A Comparison of Radiometric Calibration Techniques for Lunar Impact Flashes

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Outline

- The Problem
- Photometric Calibration and Energy Calculation – Various Approaches
- Results of our approach
  - Crater “ground-truth”
  - Meteoroid Flux
- Suggested Refinements

The Problem

- Observations are made with unfiltered cameras to provide maximum sensitivity
- Magnitudes and luminous energies are available for standard stars only in filter passbands
- Determining the energy of the lunar impact flashes requires knowledge of the spectral distribution (color or temperature) of the standards and the impact flash

Basic Photometry and Radiometry

Magnitude determined by observing catalog stars

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

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

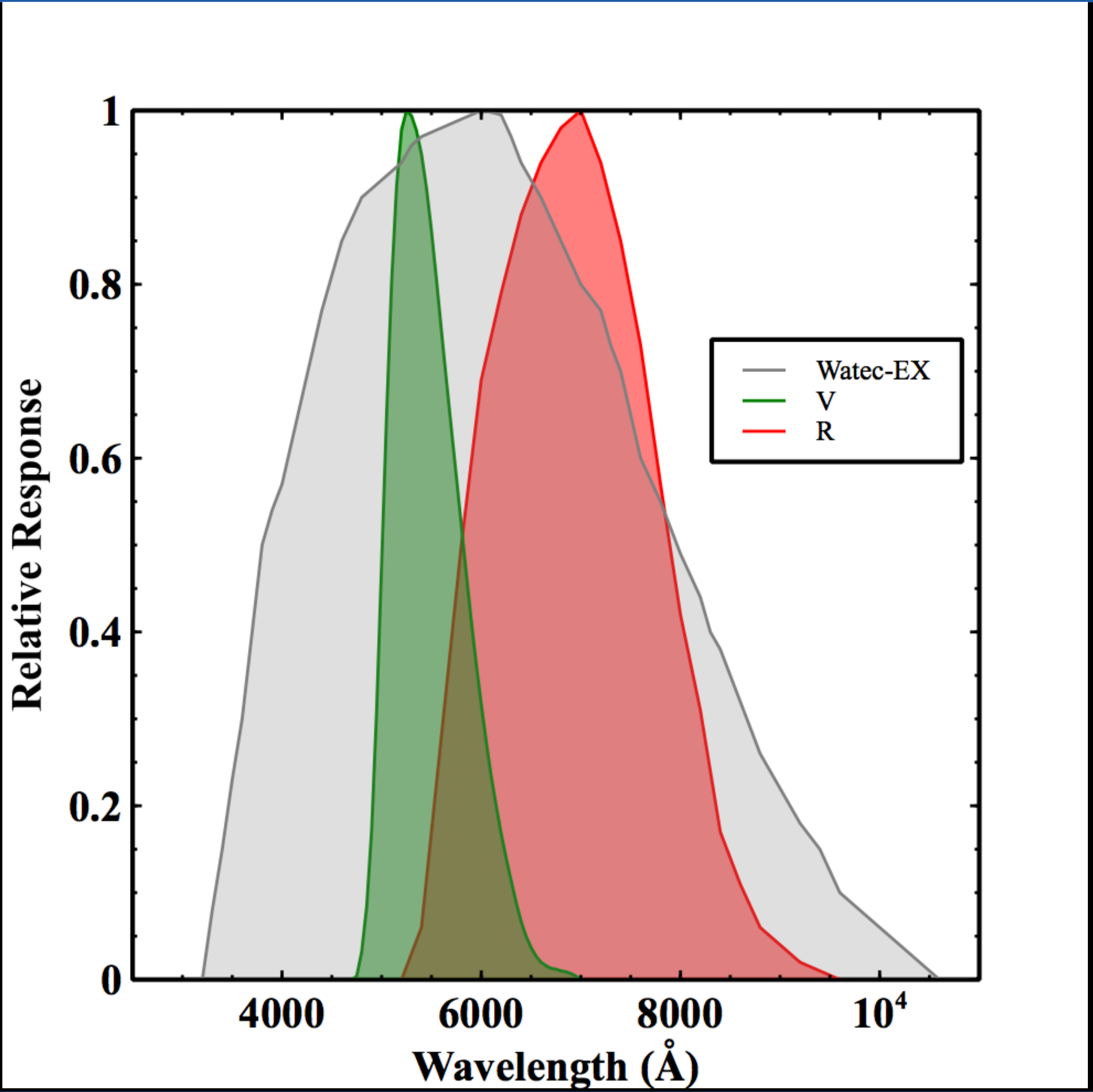
Where $f_{\lambda} = 10^{-7} \times 10^{-(R + 21.1 + zp_R) / 2.5}$ $\text{J cm}^{-2}\,\text{s}^{-1}\,\text{Å}^{-1}$

from Bessell et al. 1998

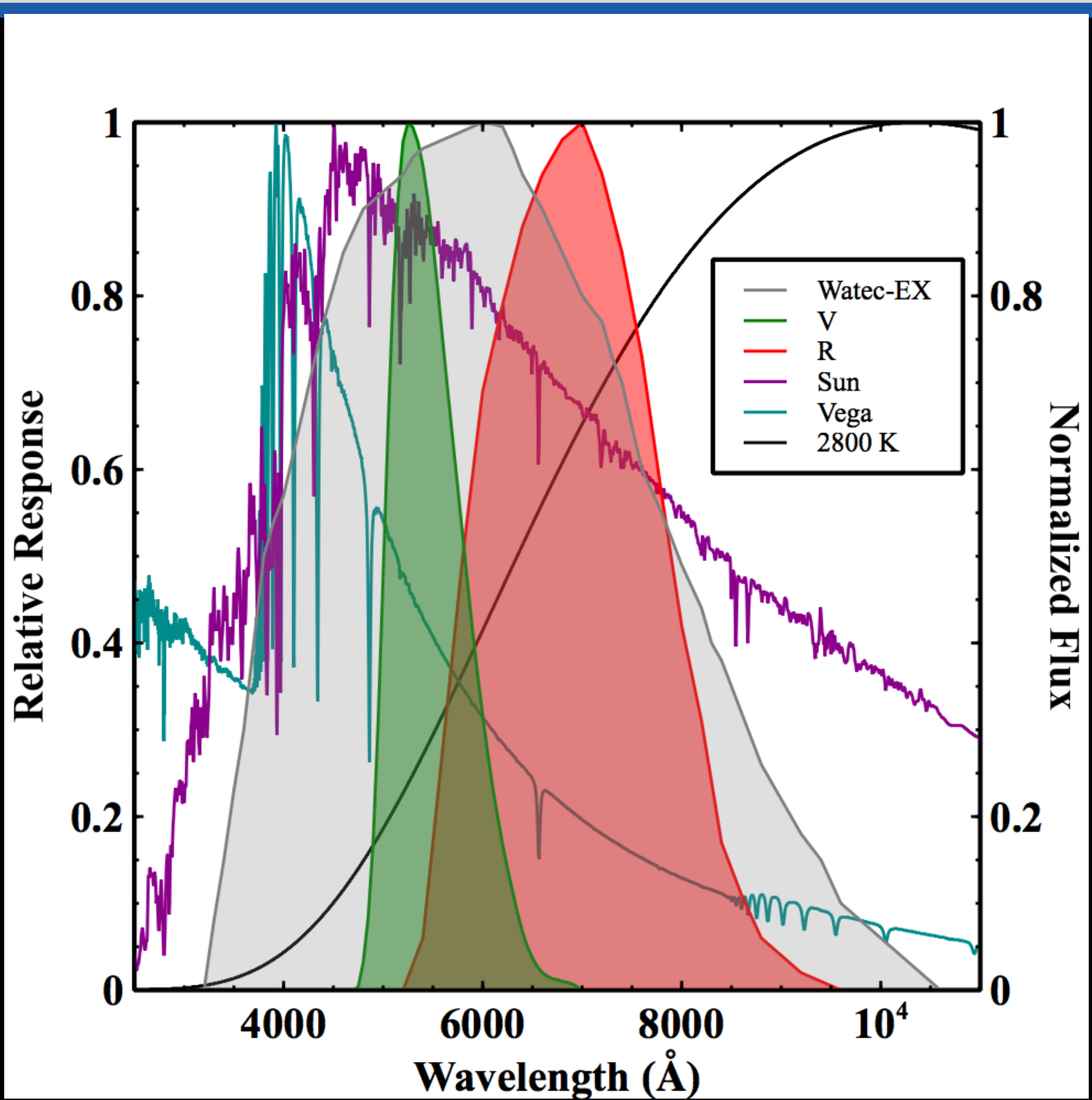
Suggs et al. 2014 and Rembold and Ryan 2015 use these expressions

Other researchers use variations of this

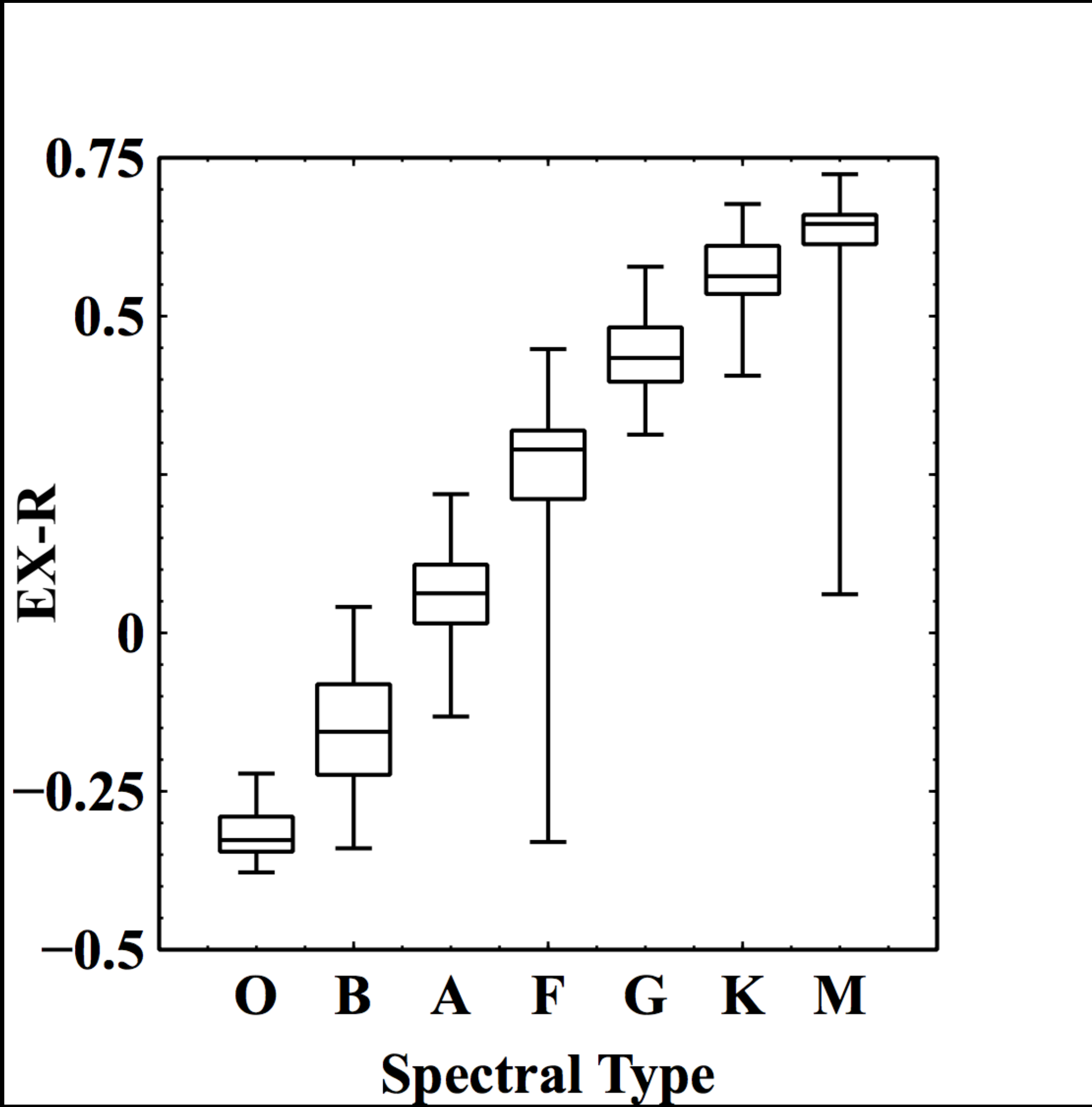
Sony HAD EX (Watec camera) response compared to Johnson-Cousins filters



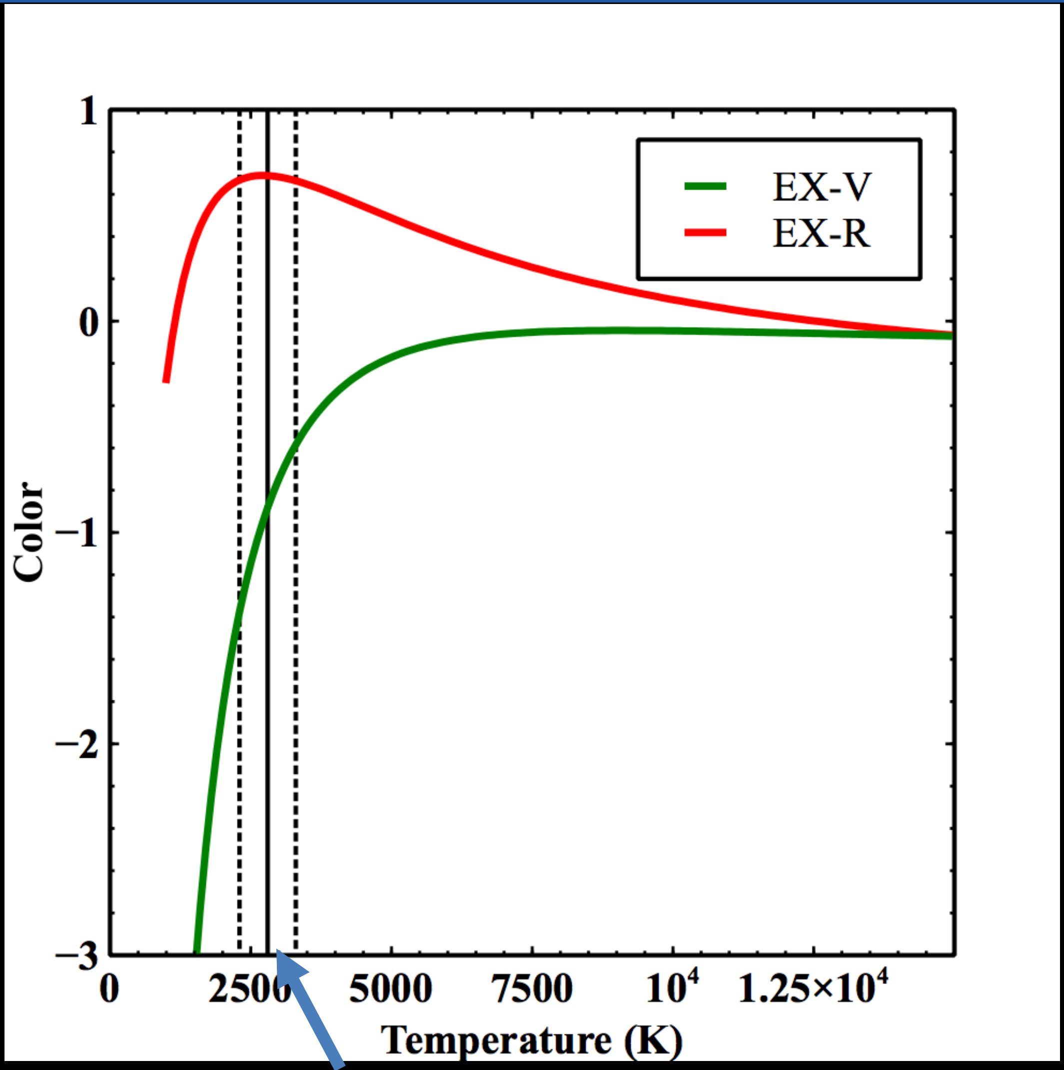
Camera and Filter Responses with Sun, Vega, and Flash Blackbody



Effect of Ignoring Colors of Comparison Stars

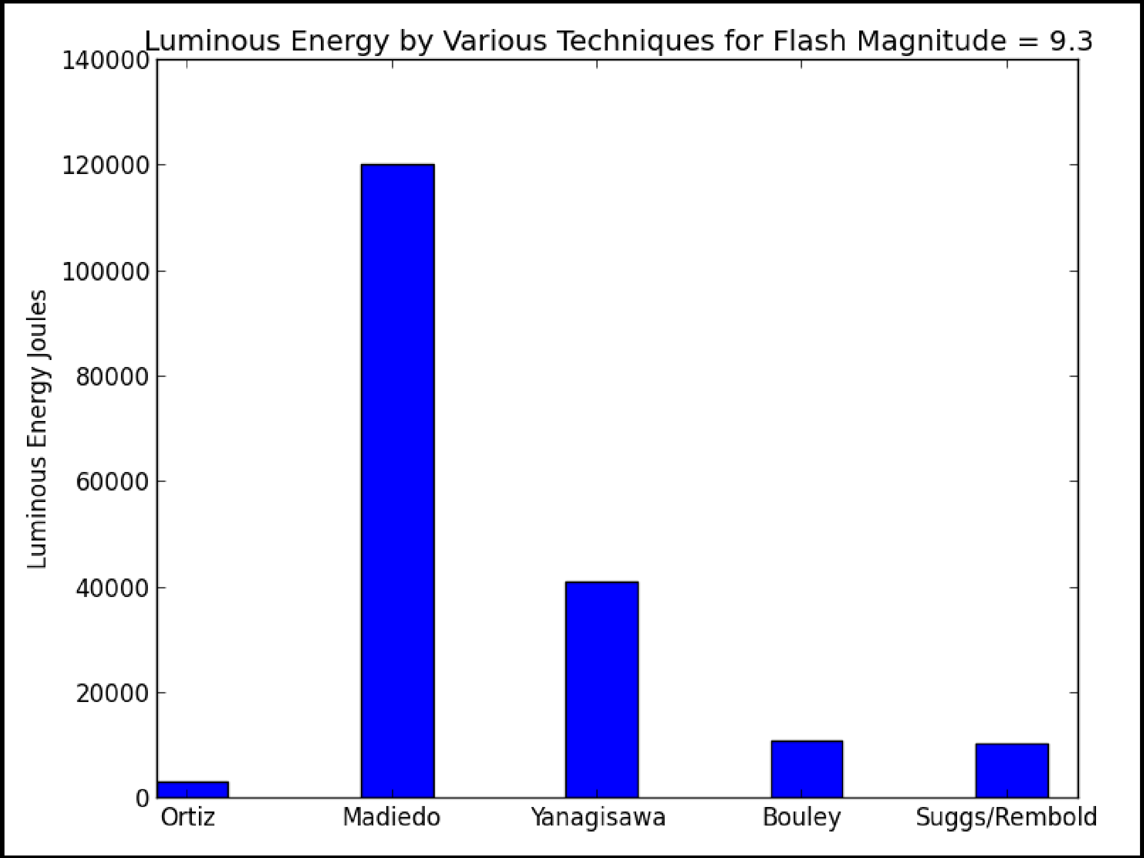


Correction from HAD EX to R filter vs blackbody temperature
R-EX replaces T(B-V)



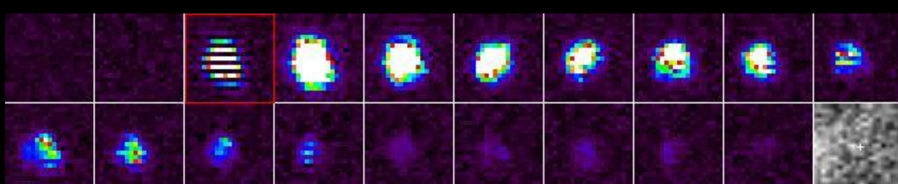
Theoretical peak flash temperature 2800K Nemtchinov et al. (1998)

Comparison of Various Methods



Ortiz published energy at earth for 9.3 magnitude. We multiplied by $dist^2$ and f=3
Yanagisawa is energy published for 9.4 magnitude flash
Suggs and Rembold calibrated to R magnitudes, others are V magnitudes

Ground Truth – Suggs et al. 2014
March 17, 2013 Flash and Crater



17 Mar 2013
03:50:54.312
1.03 s
m_R = 3.0 (saturation corrected)
Virginid

Crater info

- Rim-to-rim diameter = 18 m
- Inner diameter = 15 m
- Depth ≈ 5 m

Transient crater diameter estimates

Assumptions: Virginid v_{gfoc}=25.7 km/s, θ_h = 56°; ρ_t = 1500 kg/m^3 (regolith)

Model	Lum eff. η	KE ×10^9 (J)	Mass (kg)	ρ_p (kg/m^3)	D_{calc} (m)	D_{obs} (m)	% Err
Gault's crater scaling law (Gault 1974)	5×10^{-4} (Bouley et al. 2012)	14 [9.4,22]	42 [28,66]	1800	18.5 [16.5,21.1]	15	23%
				3000	20.2 [18.0,23.0]	15	35%
	1.3×10^{-3} (Moser et al. 2011)	5.4 [3.6,8.4]	16 [11,26]	1800	14.1 [12.5,16.0]	15	6%
				3000	15.3 [13.6,17.4]	15	2%
Holsapple's online calculator (Holsapple 1993)	5×10^{-4}	14 [9.4,22]	42 [28,66]	1800	12.2 [10.9,13.8]	15	19%
				3000	12.5 [11.1,14.2]	15	17%
	1.3×10^{-3}	5.4 [3.6,8.4]	16 [11,26]	1800	9.3 [8.3,10.5]	15	38%
				3000	9.5 [8.5,10.8]	15	37%

Two example values of η from the literature yield large ranges for KE and mass. Consequently, model results are highly dependent on luminous efficiency η.

Assuming a velocity dependent η = 1.3×10^{-3}, these model results are consistent with the observed crater diameters.

D_{calc} = 8-18 m transient crater
D_{calc} = 10-23 m rim-to-rim

D_{obs} = 15 m inner ('transient')
D_{obs} = 18 m rim-to-rim

Other Considerations (1)
Peak vs Time-Integrated Flash Energy

- Flashes can last for several video frames
- We use peak flash (1/60 sec video field) to avoid contaminating the energy calculation with regolith property and droplet cooling rates
  - Yanagisawa et al. 2002 and Bouley et al. 2012 discuss light curve physics extensively

Other Considerations (2)
Standard Photometric Calibration

- Flat fielding is important especially when focal reducers are used to increase field-of-view
  - Vingetting near the field edges can significantly affect magnitude measurements
- Dark signal is not significant at video exposure times
- Standard extinction corrections are necessary
  - Flash observations may be at higher airmasses than would ordinarily be used for astronomical photometry
- Atmospheric scintillation must be considered as an error source at video exposure times
- Non-linear camera response (gamma) must be corrected when used
  - Provides better dynamic range at low end of sensitivity
- Saturation correction may be necessary for brightest flashes

Suggested Refinements

- Record flashes in standard filter passbands
  - V, R, I for example
  - Downside is reduced sensitivity, need larger aperture
- For existing unfiltered data use an approach similar to Ehlert 2016
  - Use a catalog of stellar spectra to define a CCD "filter" response
  - Downside – spectral energy distribution of comparison star must be well-known
- Investigate use of Gaia spacecraft catalog (Jordi et al.), similar bandpass to HAD EX cameras
- Always designate luminous efficiency bandpass
  - η_R, η_I, η_{CCD}, etc.

Summary

- Early lunar impact observers made approximations in photometric calibration which led to biases in energy estimations
  - Passband too wide
  - Assumed flash spectral distribution uniform across entire passband
- More accurate energy estimates can be made using color corrections between standard filters and camera response
  - Assume flash temperature/color
  - Account for colors of comparison stars
- Camera-defined "filter" can be derived using SynPhot or Gaia catalog observations (Jordi et al., 2010)
  - http://www.stsci.edu/institute/software_hardware/stsdas/synphot

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Ortiz, J.L., Madiedo, J.M., Morales, N., Santos-Sanz, P., Aceituno, F.J., 2015. Lunar impact flashes from Geminids: analysis of luminous efficiencies and the flux of large meteoroids on Earth. MNRAS 454, 344-352.

Rembold. J.J., Ryan, E.V., 2015. Characterization and analysis of near-earth objects via lunar impact observations. Planetary and Space Science, 117, 119-126.

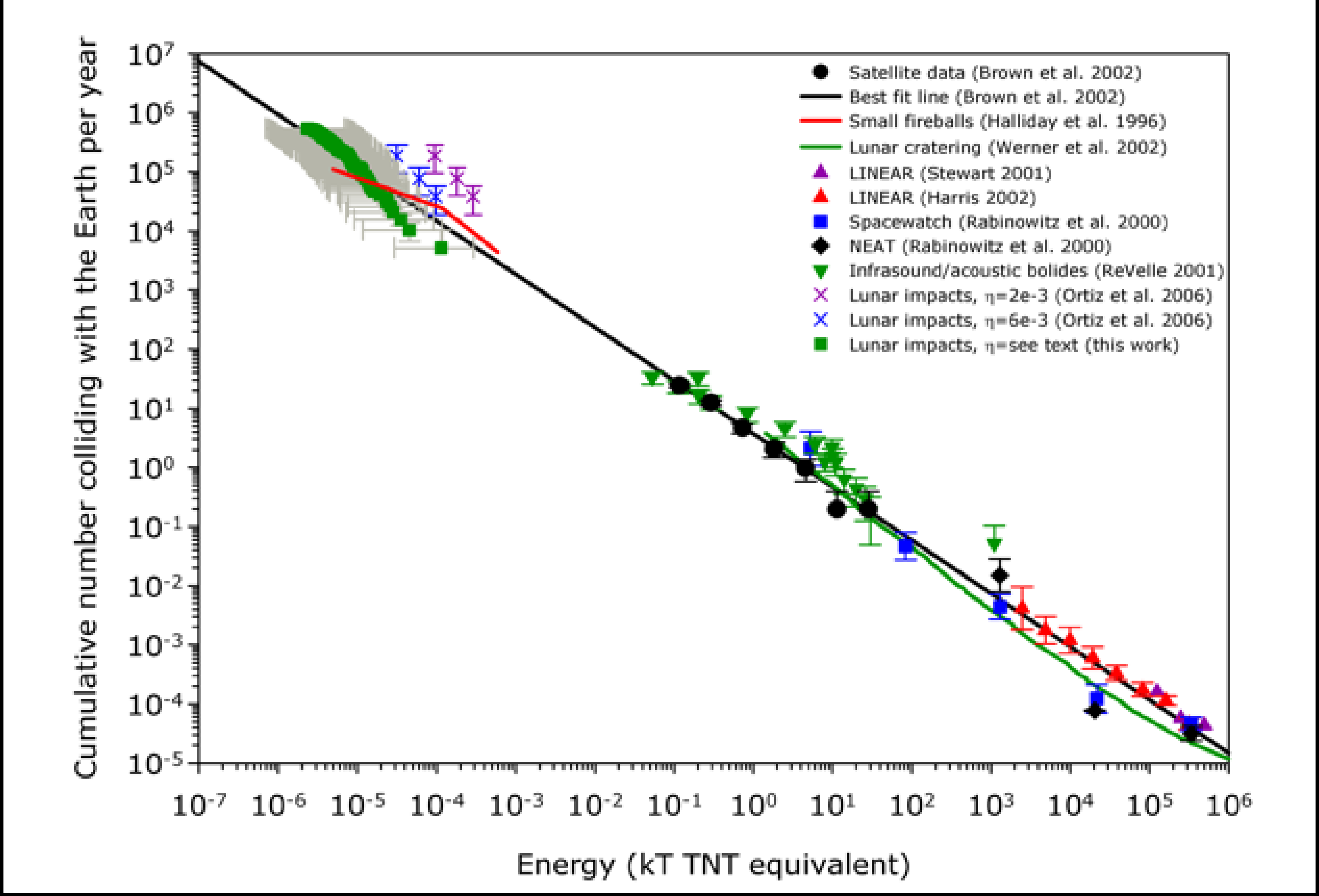
Suggs, R.M., Moser, D.E., Cooke, W.J., Suggs, R.J., 2014. The flux of kilogram-sized meteoroids from lunar impact monitoring. Icarus 238, 23-36.

Swift, W.R., Moser, D.E., Suggs, R.M., Cooke, W.J., 2011. An exponential luminous efficiency model for hypervelocity impact into regolith. In: Proceedings of the Meteoroids 2010 Conference, NASA CP-2011-216469, pp. 124-141.

Yanagisawa, M., Kisaichi, N., 2002.. Lightcurves of 1999 Leonid impact flashes on the moon. Icarus 159, 31-38.

Backup

Impact Flux at Earth Compared with Other Measurements



After Brown et al. (2002)
with adjustments for gravitational focusing and surface area of Earth at 100km altitude

Historical Approaches (1)

- Ortiz et al. – assumes energy in the V filter uniformly distributed across almost entire CCD bandwidth
  - Ref. 2001 and later? – not much detail
  - Shortcomings - leads to overestimate of energy by a factor of 2?
    - Assumed passband is even greater than FWHM of camera response (500 nm vs 400 nm)
    - Flash blackbody curve drops off rapidly and isn't flat across the camera passband
    - Need calculation for this…

Historical Approaches (2)

- Yanagisawa et al. (2002, 2006, 2008)
  - Compare flash signal to comparison star
  - Assume blackbody spectrum for comparison
  - Integrate across camera passband (400-800nm) assuming flat response
  - Shortcomings - statements in 2006 paper
    - "The spectral response of the cameras is not flat in the wavelength range between 400 and 800 nm… and the cameras have some sensitivity outside this range"
    - "The difference between the spectra for the flash and the comparison star will thus lead to some error in the calculated flux"
    - Estimated a factor of 2 error from these issues and lack of flat/dark corrections

Historical Approaches (3)

- Bouley et al., 2012, Icarus 218, 115-124.
  - $P = 183 \times 10^{-(m + 26.74)/2.5}$ sun power integrated in the visual domain (Pogson method)
  - $Ed = P * t / 2$ flash power and duration integrated over all frames assuming linear decrease
  - $E = Ed\, \pi\, f\, d^2 / \eta$
    - d = 384400 km, f = 2 (hemispherical emission)
    - $\eta = 2 \times 10^{-3}$ with range from 5×10^{-4} to 5×10^{-3}
  - Used published magnitudes from Ortiz, Yanagisawa, Cooke (mixed bag of V and R magnitudes)
  - Shortcomings
    - "Visual domain" not defined relative to camera response
    - Stellar calibration filter passband not specified
    - Time-integrated flash vs. peak flash

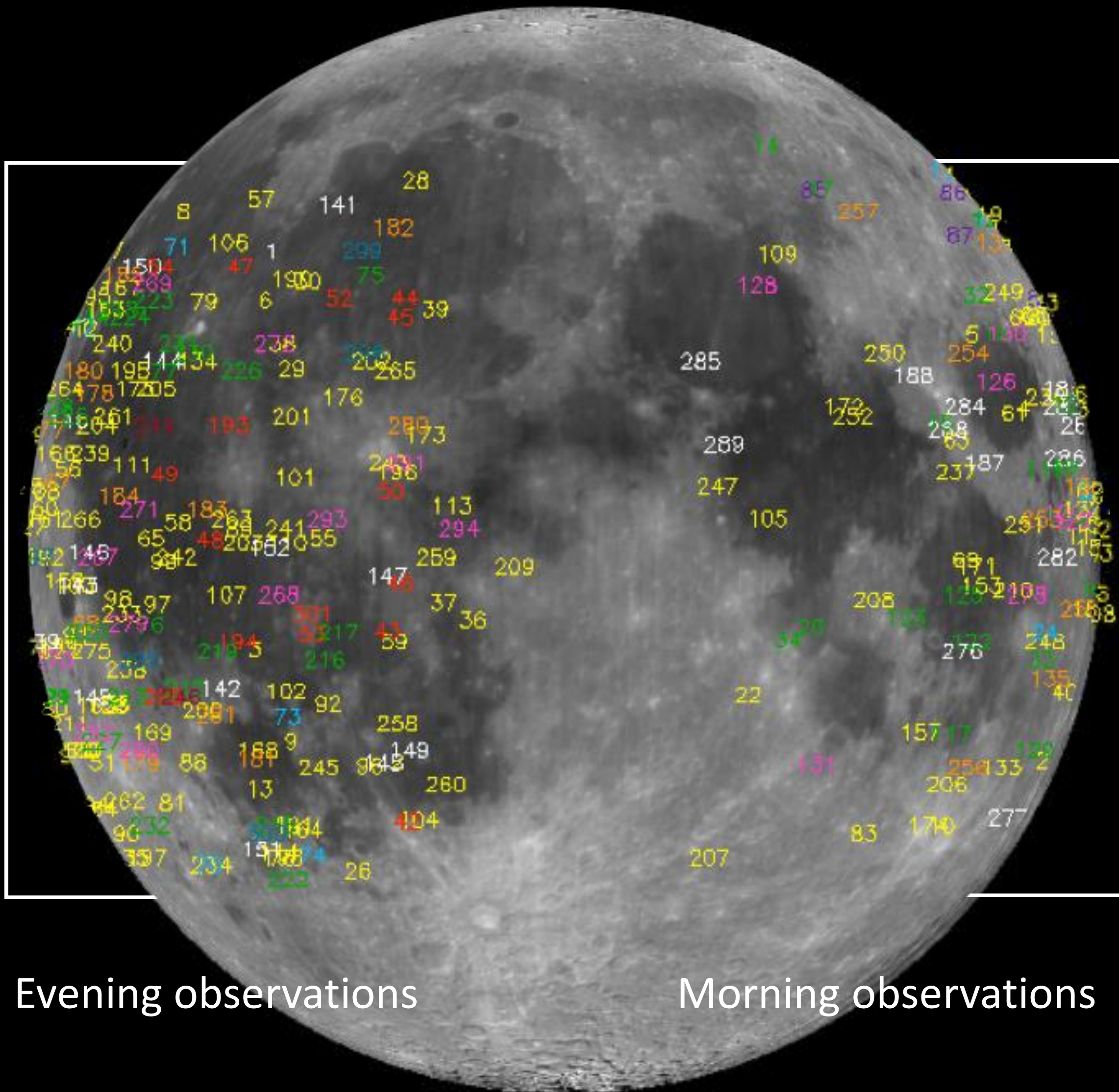
Historical Approaches (4)

- Suggs et al. 2014 (also Rembold and Ryan, 2015)
- Color correction using conventional astronomical photometric approach
  - Uses B-V colors of comparison stars to determine color correction term
  - Assumes blackbody temperature of flash from Nemtchinov modeling to correct to R filter (peak and FWHM)
    - We need good measurements of flash temperatures using measurements in independent filters (V-R, R-I, etc.)

10 Years of Observations

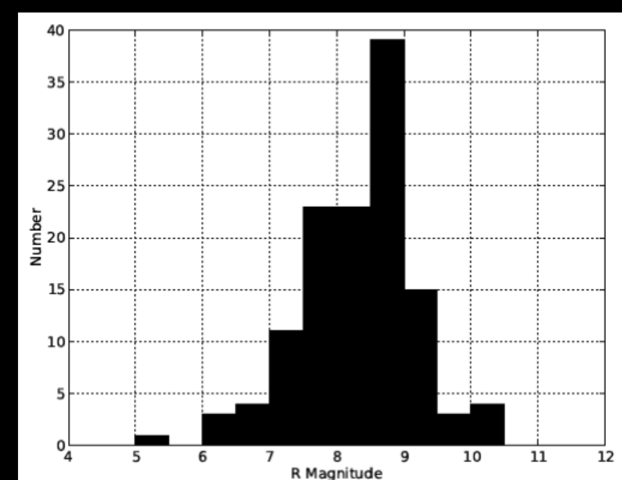
- The MSFC lunar impact monitoring program began in 2006 in support of environment definition for the Constellation Program
  - Needed a model/specification for impact ejecta risk
- Work continued by the Meteoroid Environment Office after Constellation cancellation
  - Lunar impact monitoring allows measurement of fluxes in a size range not easily observed (10s of grams to kilograms)
- A paper published in Icarus reported on the first 5 years of observations
  - **Icarus:** http://www.sciencedirect.com/science/article/pii/S0019103514002243
  - **ArXiv:** http://arxiv.org/abs/1404.6458

Observation Summary



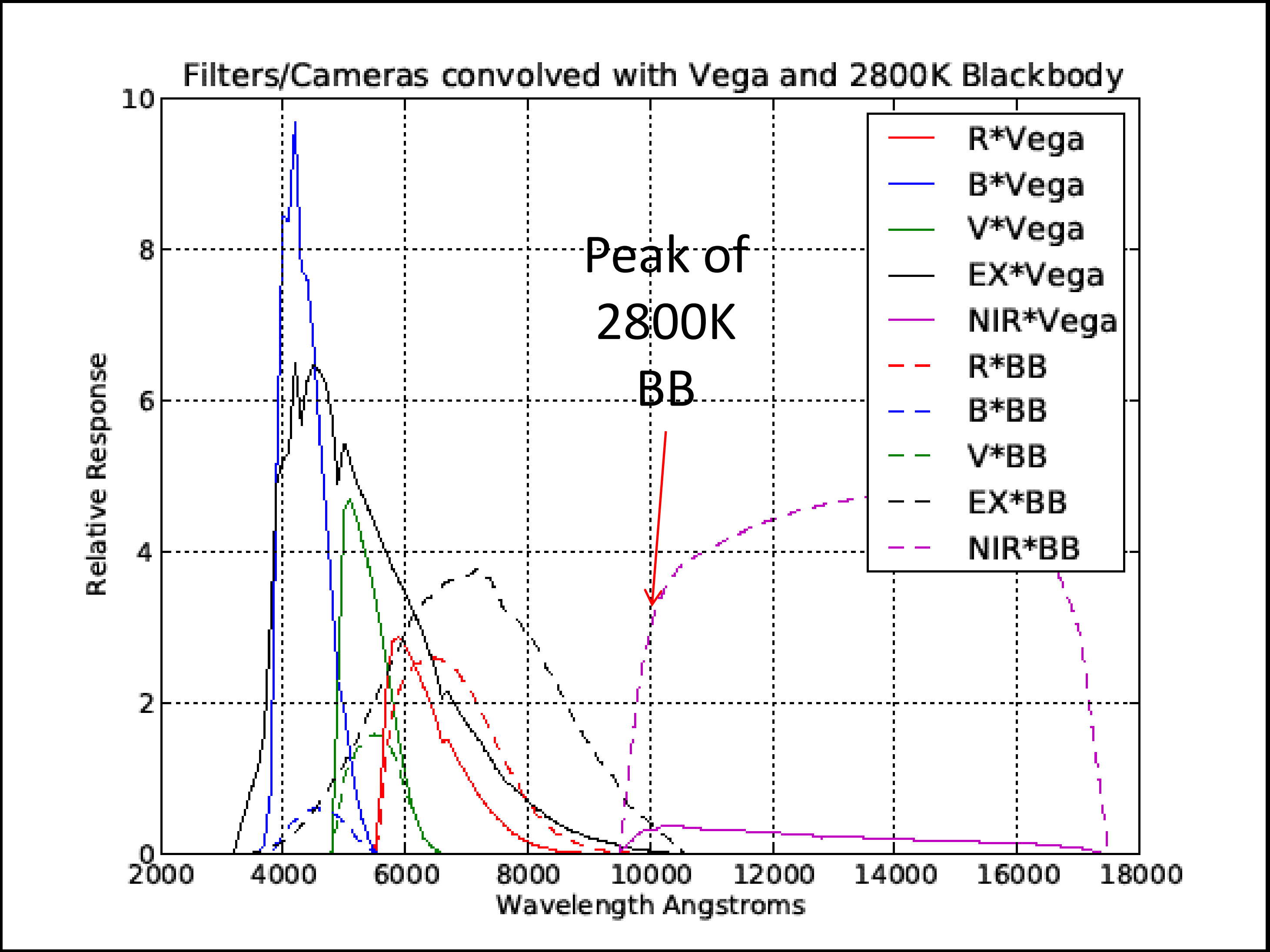
394 impacts since 2005

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 = 1.6:1

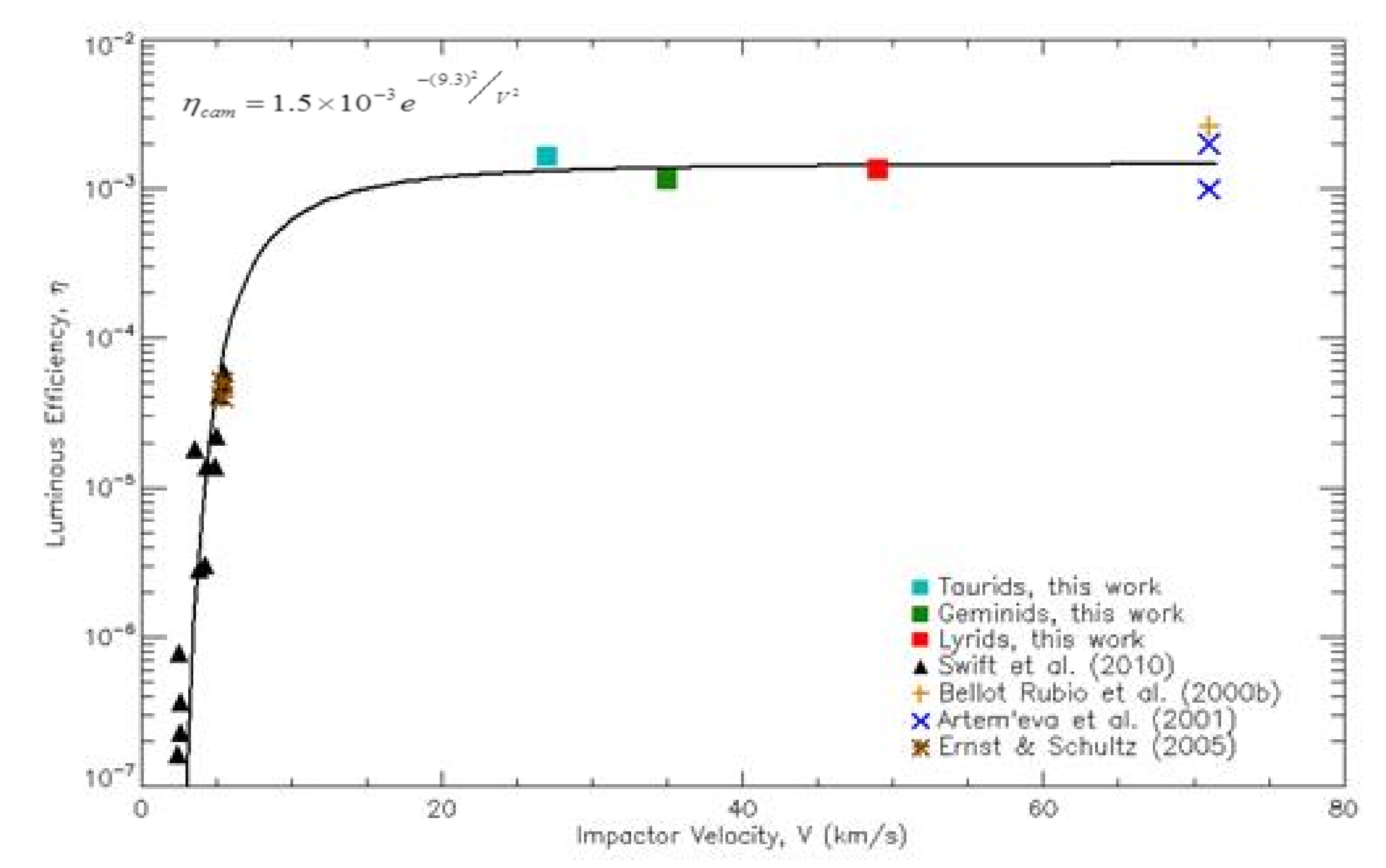


Photometric error ~0.2 mag

Filter and camera responses depend on color of object



Luminous Efficiency



From Moser et al. (2011)

Mass of the impactor assuming impact speed (shower or sporadic)

Luminous efficiency

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

v = impact speed in km/s

Kinetic Energy

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

Mass

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

Calibration: Magnitude Equation

Parameters determined by observing stars with known magnitudes

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

- R = Johnson-Cousins R magnitude
- k' = extinction coefficient
- X = airmass (zenith = 1.0)
- T = color response correction term
- $(B\text{-}V)$ = color index
  - Replace *T(B-V)* with *R-EX* for flash (next slide)
- ZP = photometric zero point for the night

$S = DN^{1/0.45}$ if camera gamma set to 0.45 which improves contrast near bottom of dynamic range

- DN = pixel value 0 – 255

Luminous energy from impact peak 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, 4 for free space

d = distance from Earth to the Moon

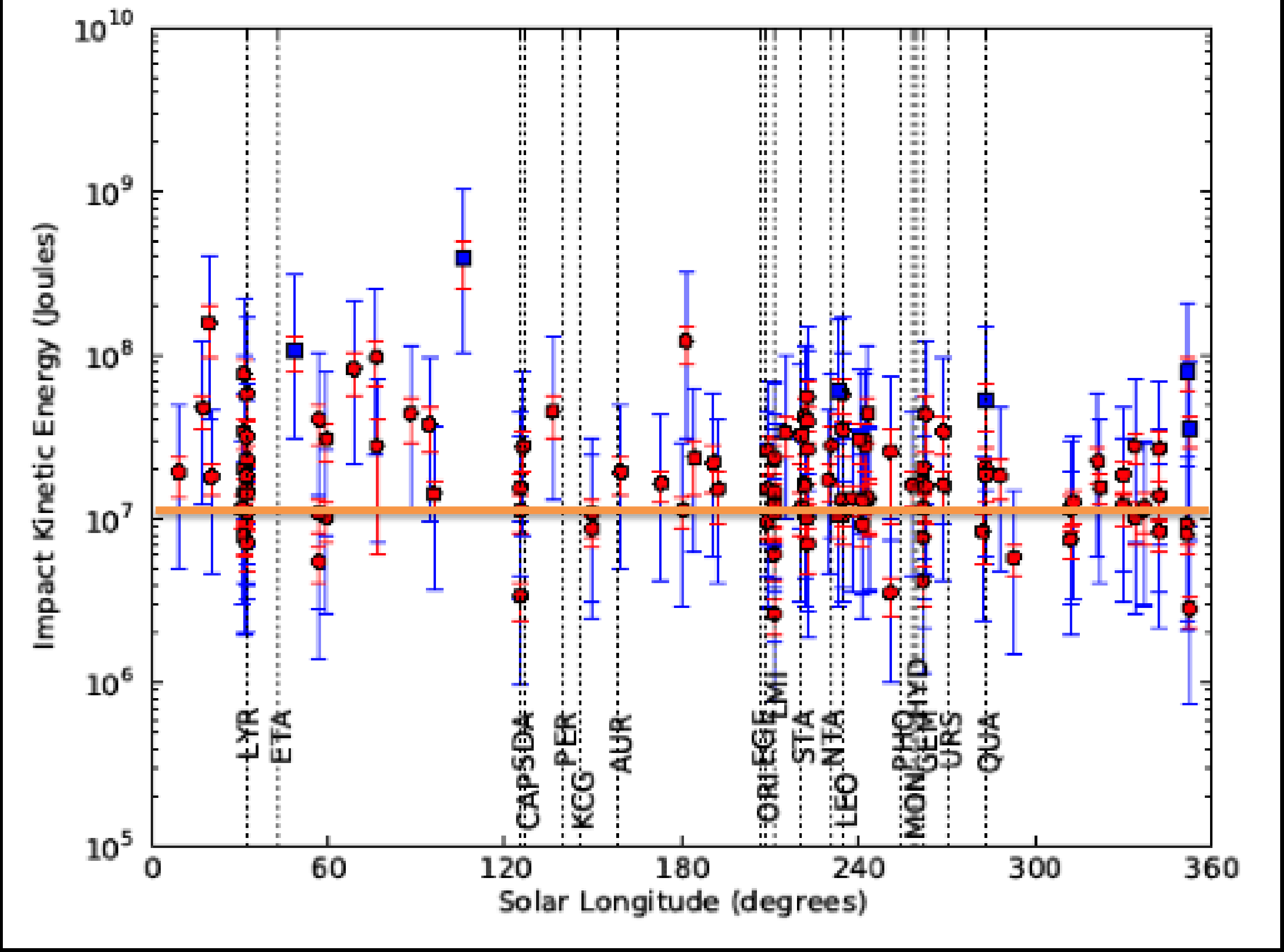
t = exposure time, 0.01667 for a NTSC field

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

R = the R magnitude

zp_R= 0.555, photometric zero point for *R* from Bessell et al. (1998). This is not the same as *ZP* in magnitude equation)

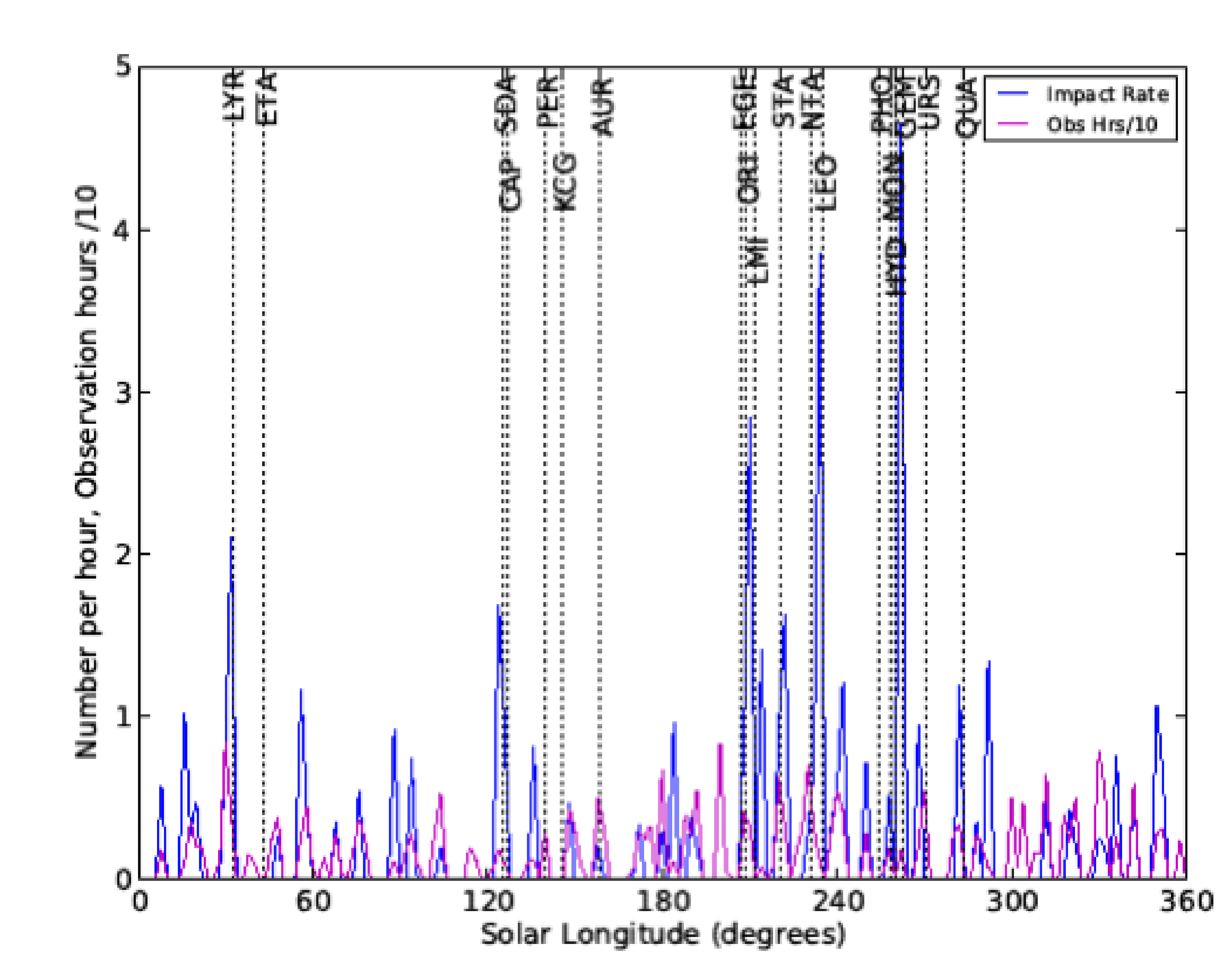
Impact Energies



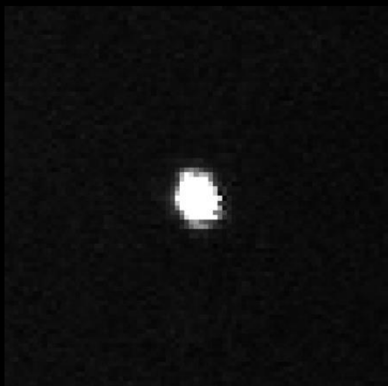
Red error bars - photometric uncertainty; Blue error bars - luminous efficiency uncertainty
Squares indicate saturation

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

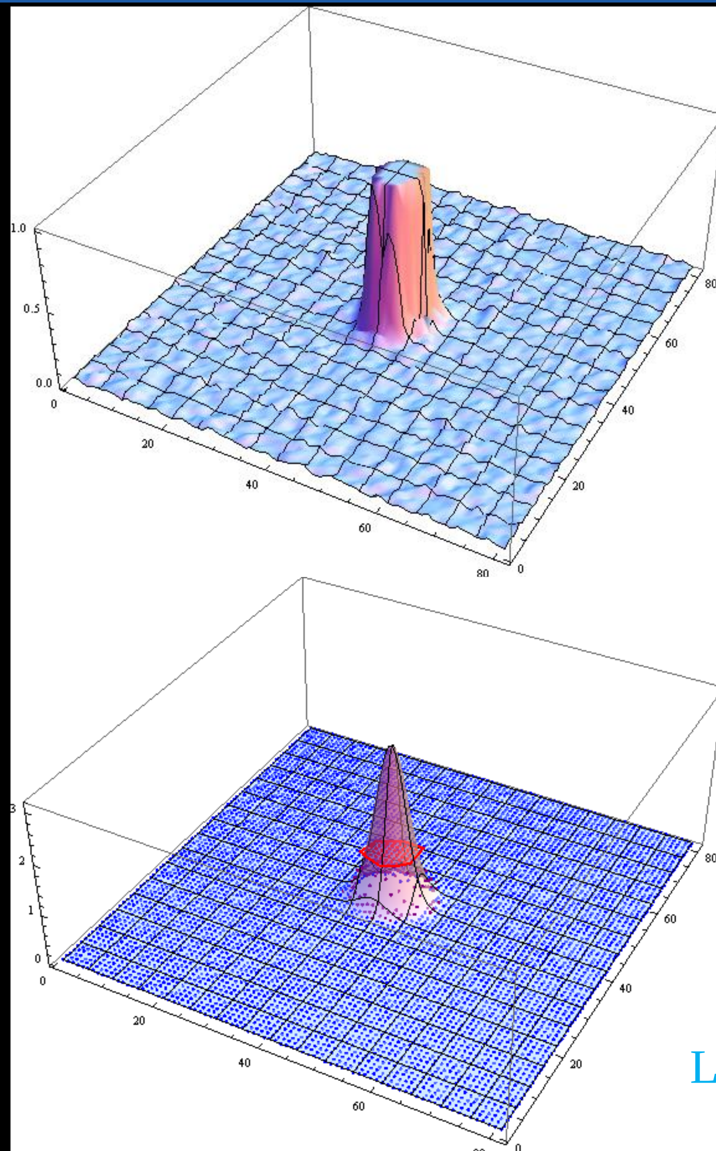
Shower Correlation



Peak R magnitude saturation correction



Photometry performed using comparison stars
(see Suggs et al. 2014)



Saturated

Peak $m_R = 4.9$

UNDERESTIMATED!

⬇

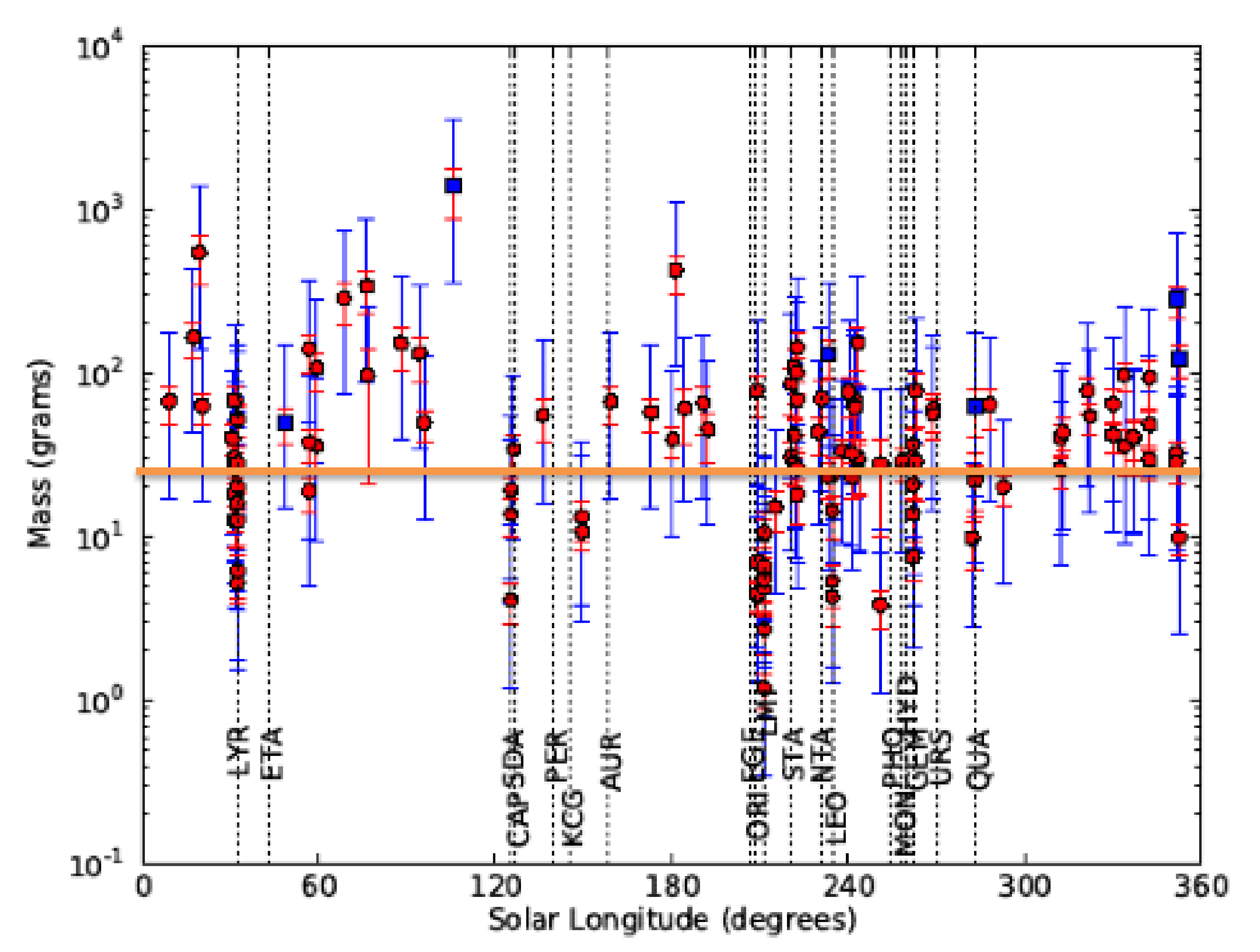
CORRECTION:

2D elliptical Gaussian fit to the unsaturated wings

Peak $m_R = 3.0 \pm 0.4$

Luminous energy = $7.1^{+3.9}_{-2.4} \times 10^{6}$ J

Meteoroid Masses



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}

Bright flash on 17 March 2013

Observed by A. Kingery & R.M. Suggs; detected by R.J. Suggs

Flash info

Detected with two 0.35 m telescopes

Watec 209H2 Ult monochrome CCD cameras

- Manual gain control
- No integration
- $\Gamma = 0.45$

Interlaced 30 fps video

Saturated → needed saturation correction!

Impact crater found by LRO!
Robinson et al. (2014)

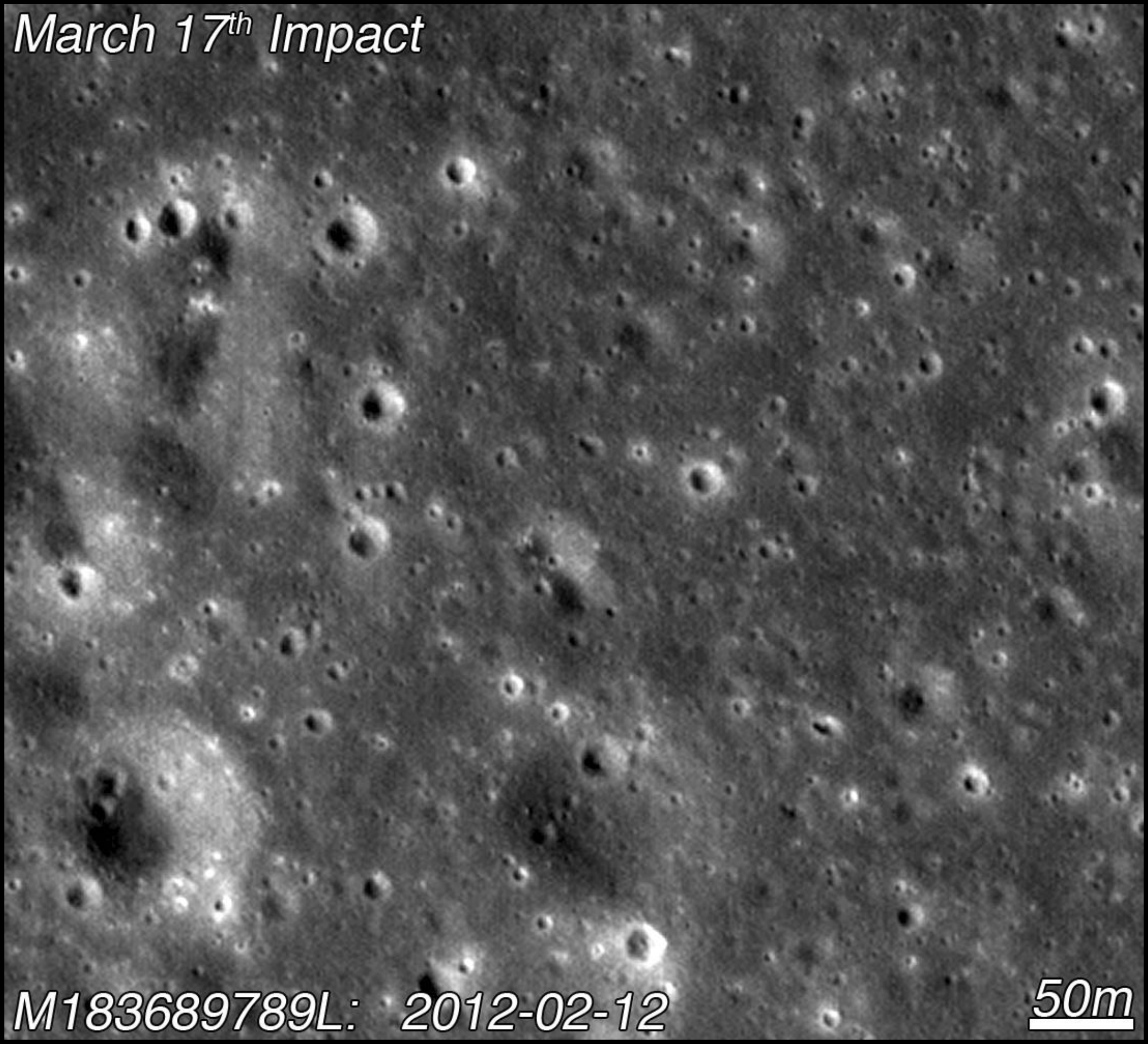


Image from Robinson (2013)
NASA/GSFC/Arizona State University

<u>Features</u>

- Fresh, bright ejecta
- Circular crater
- Asymmetrical ray pattern

<u>Crater info</u>

- Rim-to-rim diameter = 18 m
- Inner diameter = 15 m
- Depth ≈ 5 m

<u>Actual crater location</u>

- 20.7135°N, 24.3302°W

<u>Impact Constraints</u>

➡ Circular crater, impact angle constrained $\theta_h > 15°$

➡ Ejecta gives no azimuth constraint (Robinson, personal comm.)

Comparison with Grün Flux

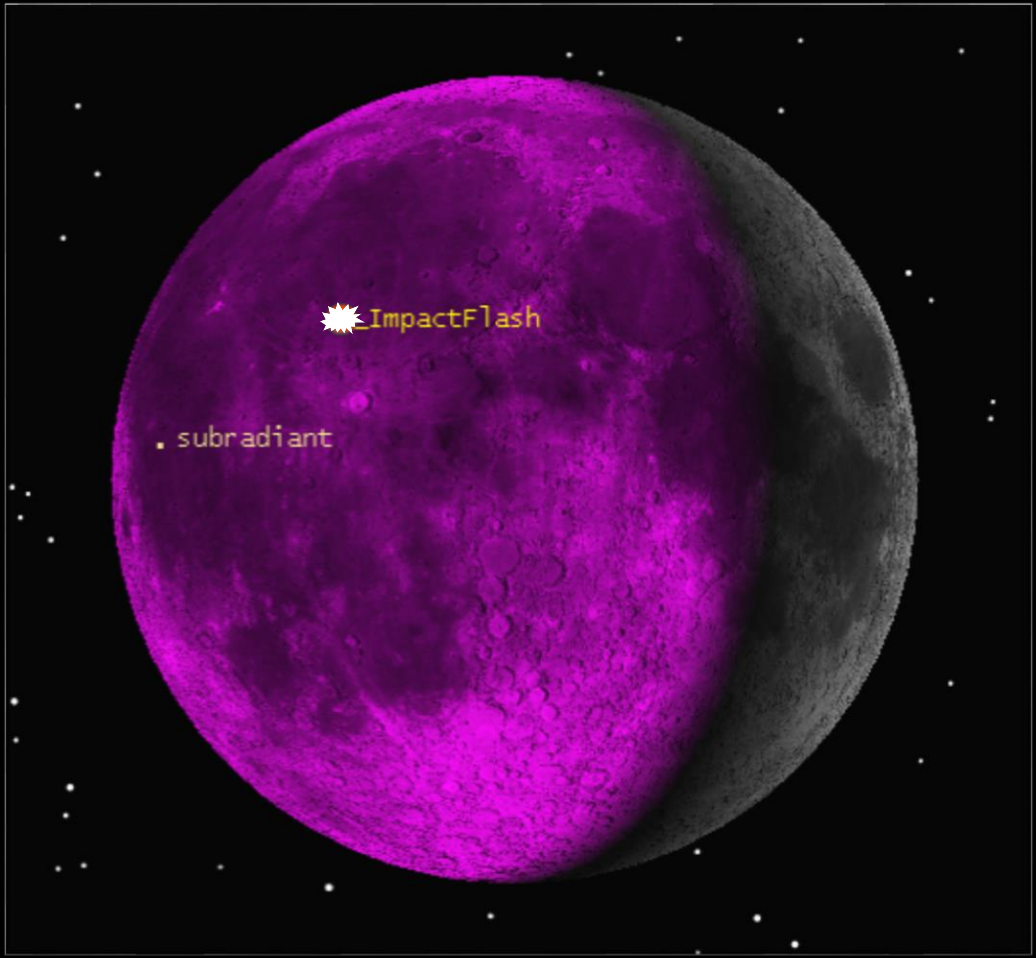
- For our completion limit of 30g we saw 71 impacts for a flux of

  $6.14 \times 10^{-10}\ m^{-2}\ yr^{-1}$

- The Grün et al. (1985) flux above a mass of 30g is

  $7.5 \times 10^{-10}\ m^{-2}\ yr^{-1}$

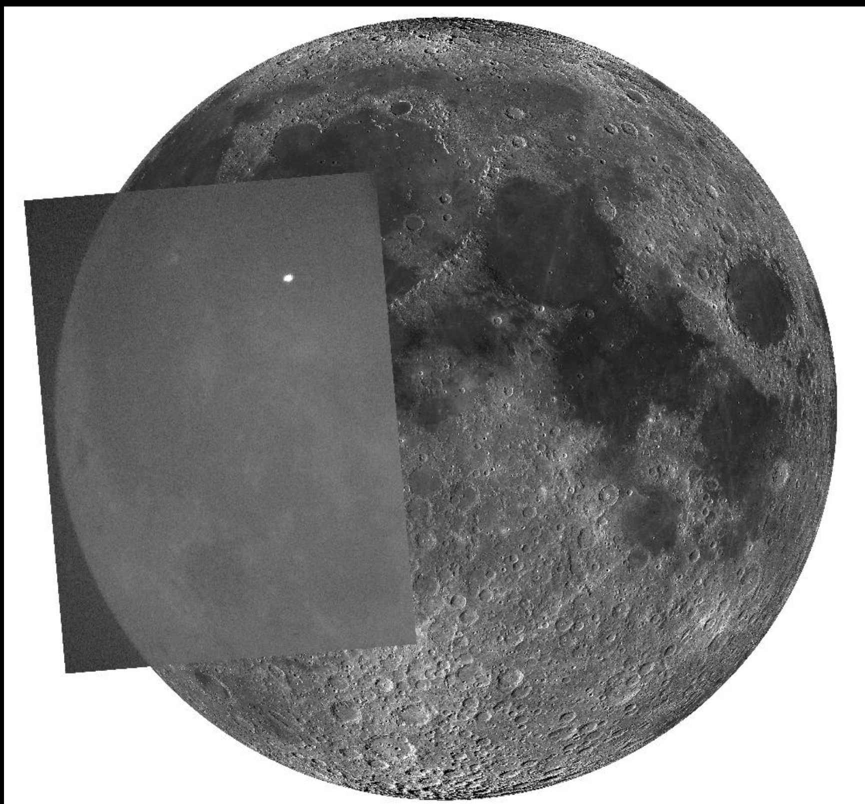
Favorable Virginid radiant geometry



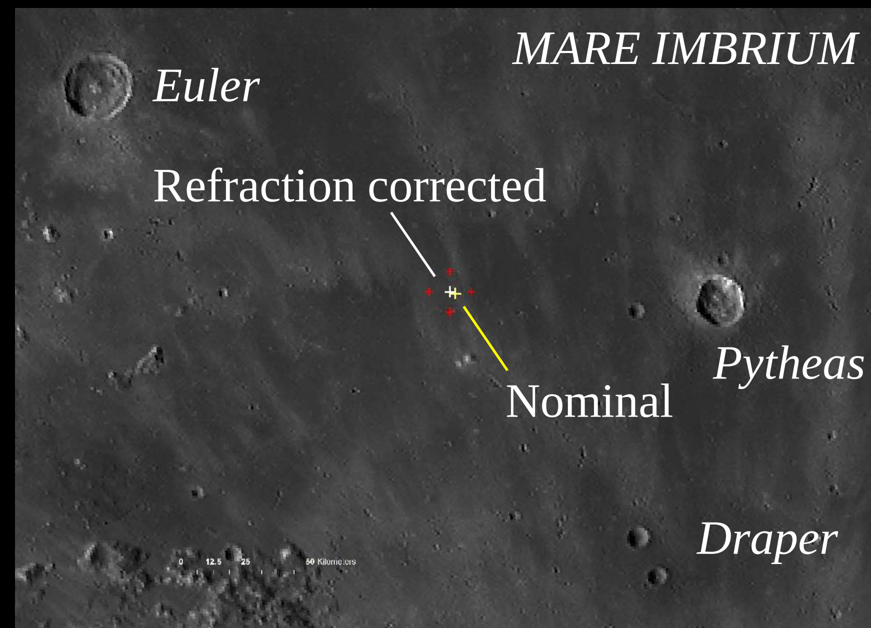
Pink indicates the portion of the moon visible to the radiant.
Impact angle ~56° from horizontal.

Mapping the impact location

LRO basemap



ArcMap was used to georeference the lunar impact following the geolocation workflow.

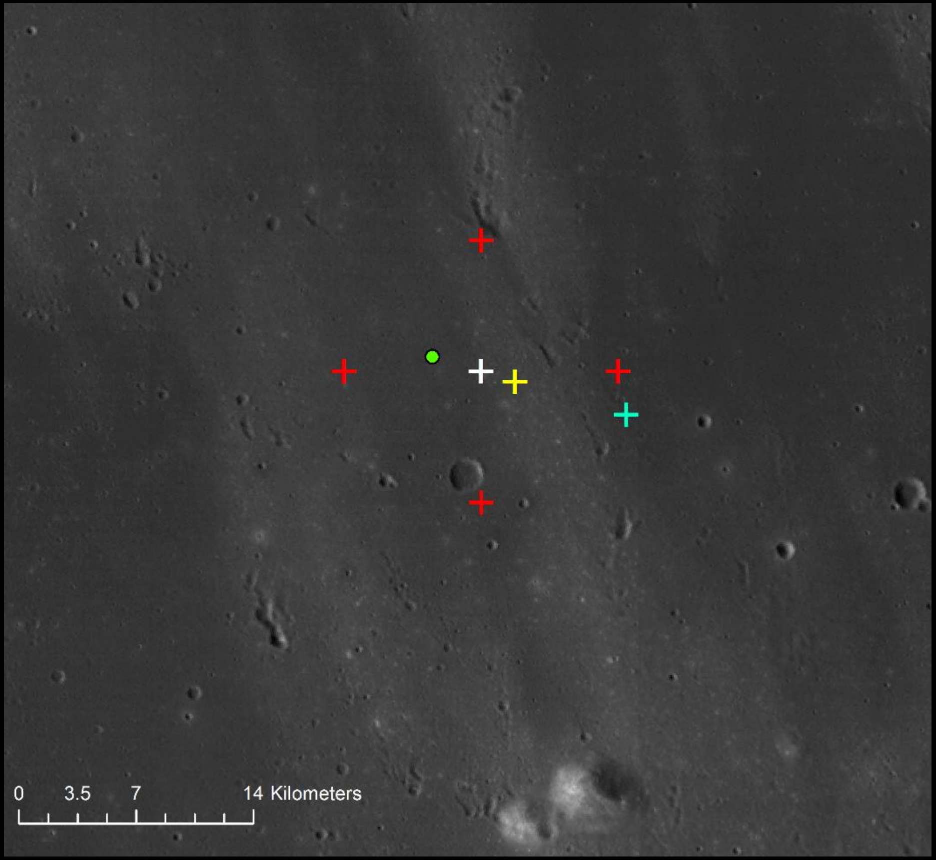


Nominal predicted crater position
20°.6644 N, 24°.1566 W

Refrac corr:

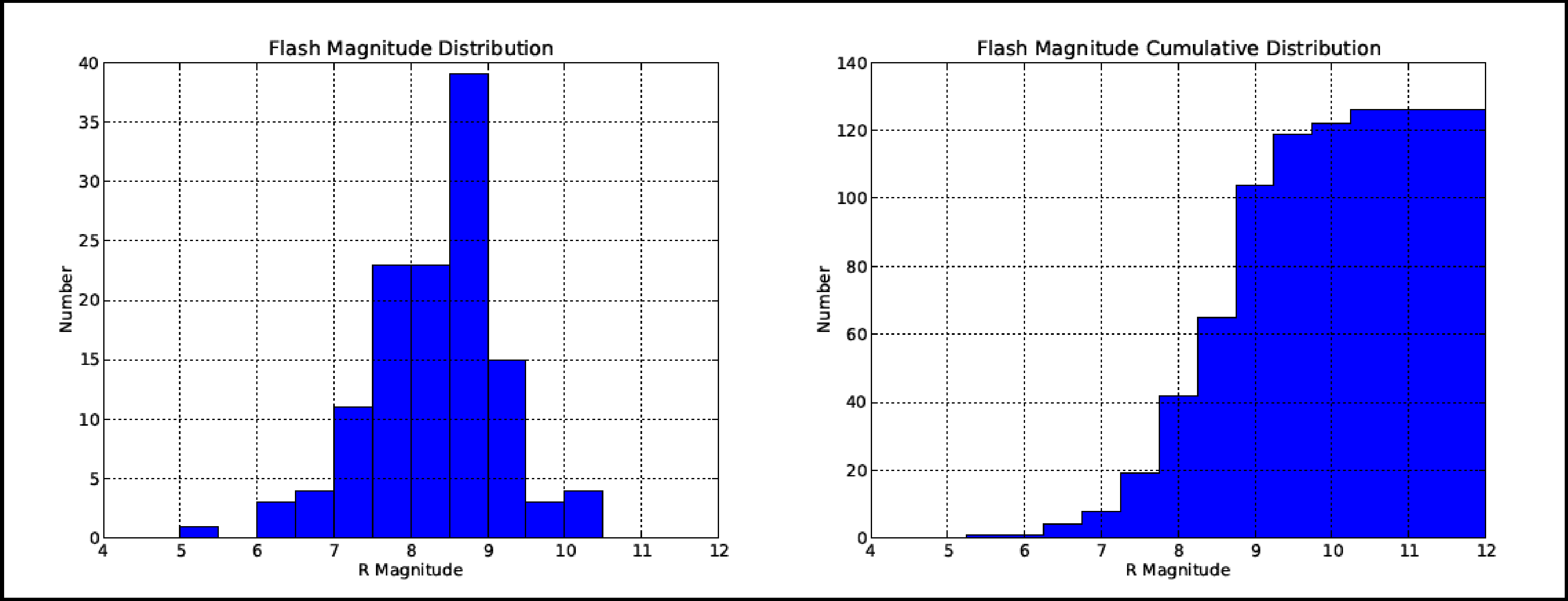
$$20°.6842^{+0.2585}_{-0.2581}\ \mathrm{N}, 24°.2277^{+0.2881}_{-0.2887}\ \mathrm{W}$$

Comparison of geolocation results to obs crater location

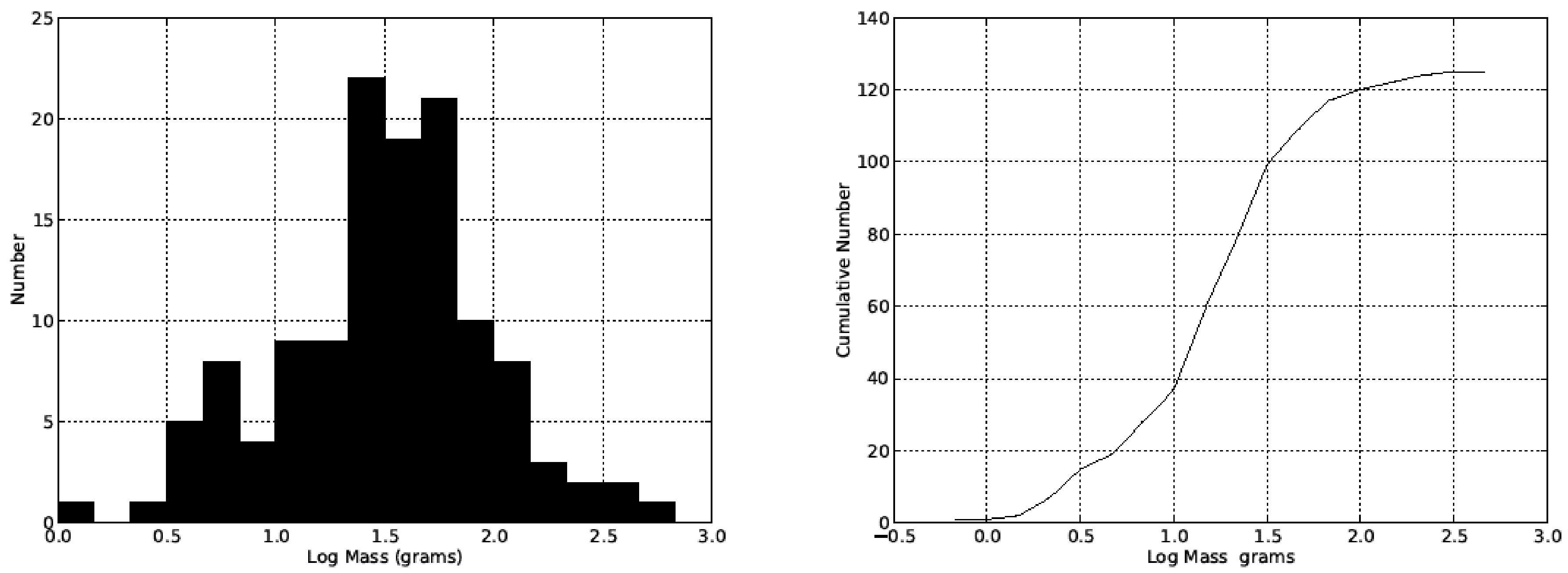


Method	Longitude (° W)	Latitude (° N)	Angular distance from observed (°)	Surface distance from observed (km)
Rough workflow	23.922	20.599	0.39875	12.096
Refined workflow	24.1566	20.6644	0.169665	5.1469
Refined, with refraction correction	$24.2277^{+0.2881}_{-0.2887}$	$20.6842^{+0.2585}_{-0.2581}$	0.100261	3.0415
LRO observed	24.3302	20.7135	-	-

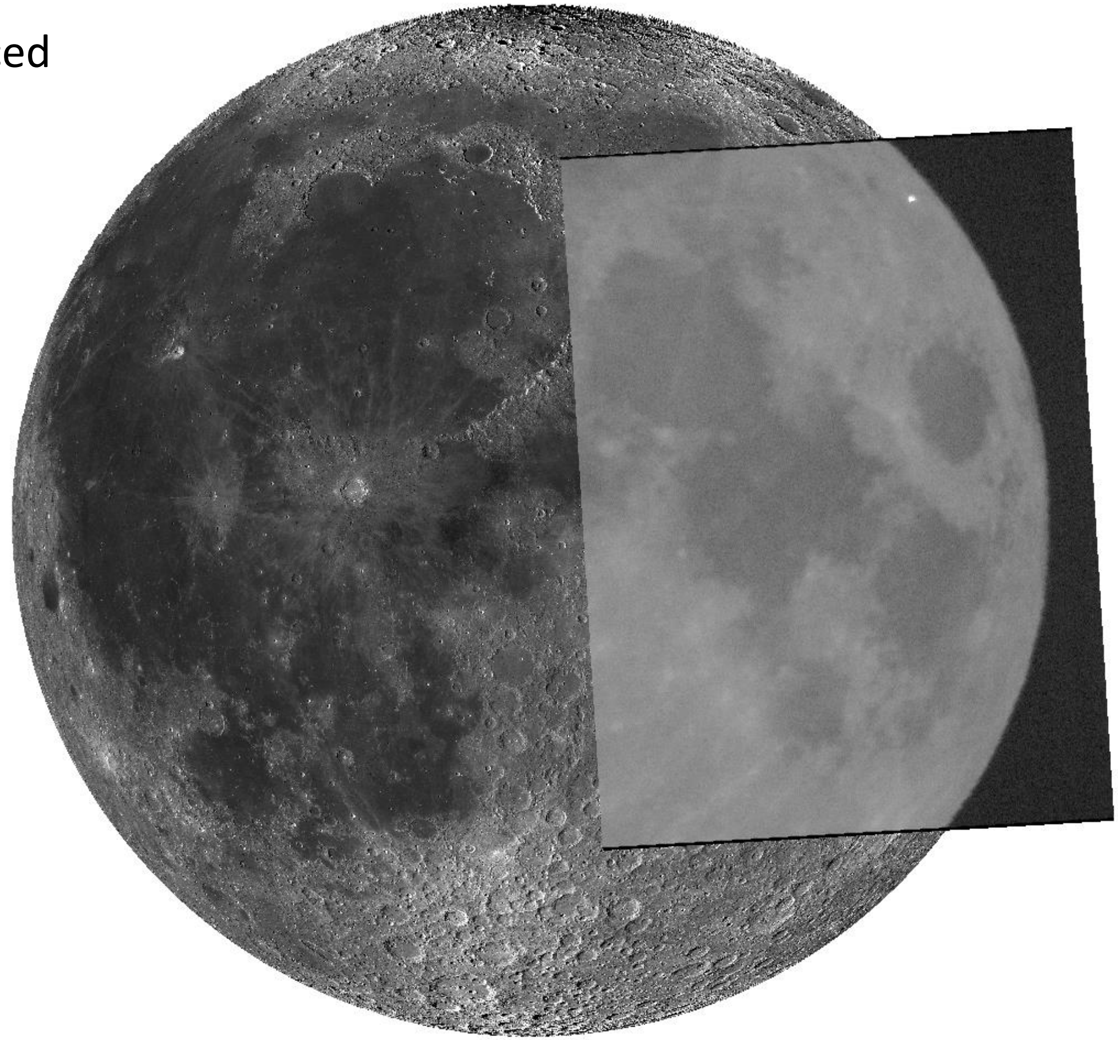
Limiting Magnitude



Limiting Mass



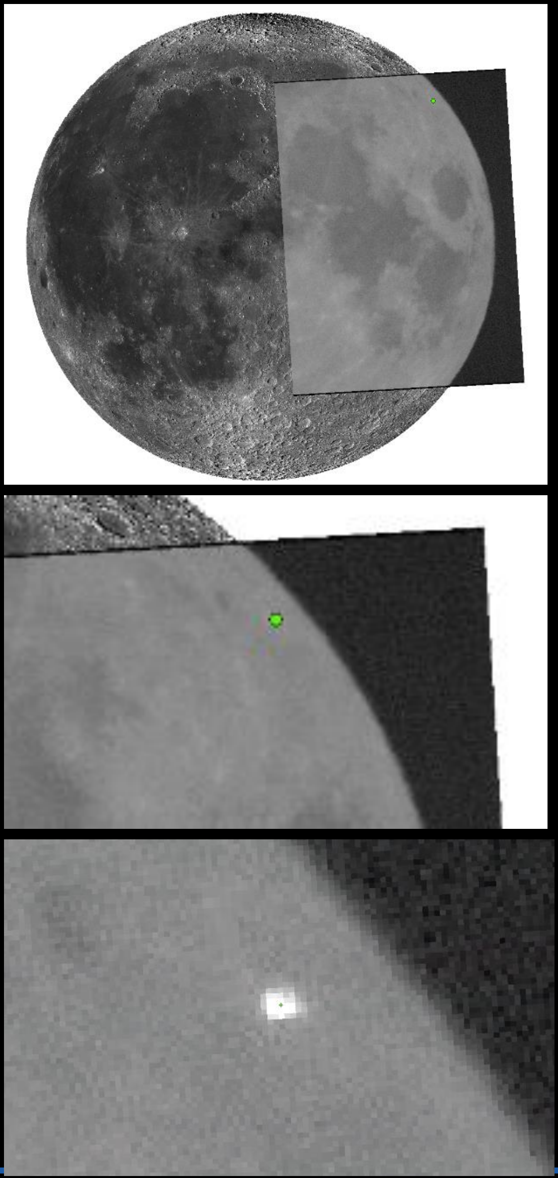
4. Georeference flash image



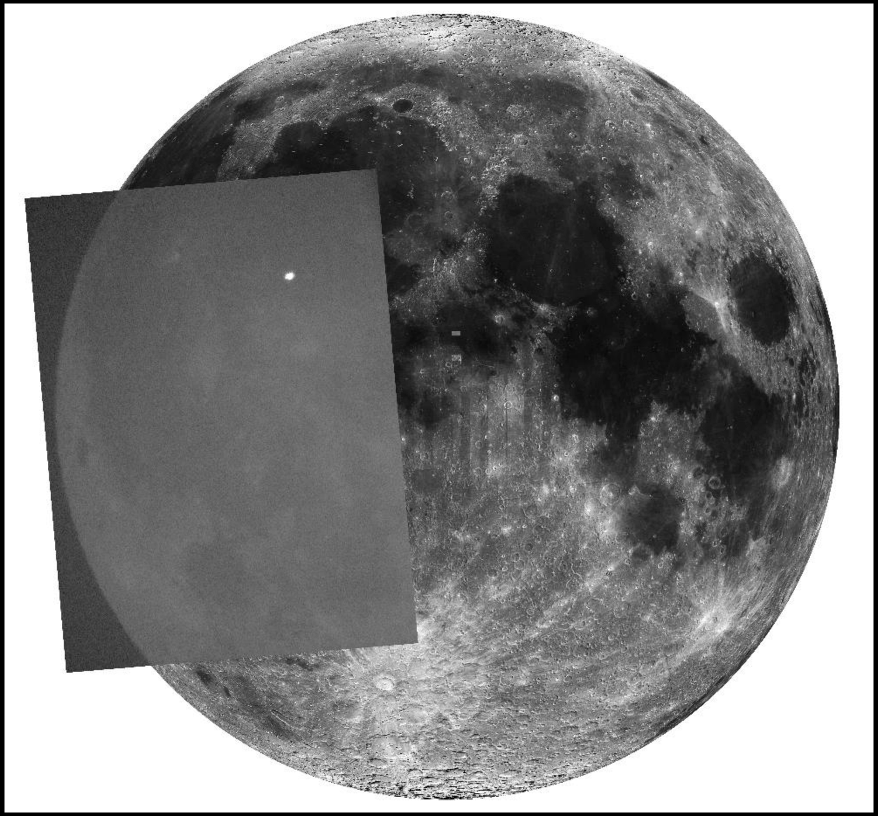
Final georeferenced impact image

6. Determine flash location

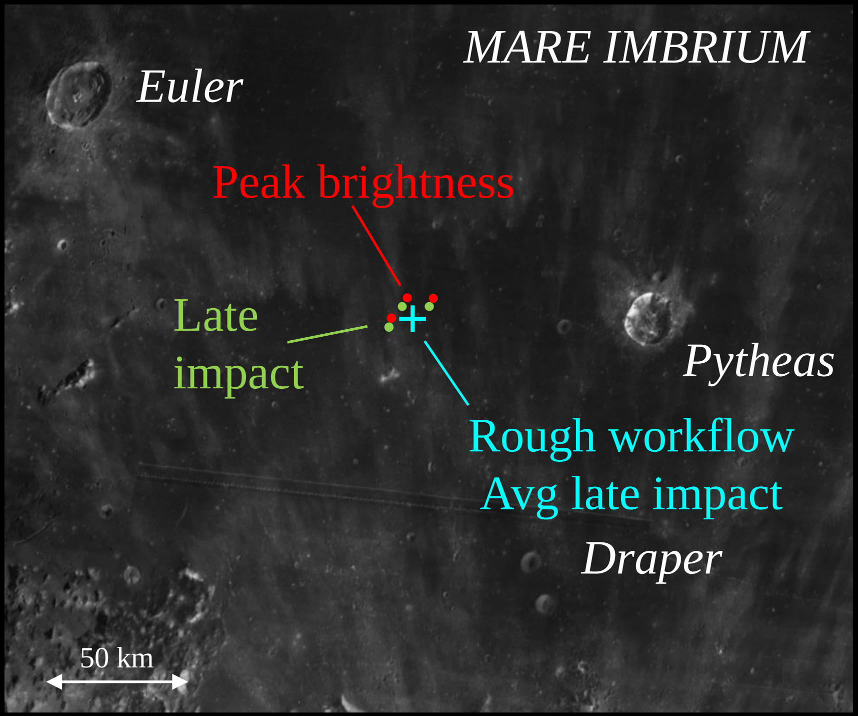
- Input flash location $(\bar{x}_f{}', \bar{y}_f{}')$ to ArcMap's "Go to XY" tool
- Read & record selenographic coordinates (λ, φ) transformed by ArcMap
- Place marker at flash location, add point to database and shapefile



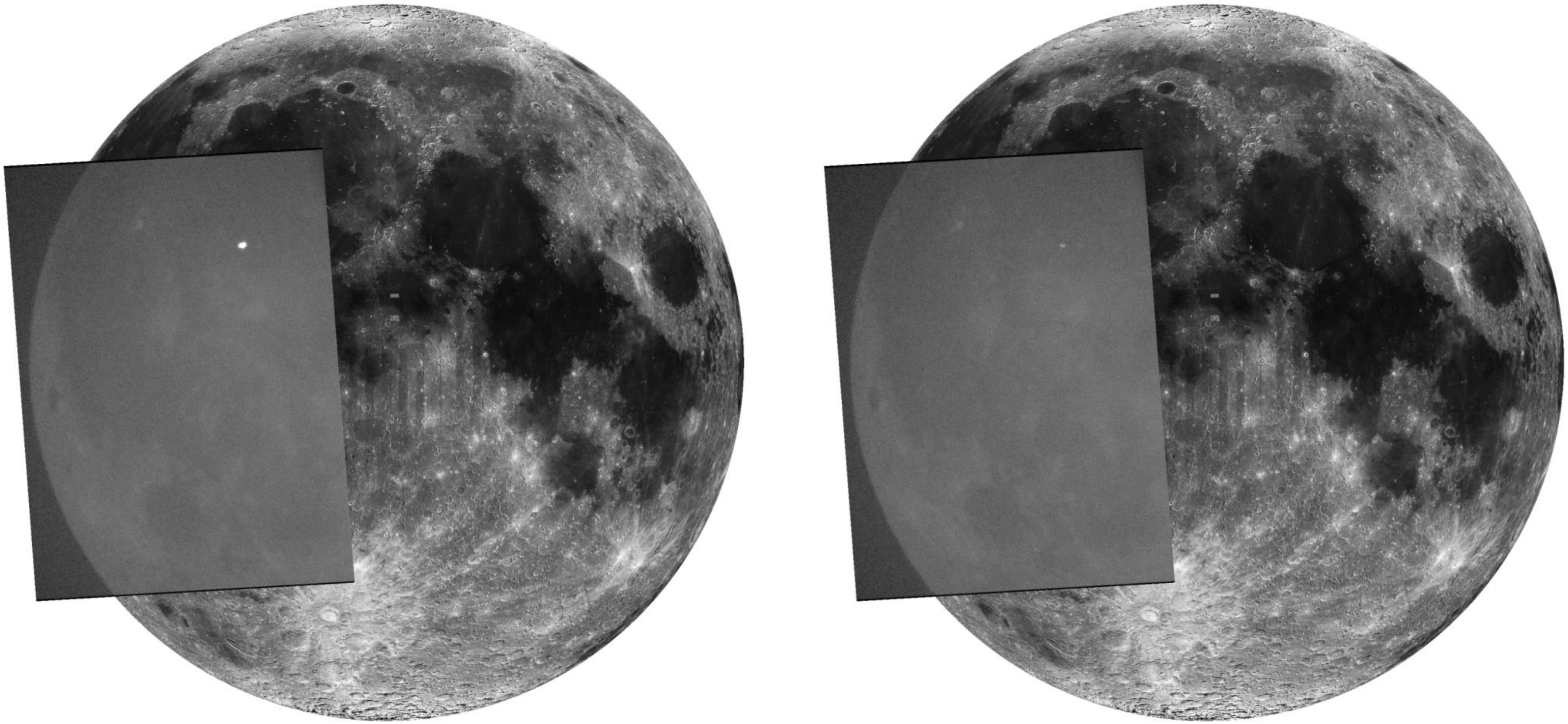
Mapping the impact location
"Rough workflow"



ArcMap was used to georeference the lunar impact 3 times, at peak brightness and late impact.



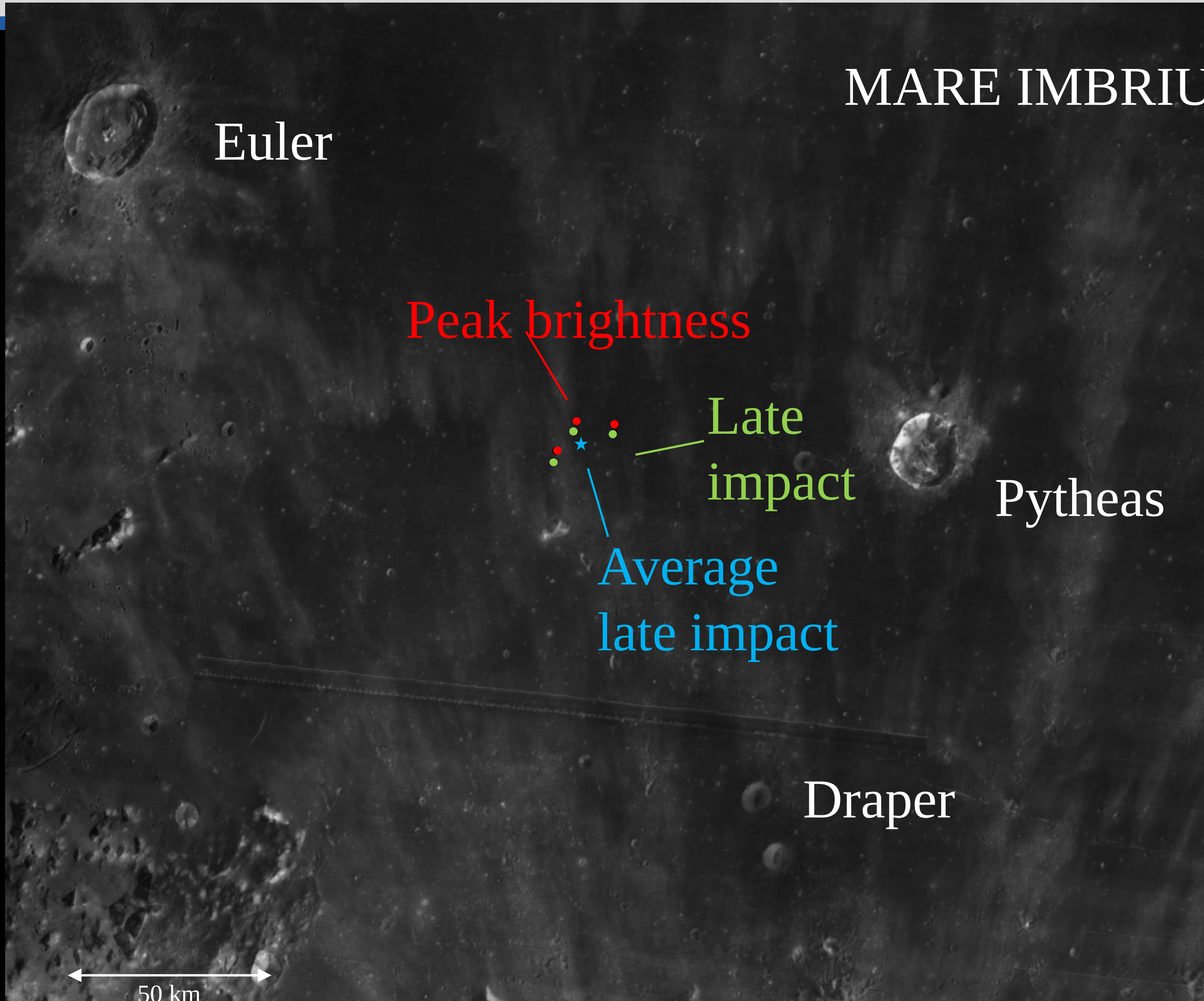
Mapping the impact location



[redacted]

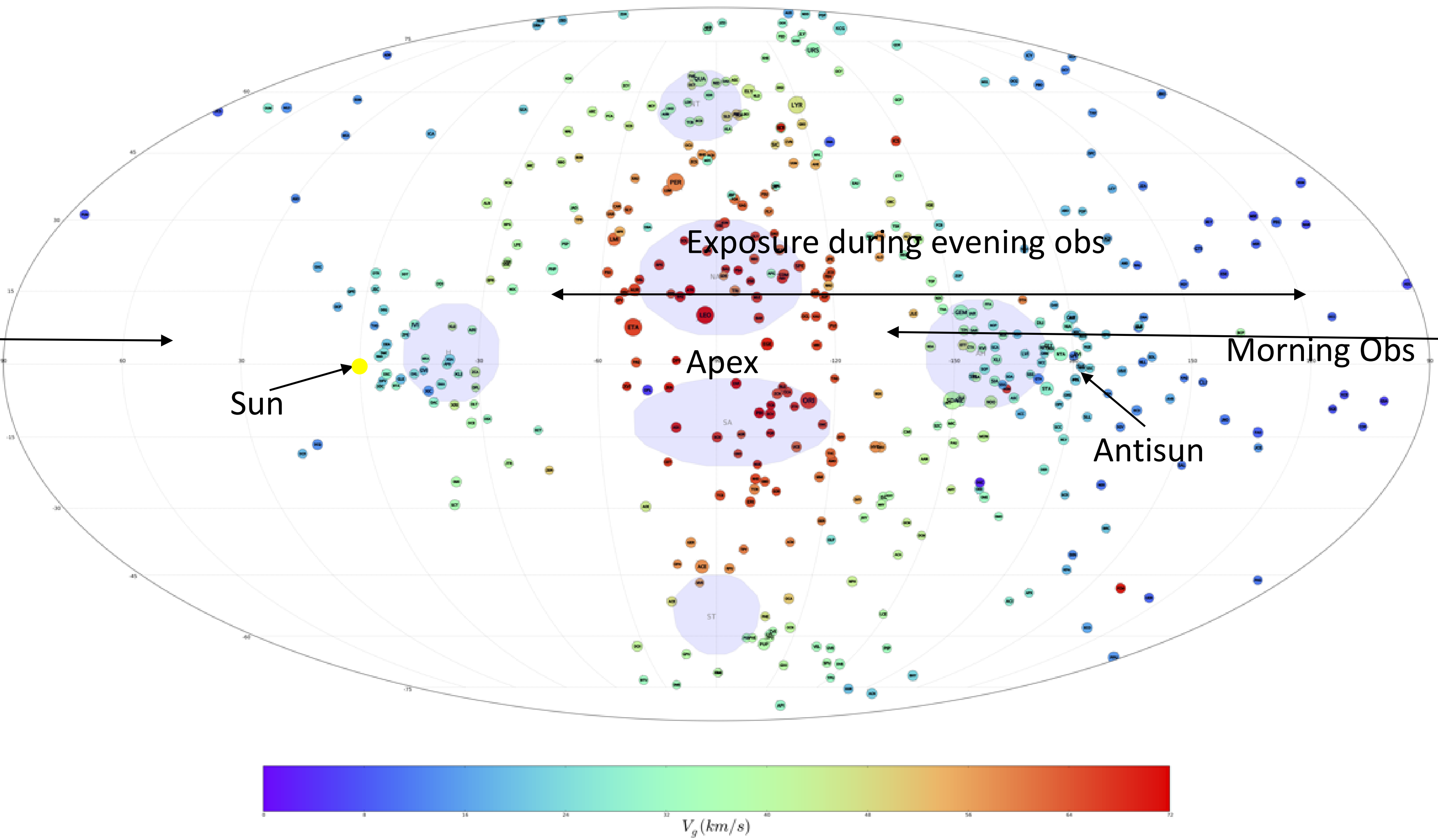
Impact location

Results of several attempts with different features and frames



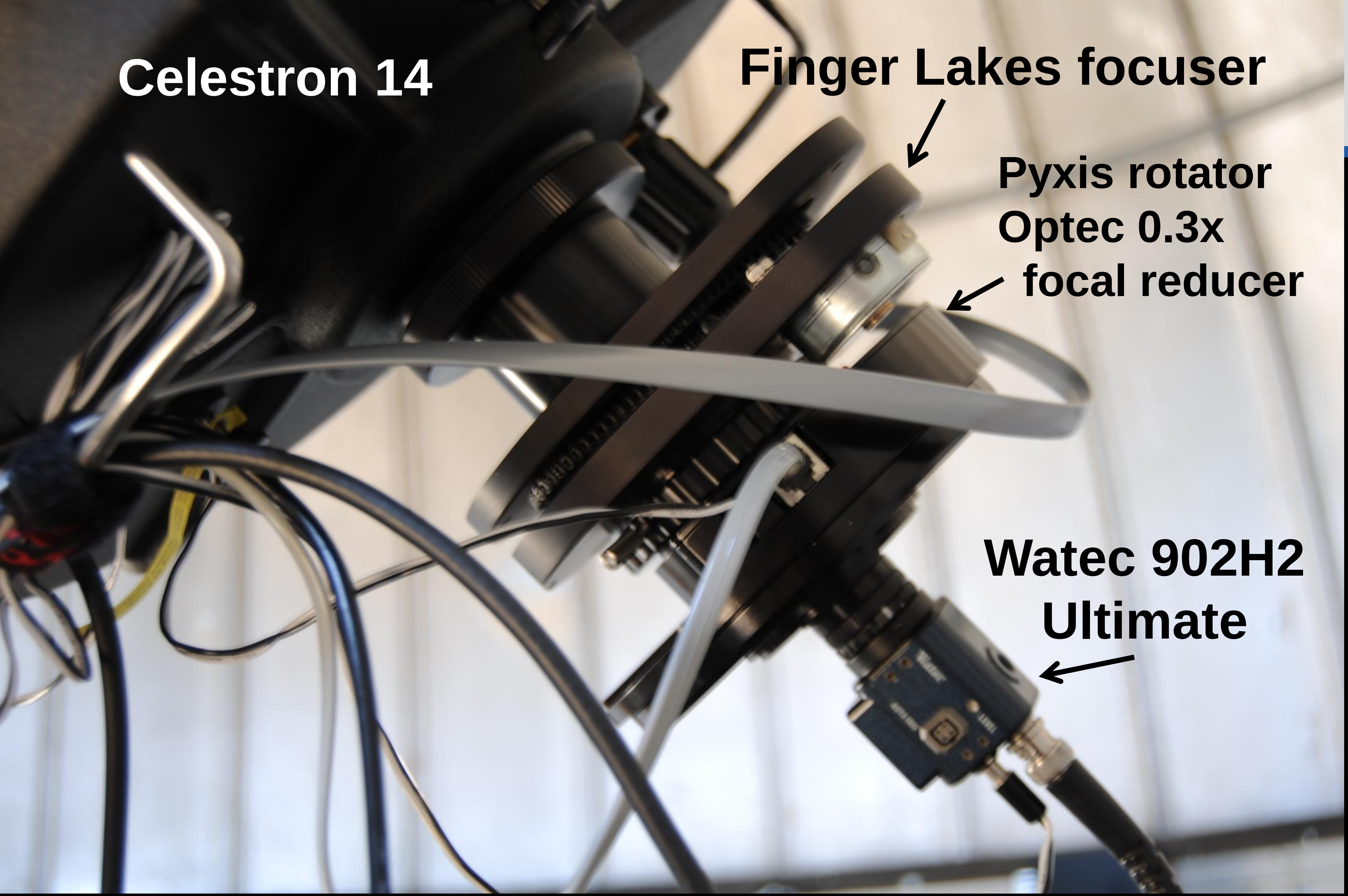
Average location: 20.599 ± 0.172° N, 23.922 ± 0.304° W

Meteor Shower and Sporadic Source Radiants



Equipment

- Telescopes – 14 inch (0.35m), have also used 0.5m and 0.25m
- 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


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