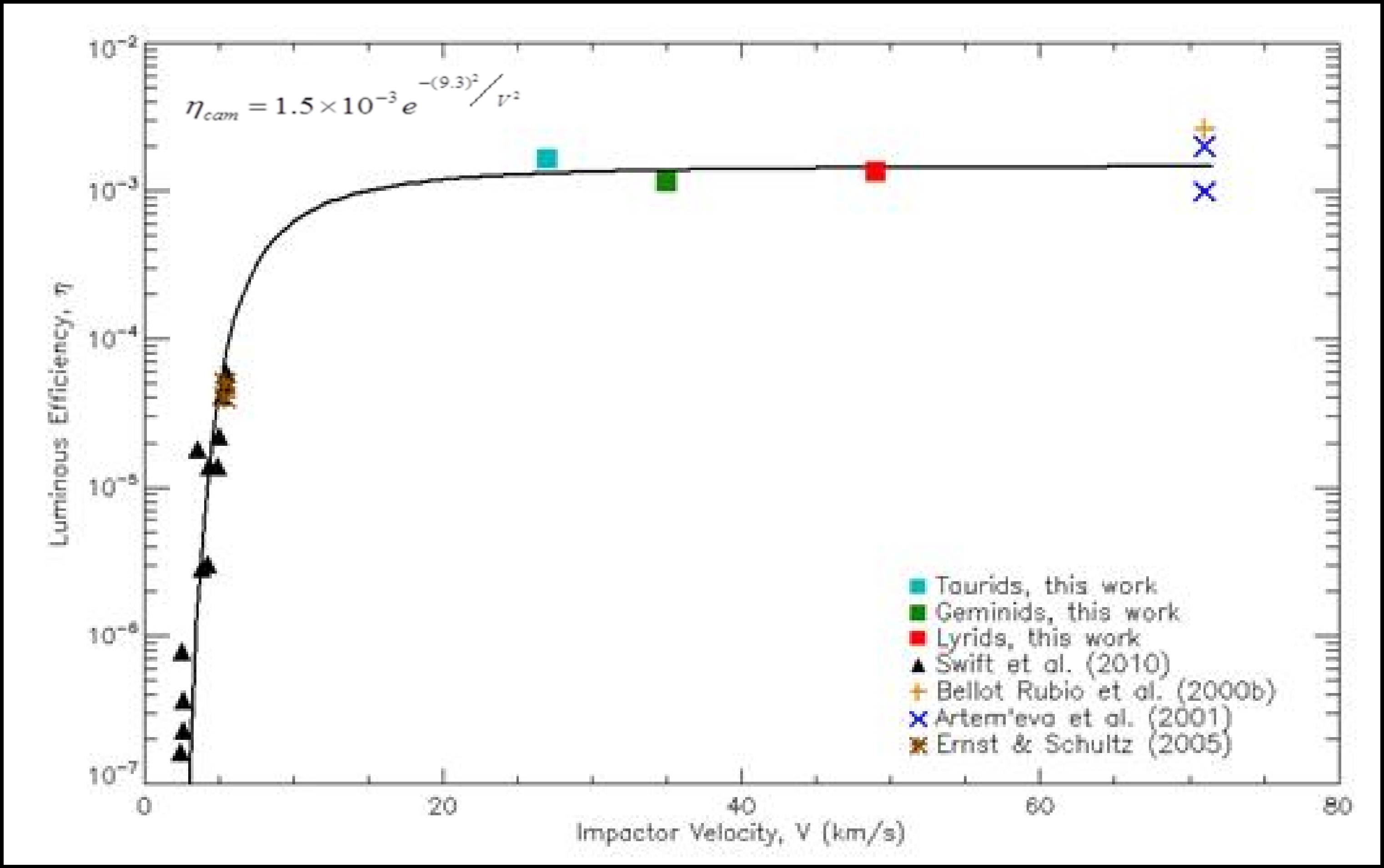
Kinetic Energy

$$KE = E_{lum} / \eta$$

Mass

$$M = 2\,KE / v^2$$

Luminous Efficiency



Moser, D.E. et al., "Luminous Efficiency of Hypervelocity Meteoroid Impacts on the Moon Derived from the 2006 Geminids, 2007 Lyrids, and 2008 Taurids", Meteoroids 2010 Proceedings (NASA CP-2011-216469)

To compute energy from impact magnitude

- $E_{lum} = f_\lambda \, \Delta\lambda \; f \; \pi \; d^2 \; t$ Joules

  E_{lum} = luminous energy

  $\Delta\lambda$ = filter half power width, 1607 Ångstroms for R

  f = 2 for flashes near the lunar surface

  d = distance from Earth to the Moon

  t = exposure time, 0.01667 for a NTSC field

  $f_\lambda = 10^{-7} \times 10^{(-R + 21.1 + zp_R)/2.5}$ $J\ cm^{-2}\ s^{-1}\ Å^{-1}$

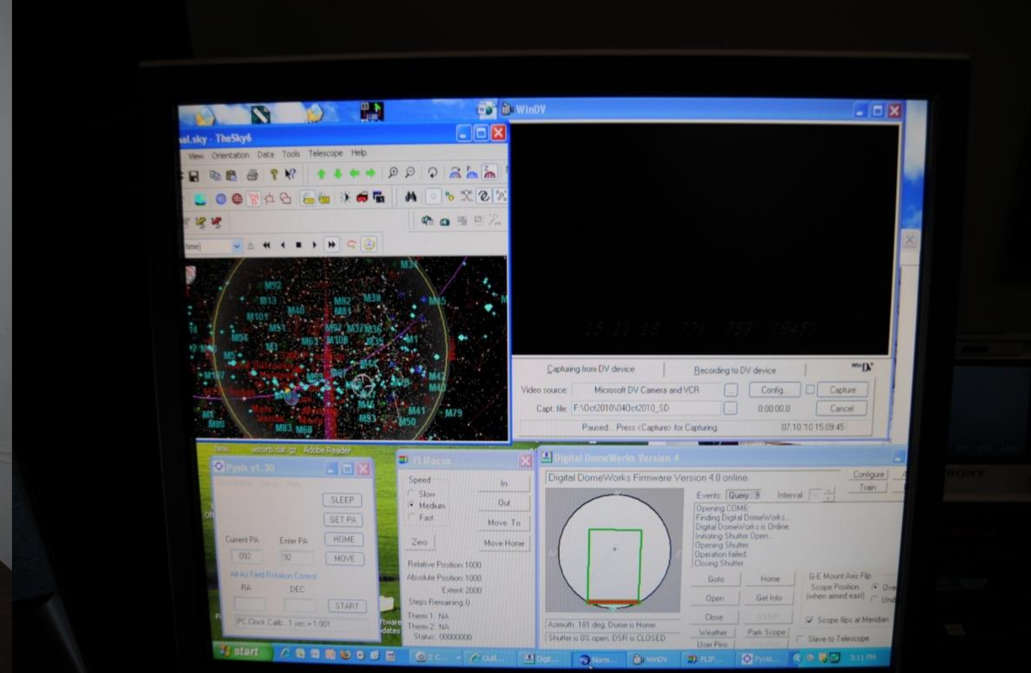
  R = the R magnitude

  zp_R photometric zero point for R (not the same as ZP in magnitude equation)

Software we have used

- WinDV for recording windv.mourek.cz
- LunarScan detection software (Gural will discuss) www.lunarimpacts.com/lunarimpacts.htm
- VirtualDub for slicing out relevant sections of video and converting to "Old AVI" for reading into Limovie www.virtualdub.org/download.html
- Limovie for checking photometry of flashes and calibration stars www005.upp.so-net.ne.jp/k_miyash/occ02/limovie_en.html
- MaximDL can convert video segments to FITS
  - Don't use the aperture photometry tool until after each pixel is gamma corrected by $S = DN^{1/0.45}$ if camera gamma set to 0.45
- Python and Pyraf may be used for aperture photometry www.stsci.edu/institute/software_hardware/pyraf/current/download

Backup



Telescope Control and Recording

TheSky X (Paramount)

WinDV to record via

Firewire from Sony DV or Canopus deck/digitizer

Kiwi or IOTA GPS time stamper

Pyxis rotator control

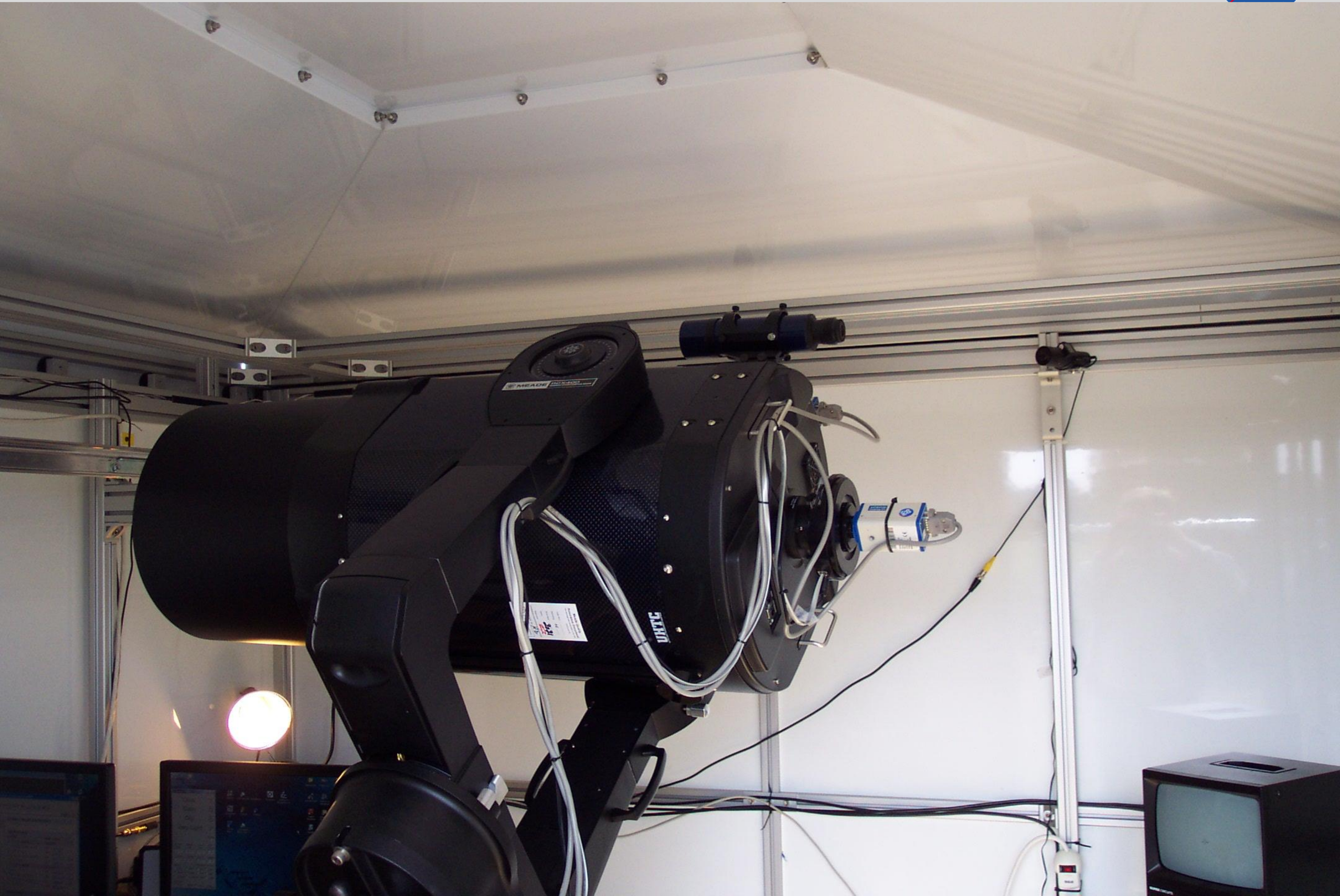
Finger Lakes focuser control

DDW dome control

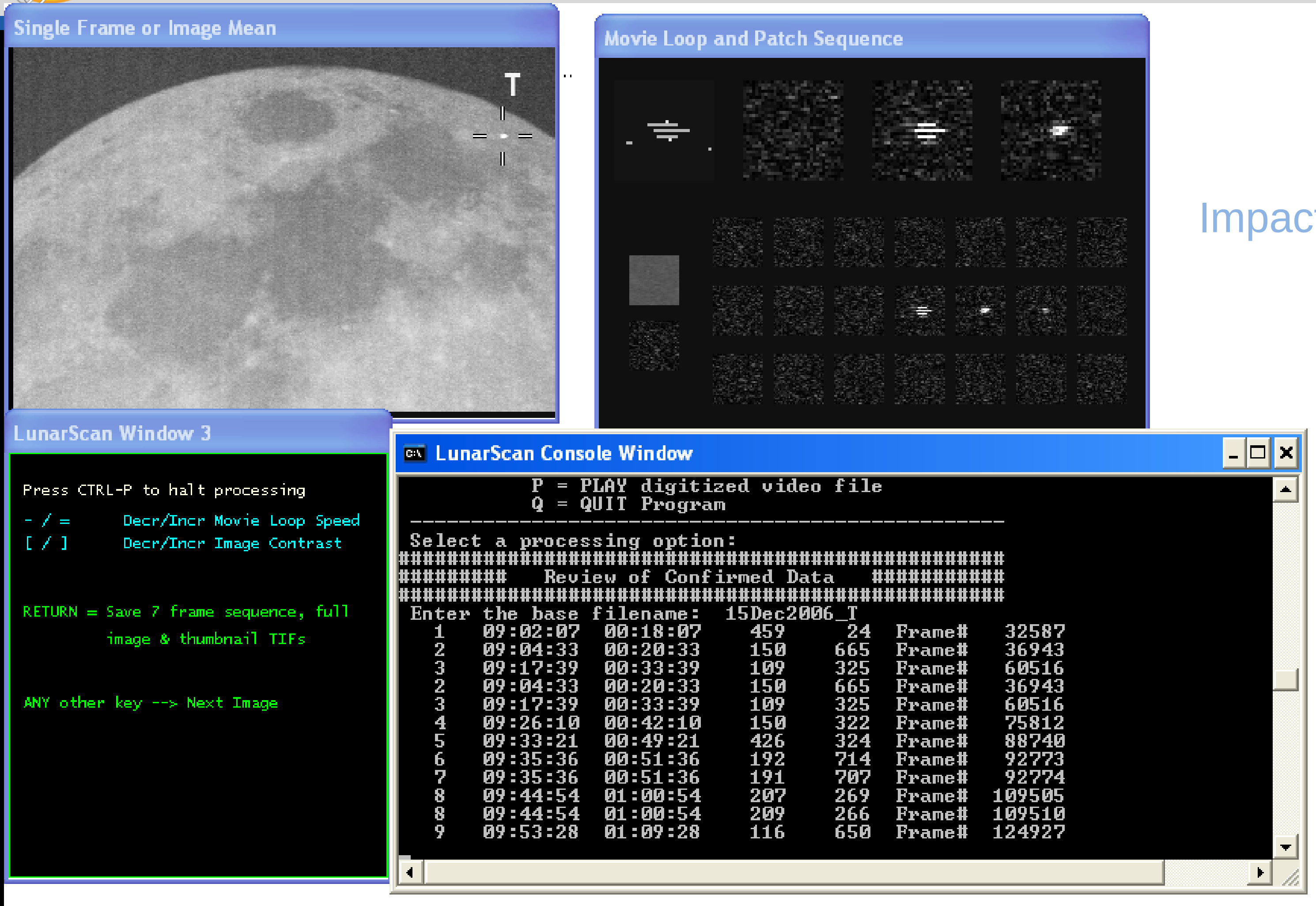
DLI power control

Automated Lunar and Meteor Observatory

Meade 14 in (0.35m)



LunarScan (Gural)



Impact 15 Dec 2006

Free download from http://www.lunarimpacts.com/lunarimpacts.htm

Lunar Impact Flash Locations 2: Differential Refraction Correction and Uncertainty Determination

R. M. Suggs

NASA, Meteoroid Environment Office, NASA Marshall Space Flight Center

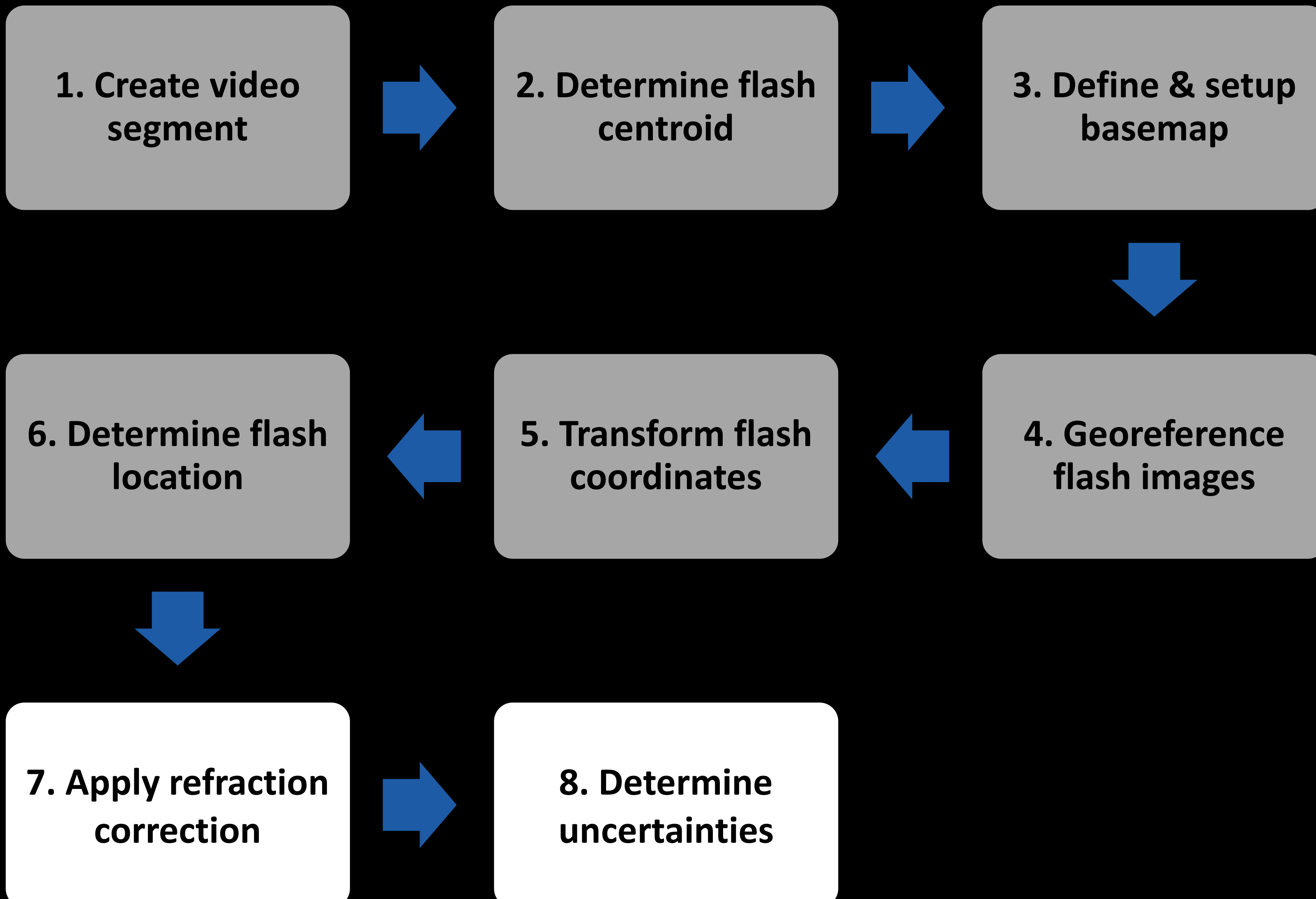
D. E. Moser

ESSSA/Jacobs, Meteoroid Environment Office, NASA Marshall Space Flight Center

Overview

- Describe an approach for correcting geolocated lunar impact locations for the effect of differential atmospheric refraction
  - The red flash and blue-green earthshine-illuminated lunar surface are refracted by different amounts depending on zenith distance
- Describe an approach for estimating the uncertainties in lunar impact locations
  - The georeferencing process requires a human-in-the-loop
- See NASA TM-2015-TBD for details

Geolocation workflow



Refraction Shift Between Flash Lunar Surface

Effective Wavelengths

- Effective wavelength for impact flash

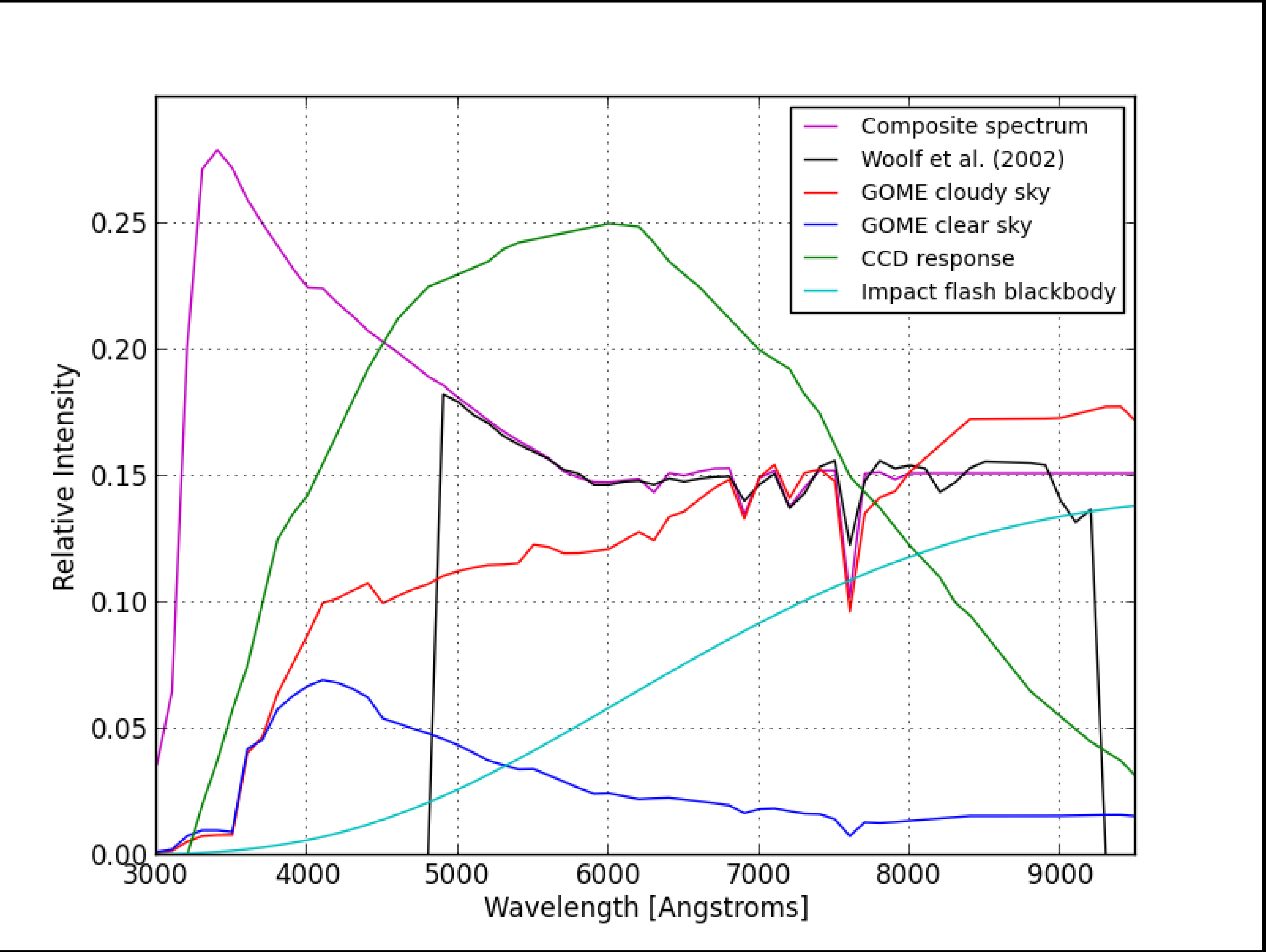
$$\lambda_{eff\ Flash} = \frac{\int \lambda\, F_{flash}(\lambda)\, R_{CCD}(\lambda)\, d\lambda}{\int F_{flash}(\lambda)\, R_{CCD}(\lambda)\, d\lambda}$$

- Effective wavelength for earthshine

$$\lambda_{eff\ ES} = \frac{\int \lambda\, F_{Earth}(\lambda)\, r_{Moon}(\lambda)\, R_{CCD}(\lambda)\, d\lambda}{\int F_{Earth}(\lambda)\, r_{Moon}(\lambda)\, R_{CCD}(\lambda)\, d\lambda}$$

Where F is the spectral irradiance for the flash and Earth, r_{Moon} is the spectral reflectivity of the lunar surface, R_{CCD} is the spectral response of the video camera CCD

Determining Effective Wavelengths



Differential Refraction

Evans, D.W. (2004)

- Constant of refraction (arcsec)

$$R = 206265\,\frac{n^2 - 1}{2n^2}$$

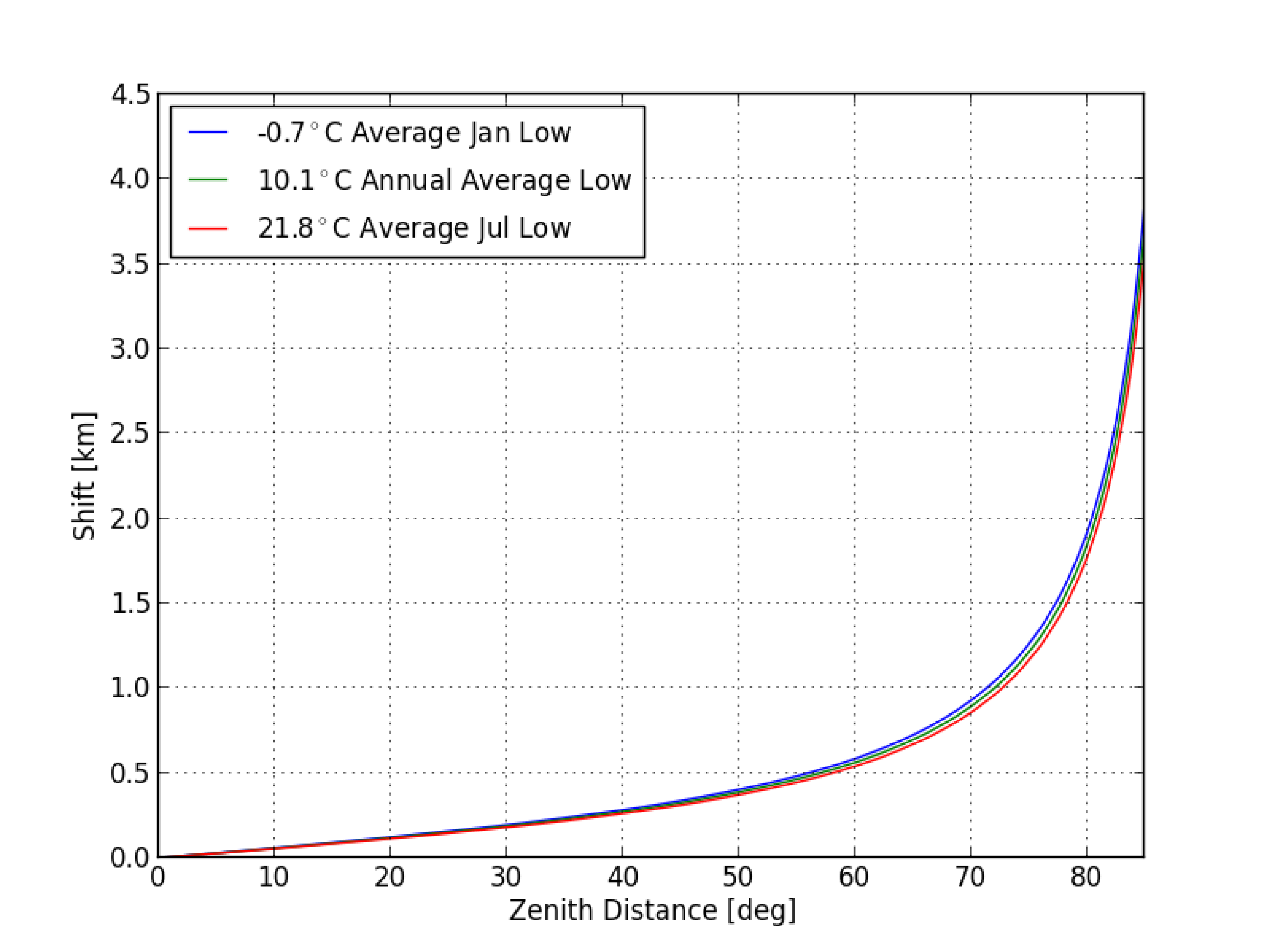
- Shift in zenith distance

$$z_t - z_a = R \tan z_t$$

Source	Effective wavelength (Å)	Index of refraction	Constant of refraction (arcsec)
Impact flash	7093.3	1.000291005	59.9979
33% cloudy + 67% clear Earth and Moon	6303.5	1.000291897	60.1818
100% cloudy Earth and Moon	6438.5	1.000291720	60.1454
100% clear Earth and Moon	5474.5	1.000293297	60.4703

For air temperature = 0 C, pressure = 1000 mb

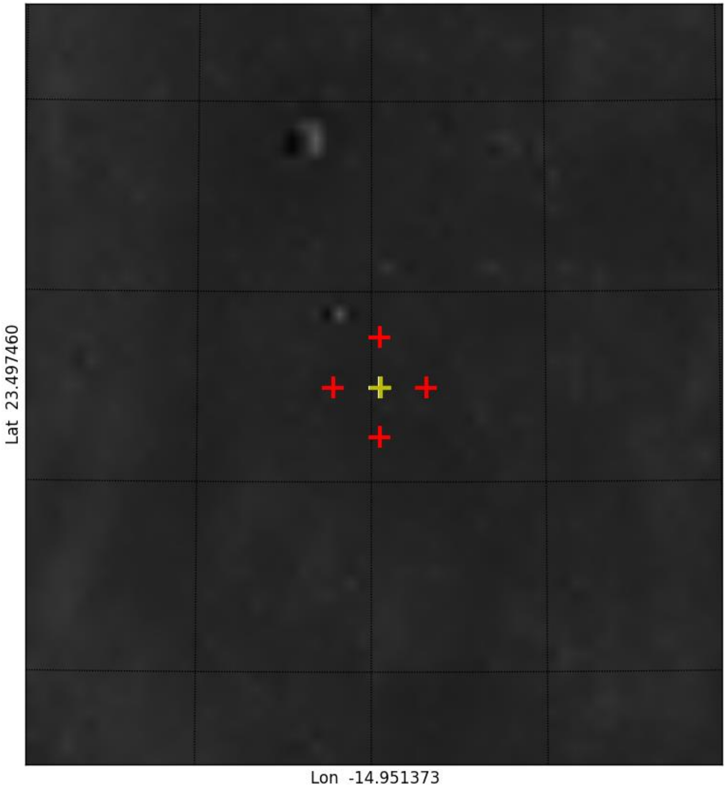
Differential Refraction Correction on the Moon as a Function of Temperature and Zenith Distance

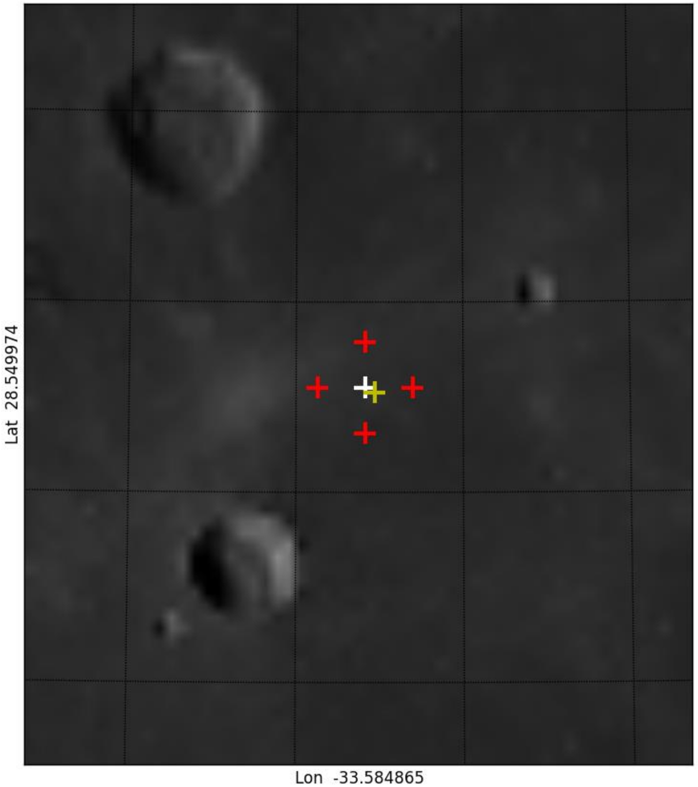


Refraction Shift Direction

- Flash location must be shifted toward the zenith
- JPL Horizons is used to compute:
  - Position angle of lunar pole
  - Sub-observer longitude and latitude (libration)
  - Distance to the Moon
  - Right Ascension and Declination of Moon
  - Local sidereal time
  - Zenith distance
- Python mpltoolkit.basemap is used to compute latitude and longitude of shifted position and plot results

Refraction Correction





25 Mar 2007 z = 23.2 deg, 0.1 km correction

26 Nov 2006 z = 76.3 deg, 1.3 km correction

Georeferencing Uncertainties

- Applying the transformation to each control point yields a residual error ε

- ArcMap displays ε for each control point and calculates the root means square (RMS) error

$$RMS\ error = \sqrt{\frac{\sum_{i=1}^{n} \varepsilon_i^2}{n}} \qquad n = \#\ of\ control\ points$$

- The RMS error is saved for subsequent uncertainty calculations

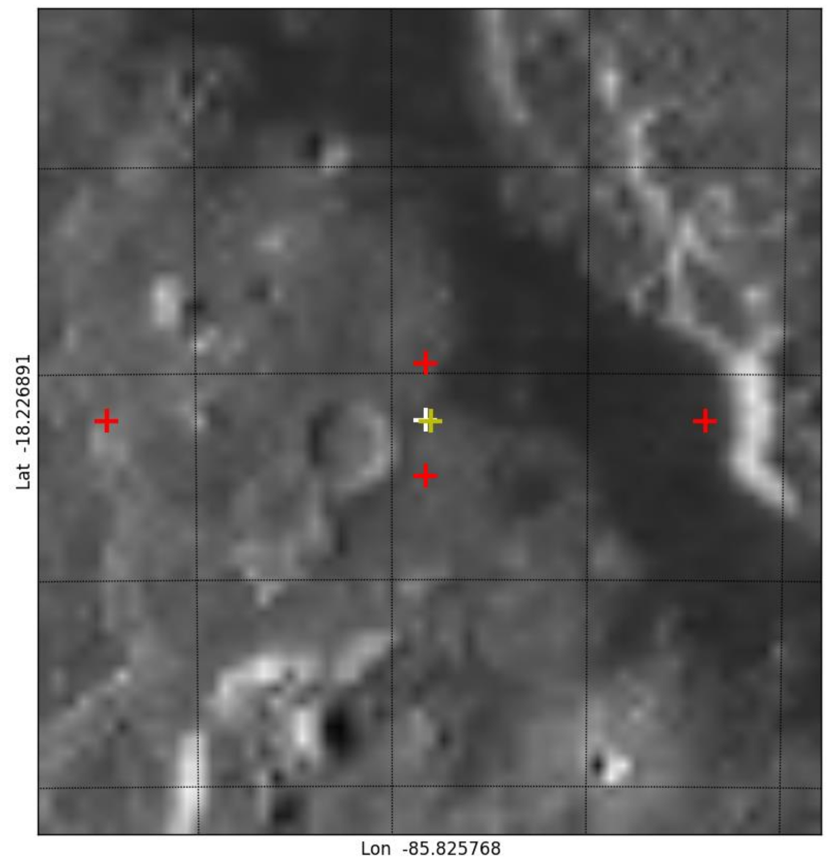
Human Uncertainties for the 9 Oct 2012 Impact Flash

- Root sum of squares of stdev X and Y is 6234.096 km

Analyst	λ (°)	φ (°)	$\bar{x}_f{}'$ (m)	$\bar{y}_f{}'$ (m)
1	50.0890	-12.3457	1395696.818030060	-473475.52735959200
2	50.6385	-12.4784	1404179.200895170	-475879.0852216600
stdev			5997.950444540	1699.572063243

- RSS this with the RMS error for each georeferencing run to get the uncertainty for each flash location

Map Projection Effect
Longitude Uncertainties Greater Near Limb



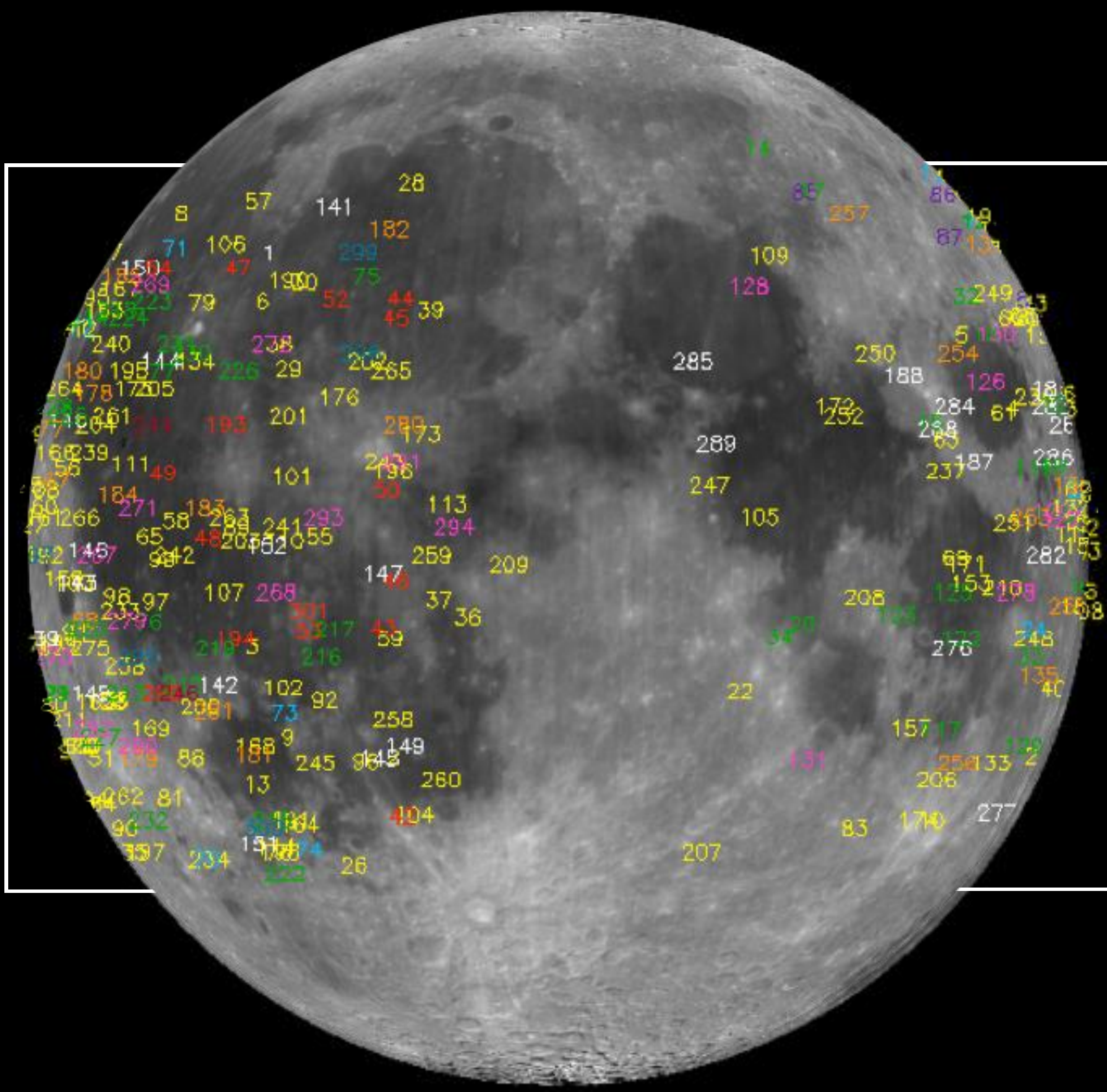
18 Dec 2007 8.6 km uncertainty

Summary

- Differential atmospheric refraction correction is important at large airmasses
  - Geolocation of a red flash on bluish earthshine
  - This effect is easily calculated and corrected
- Geolocation uncertainties are difficult to determine due to the human measurement errors but an approach was developed to account for these
  - Flash location pixel coordinates is very accurate due to centroiding
  - Georeferencing requires a human to locate surface features, frequently in the presence of glare
- Python's mpltoolkits.basemap is useful for conversion between selenographic and orthographic coordinates

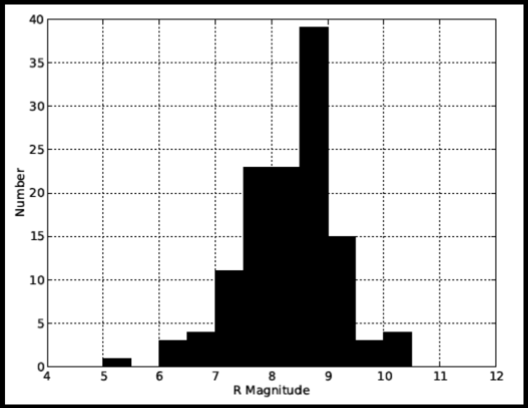
The Flux of Large Meteoroids Observed with Lunar Impact Monitoring

Observation Summary



330+ impacts since 2005

Subset of 126 flashes on photometric nights to 2011
141 hrs evening - 81 flashes
126 hrs morning - 45 flashes
Average: 2.1 hrs/flash
evening/morning = 1.61:1

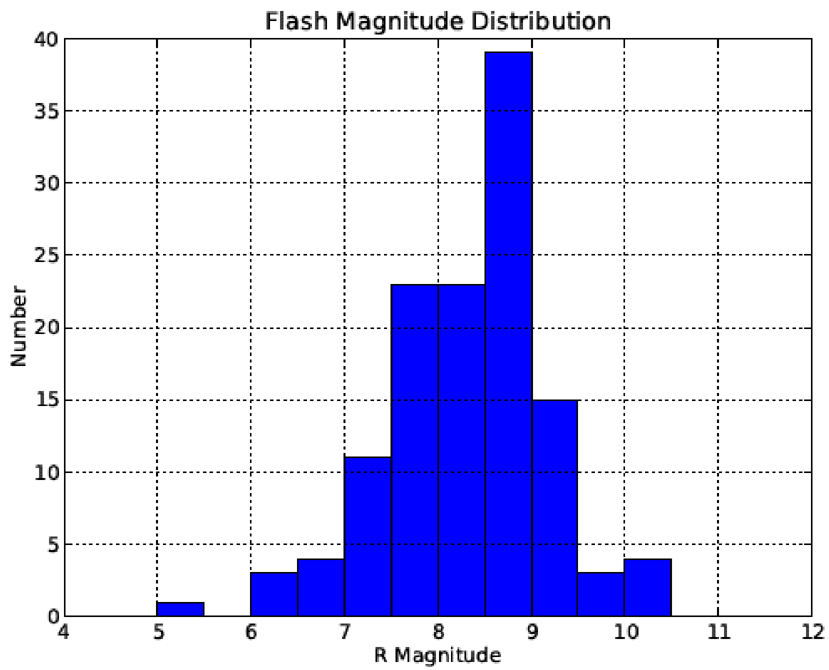


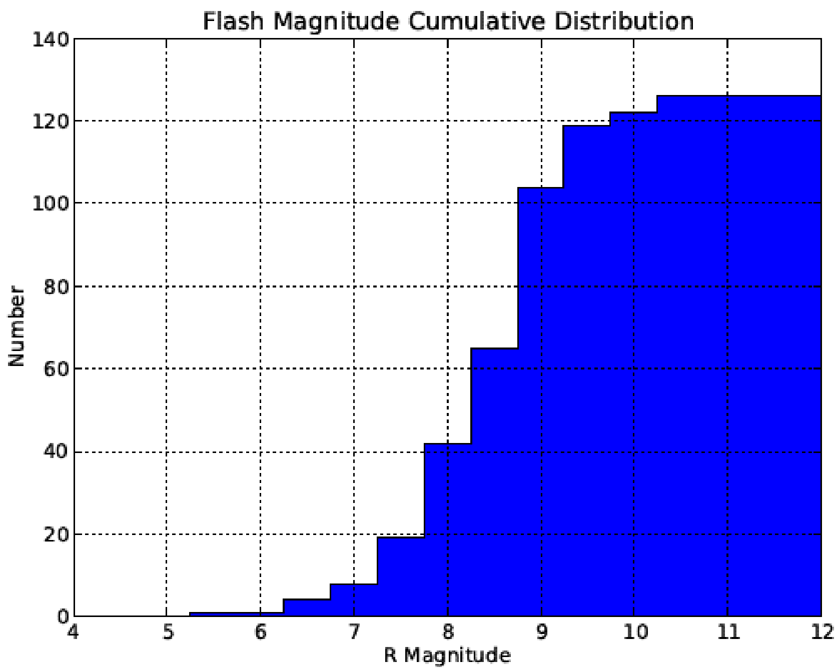
Photometric error ~0.2 mag

Important Points

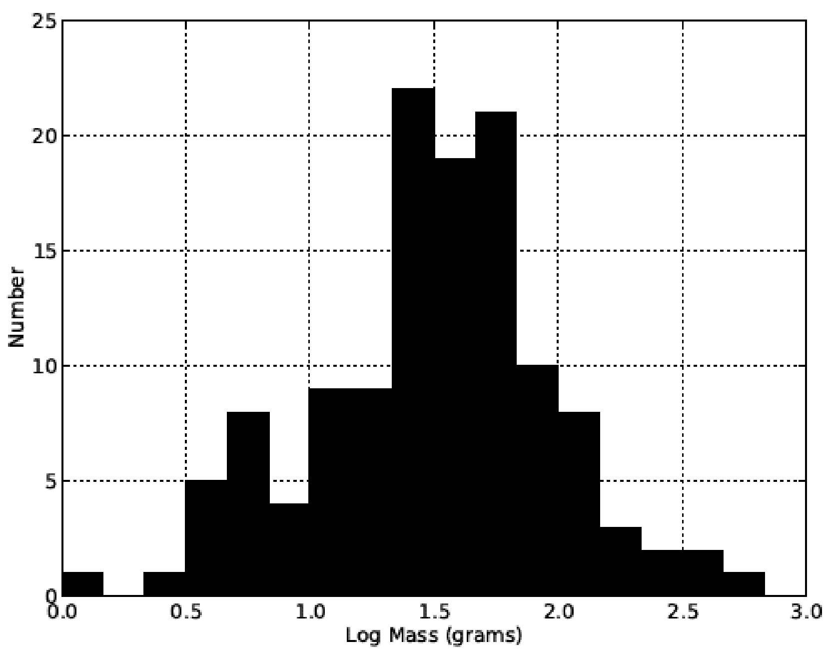
- Flux determination requires a measurement of the number of hours of observation to a particular limiting magnitude
  - Do not count cloudy hours
  - Cumulative peak magnitude diagram is useful
- We use peak magnitude rather than a time integrated magnitude
  - Later phases of an impact “light curve” are dominated by cooling of the ejecta and crater – relation to impact energy is contaminated by regolith properties
  - How long the flash is visible depends on variables such as atmospheric transparency and earthshine

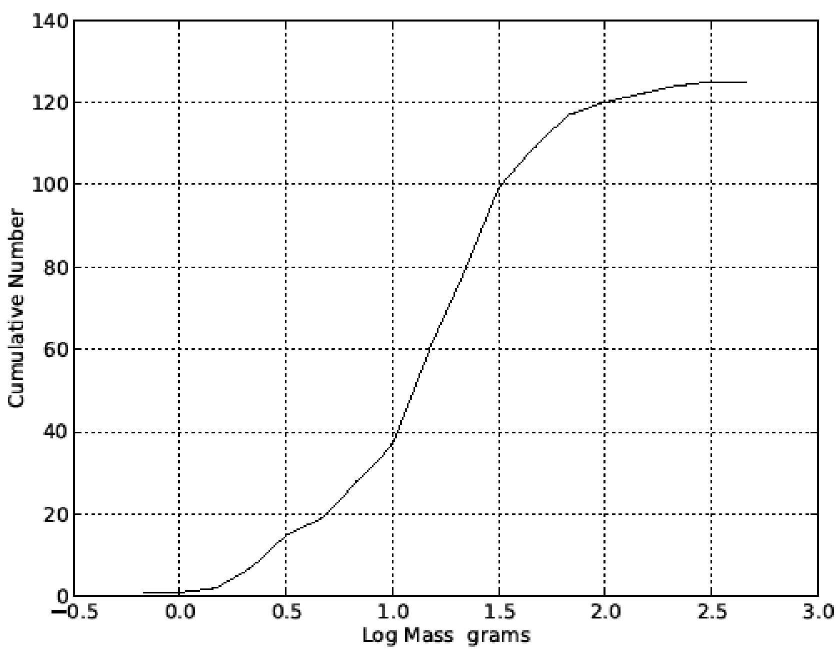
Limiting Magnitude



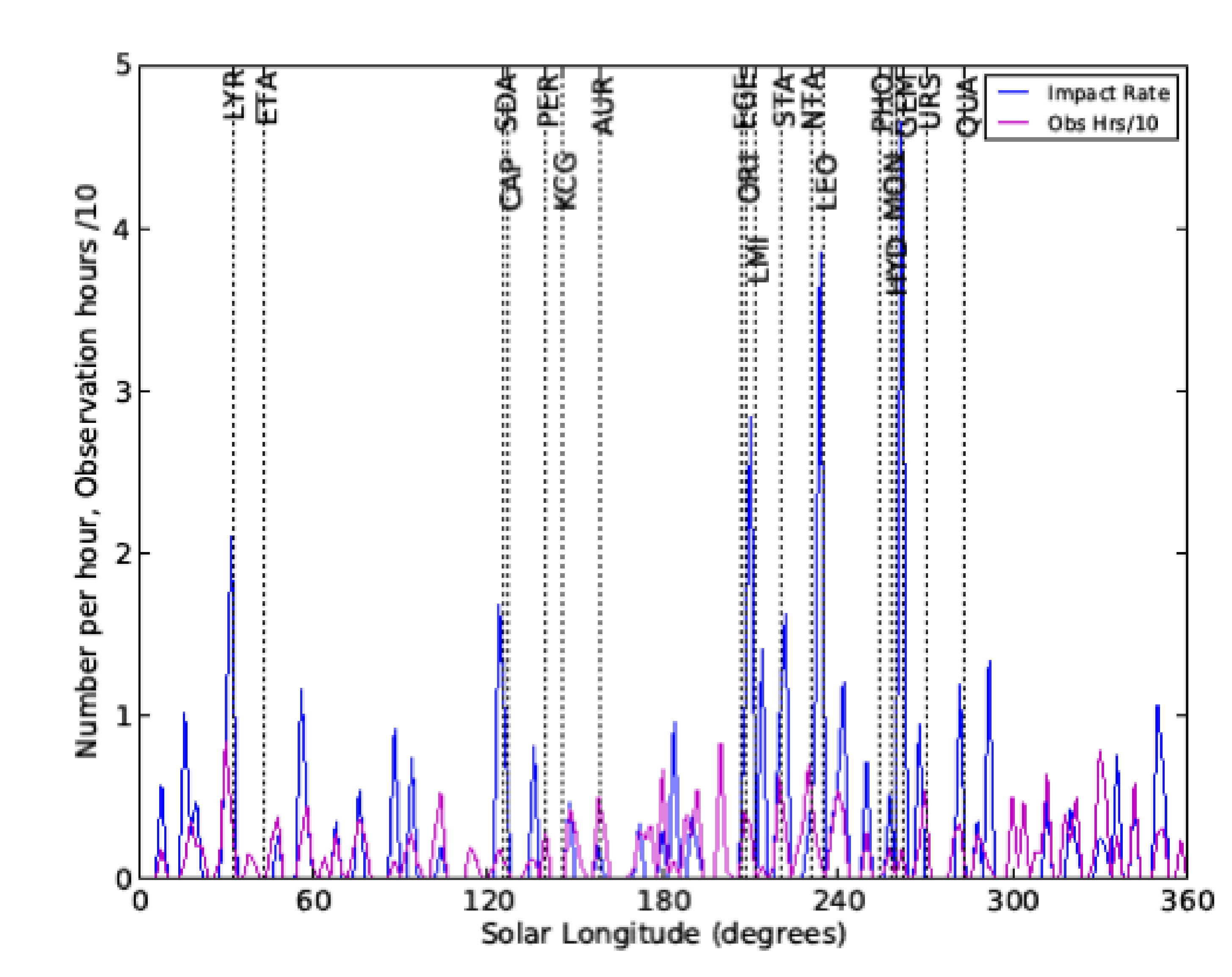


Limiting Mass

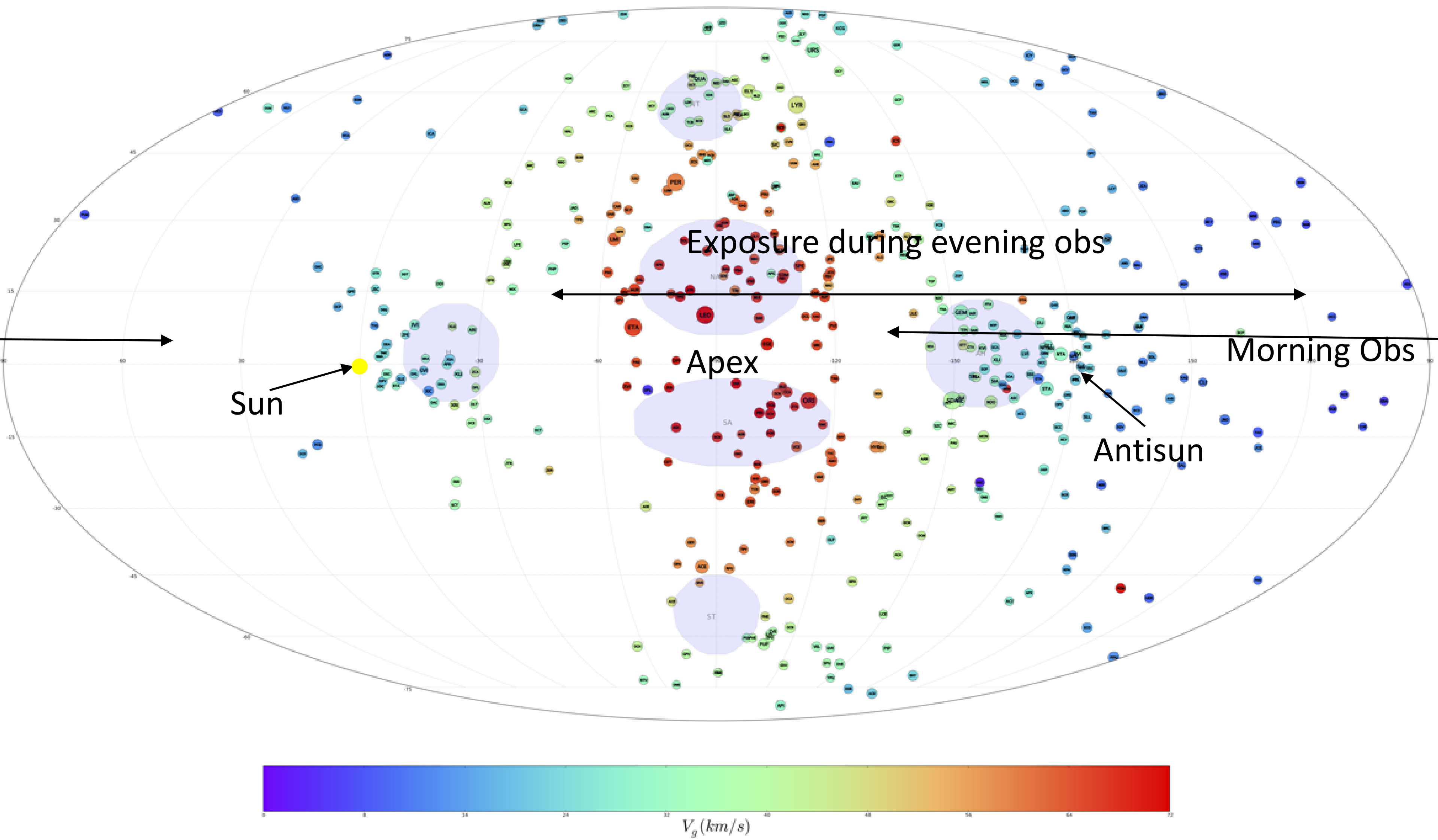




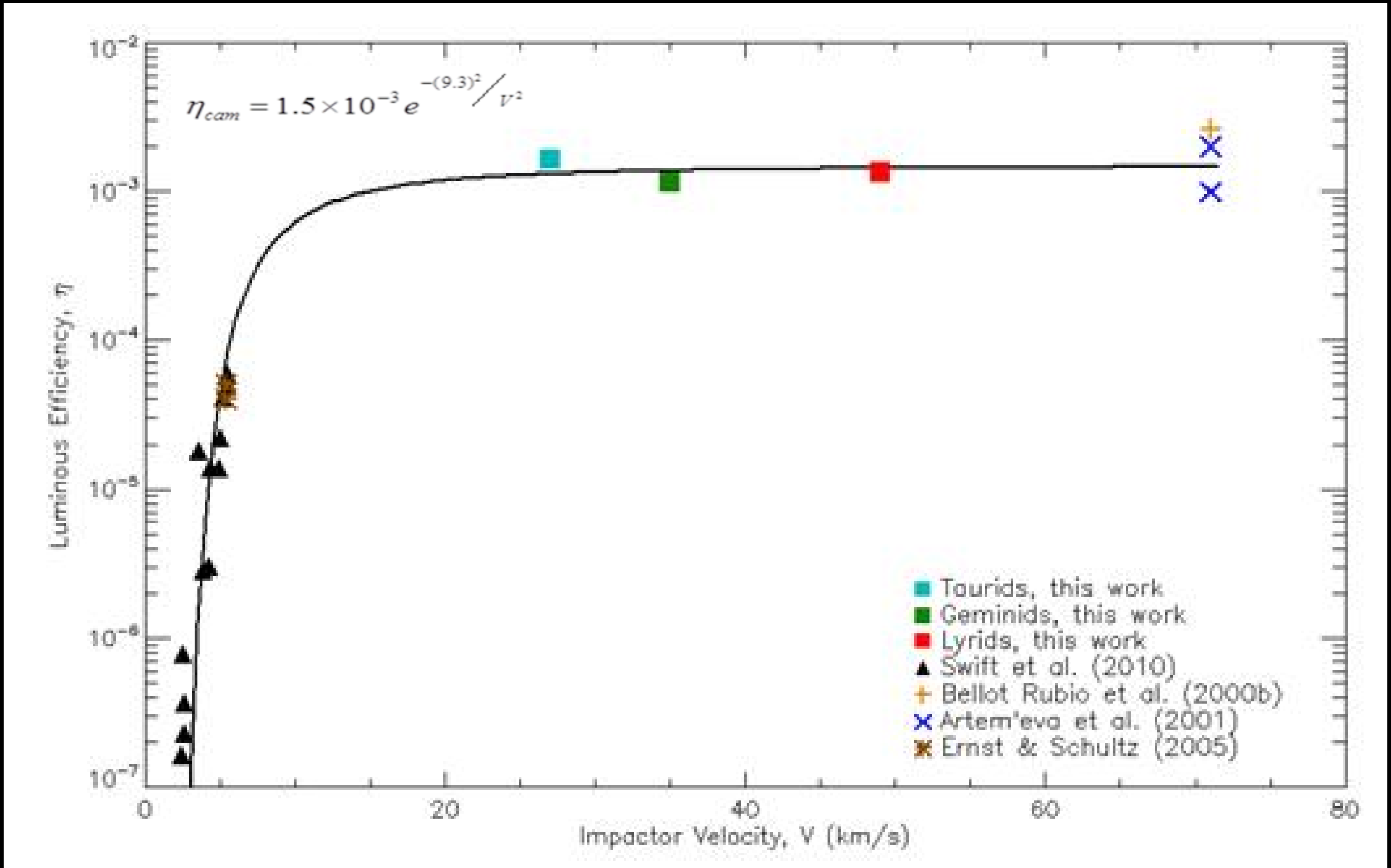
Shower Correlation



Meteor Shower and Sporadic Source Radiants

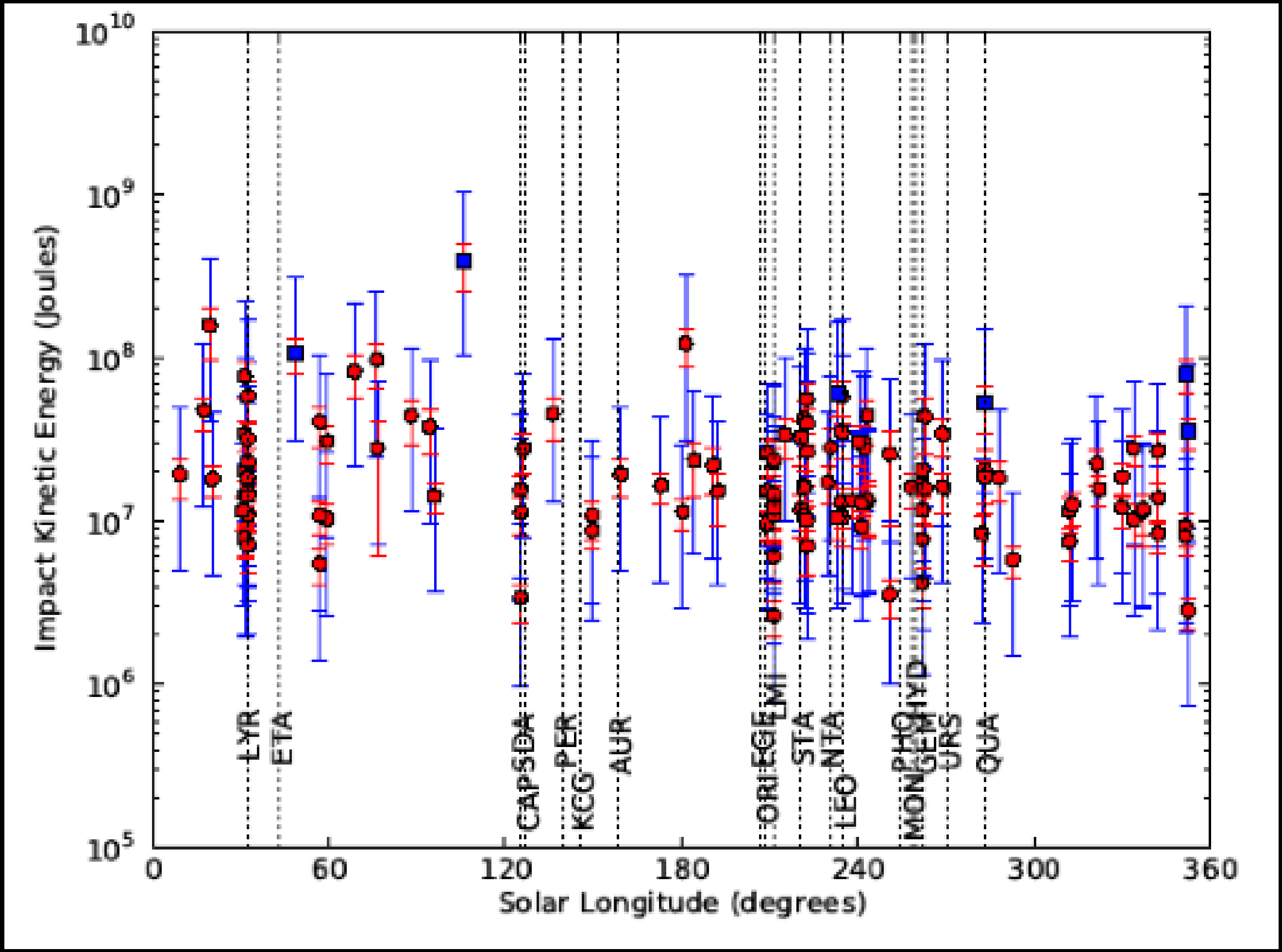


Luminous Efficiency



Moser, D.E. et al., "Luminous Efficiency of Hypervelocity Meteoroid Impacts on the Moon Derived from the 2006 Geminids, 2007 Lyrids, and 2008 Taurids", Meteoroids 2010 Proceedings (NASA CP-2011-216469)

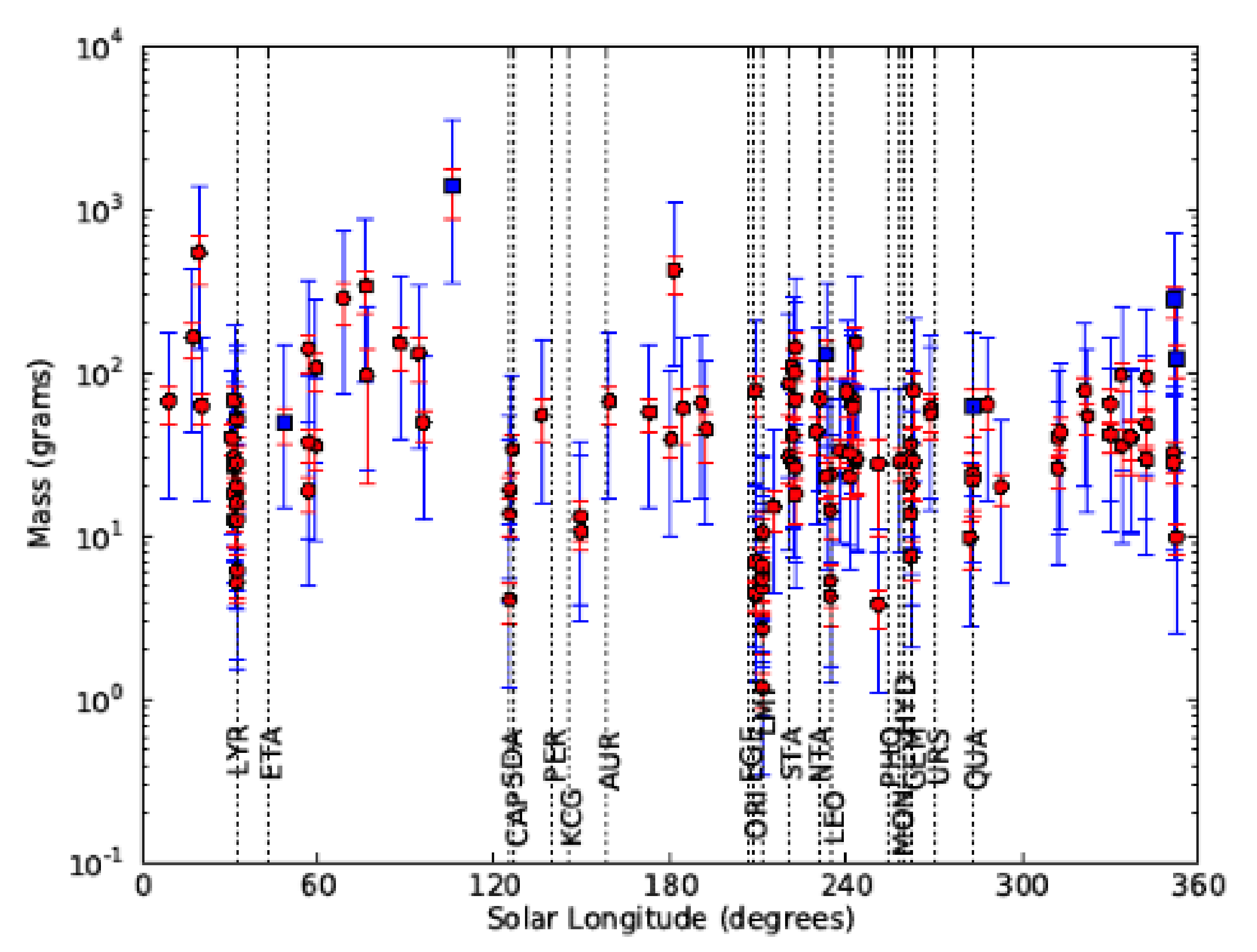
Impact Energy vs Solar Longitude



Red error bars - photometric uncertainty; Blue error bars - luminous efficiency uncertainty
Squares indicate saturation

The flux to a limiting energy of 2.5×10^{-6} kT TNT or 1.05×10^{7} J is 1.03×10^{-7} km^{-2} hr^{-1}

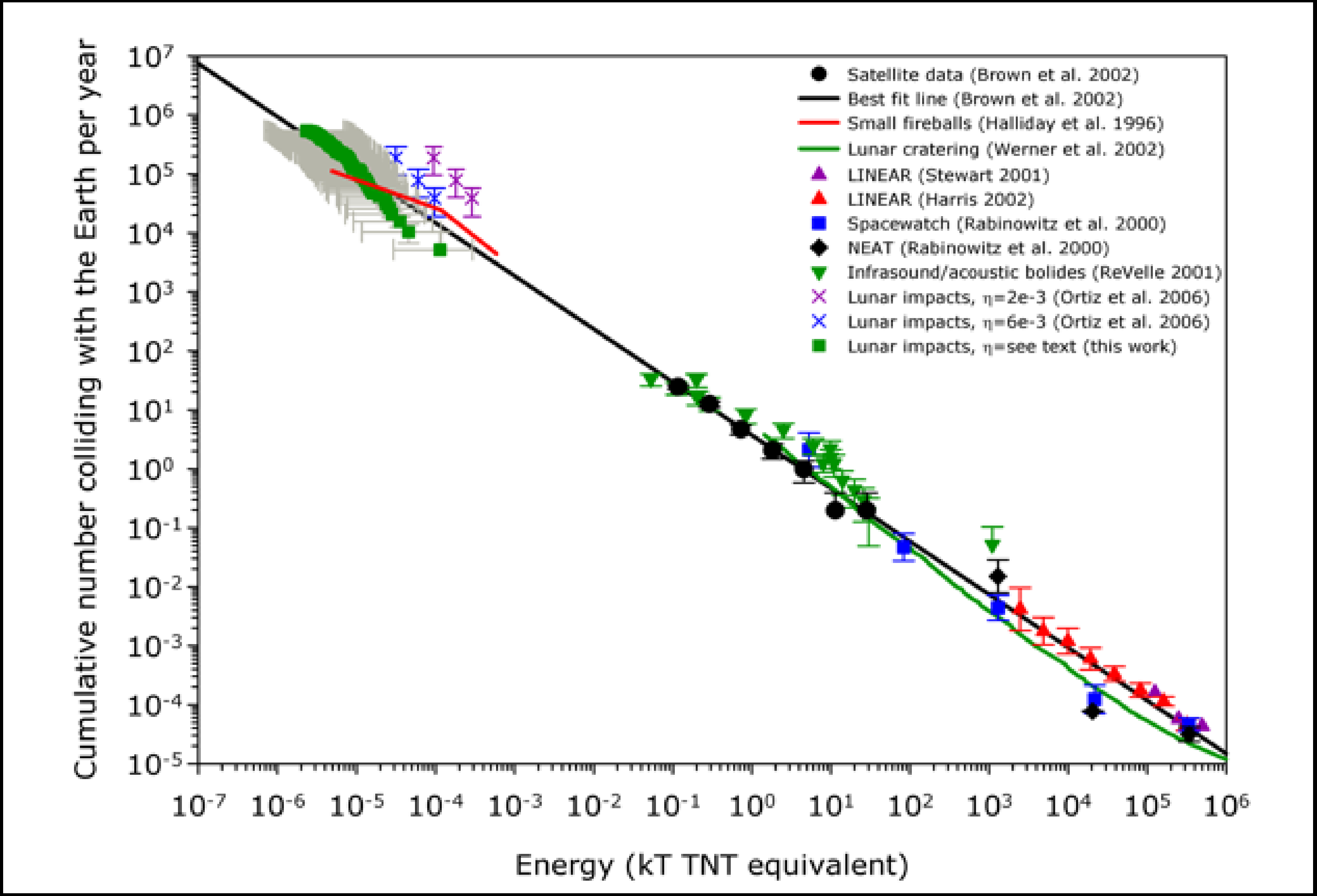
Mass vs Solar Longitude



Red error bars - photometric uncertainty; Blue error bars - range of reasonable luminous efficiencies
Squares indicate saturation

The flux to a limiting mass of 30 g is 6.14×10^{-10} m^{-2} yr^{-1}

Impact Flux Compared with Other Measurements



Summary

- Shower membership determined based on radiant visibility from impact location (zenith distance), time from maximum, and peak zhr (Figure of Merit in Suggs et al. 2014)
- Meteor showers are a significant contributor at cm sizes (>60%) - looking into radiant distribution as possible explanation for observed asymmetry
- Uncertainty in luminous efficiency dwarfs photometric errors
- We have used a rigorous photometric procedure (observation of standards, color and extinction corrections, etc) to derive flash magnitudes
  - Brightest flashes are saturated; energy/mass underestimated
- We have used rigorous criteria for selection of flashes only observed during “photometric” clear periods in the flux determination
- Results consistent with other observational studies