Lunar Meteoroid Impact Observations and the Flux of Kilogram-sized Meteoroids

Rob Suggs
Space Environments Team Lead/MSFC/EV44/MEO

Bill Cooke/MSFC/EV44/MEO
Heather Koehler/MSFC/EV44/MEO
Danielle Moser/Dynetics
Ron Suggs/MSFC/EV44
Wes Swift/Raytheon

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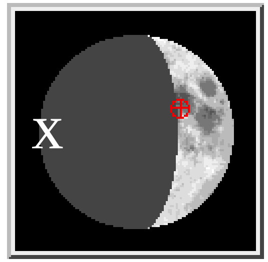
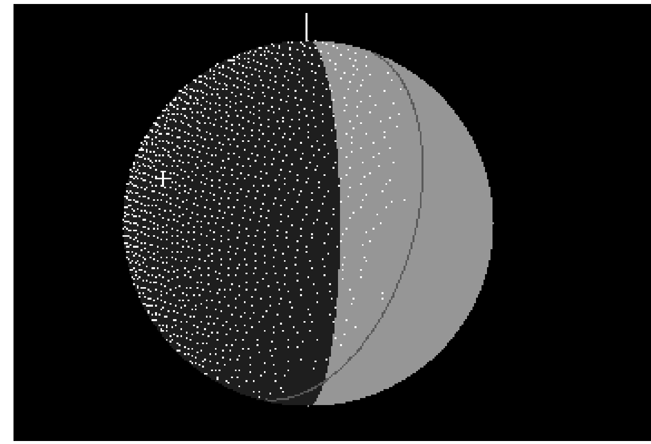
Jack Schmitt/Apollo 17 observation of lunar impact





Geminids 12/13/1972

"NASA Apollo 17 transcript" discussion is given below (before descent to lunar surface):
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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?

LMP I keep looking for -- yes, we will. I was planning on looking for those kind of things....

Why is lunar impact monitoring useful?

- Started the project to develop a better meteoroid ejecta model for use by the Constellation Program in shielding design and risk assessments
  - Existing spec is for Apollo – circa 1969, probably overly conservative
- We realized that the flux we were measuring is important to understanding the meteoroid environment in this size range
  - The collecting area is much larger than that available for all-sky cameras
  - Allows better determination of meteor shower population indices
- Future application to lunar seismic stations and dust experiments

Observation and Analysis Process

Night side only

- Earthshine illuminates lunar features
- FOV is approximately 20 arcmin – covering
  - 3.8 million square km ~ 12% of the lunar surface
- FOV selected to maximize collecting area while avoiding glare from sunlit portion of Moon
  - Baffles are important in the optics
- 12th magnitude background stars are visible at video rates

Crescent to quarter phases – 0.1 to 0.5 solar illumination

- 5 nights waxing (evening, leading edge, Lunette landers will be here)
- 5 nights waning (morning, trailing edge)

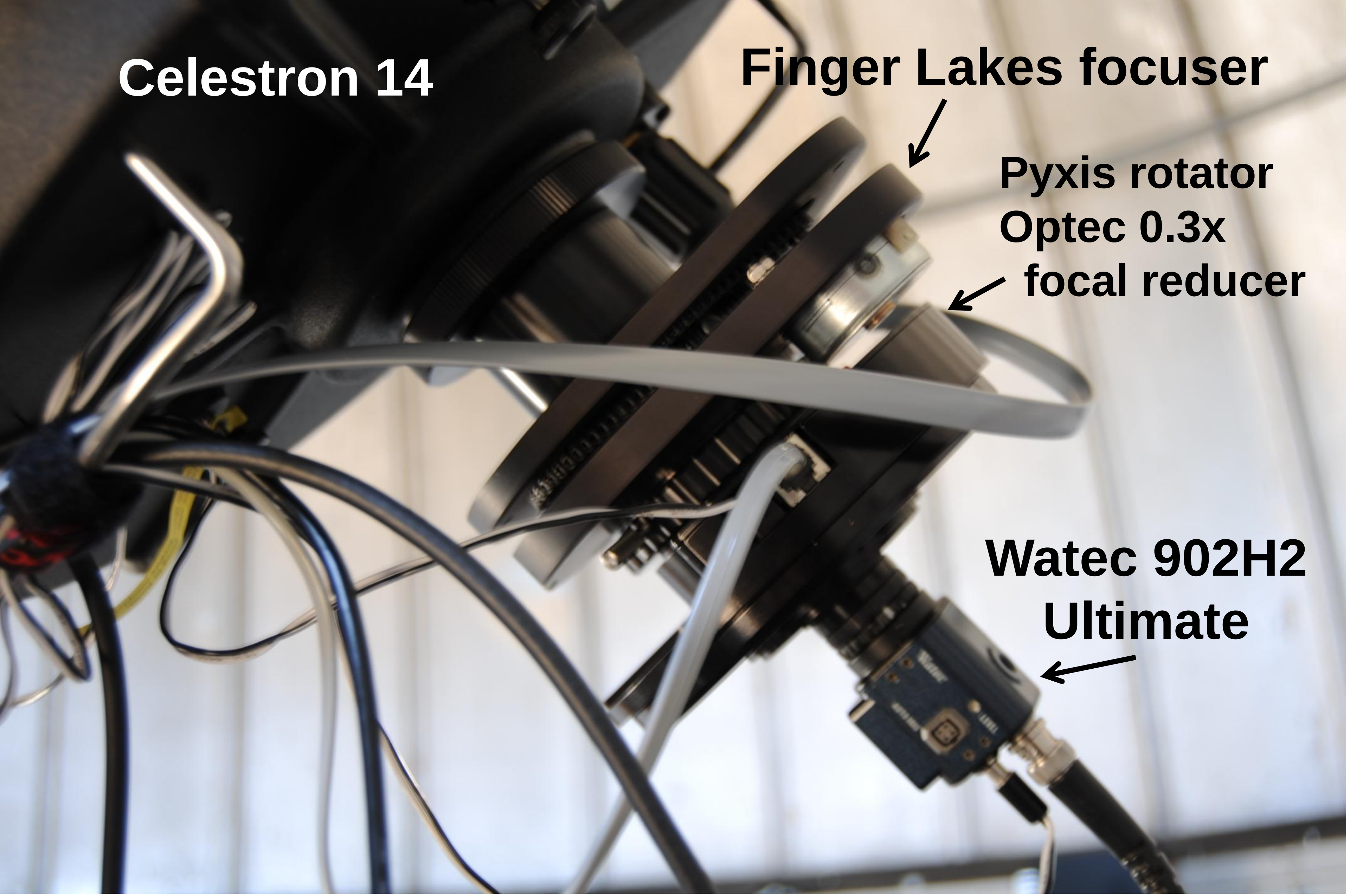
Have taken data on about half of the possible nights, > 212 hours of photometric quality data in first 3 years.

Automated Lunar and Meteor Observatory

- Telescopes
  - 3 14” (0.35m)
    2 Meade, 1 Celestron
  - RCOS 20 inch (0.5m)
- Detectors
  - Watec 902H2 Ultimate
  - Astrovid Stellacam EX
  - Gamma=0.45, man.gain

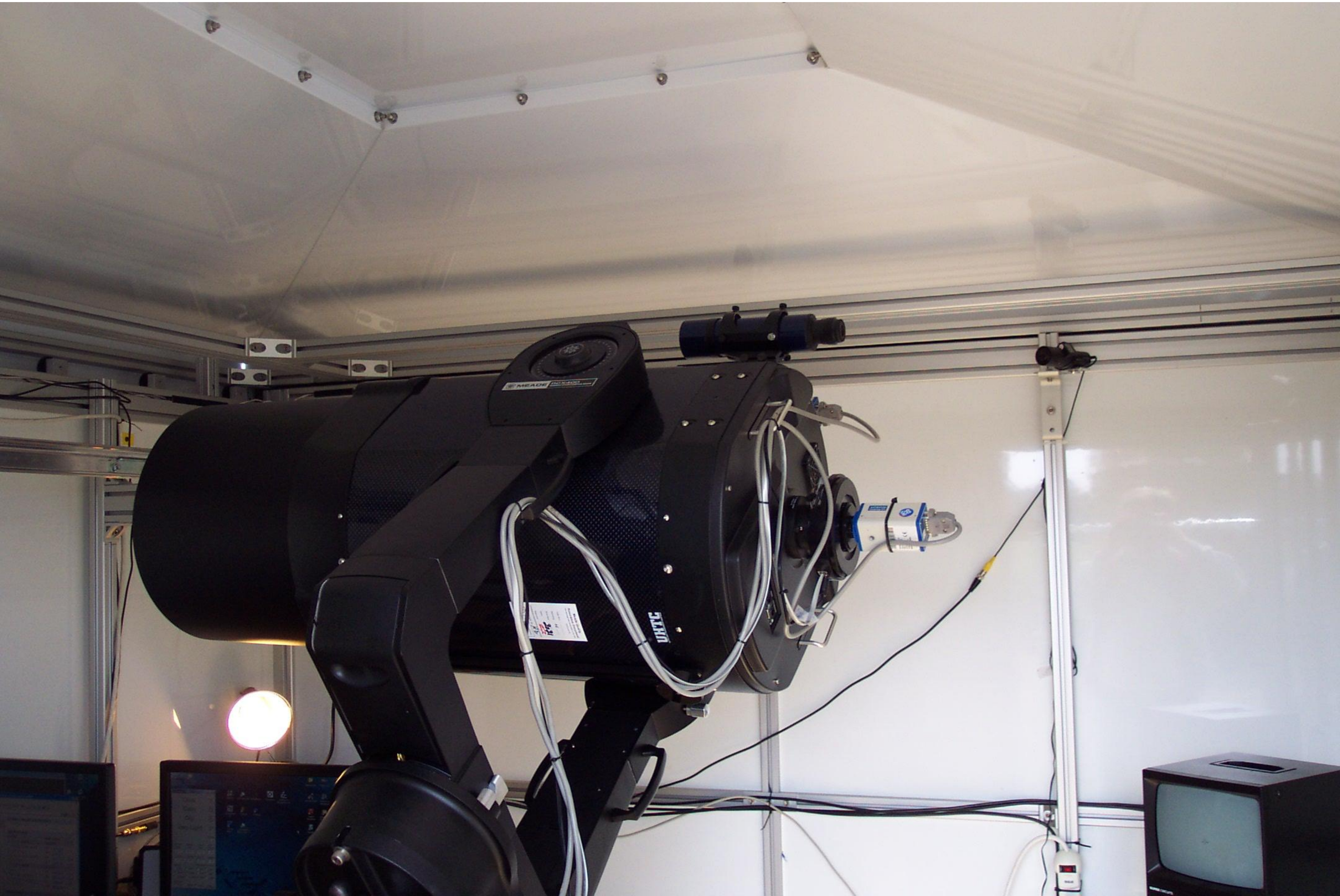
Huntsville, Alabama

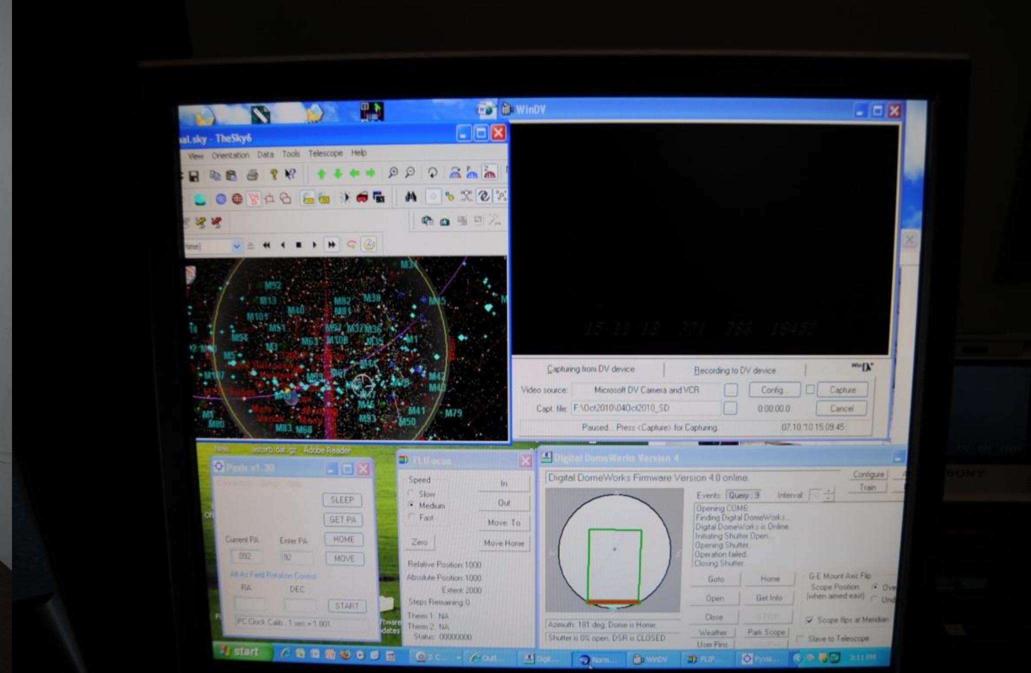
Chickamauga, Georgia


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

Automated Lunar and Meteor Observatory

Meade 14 in (0.35m)

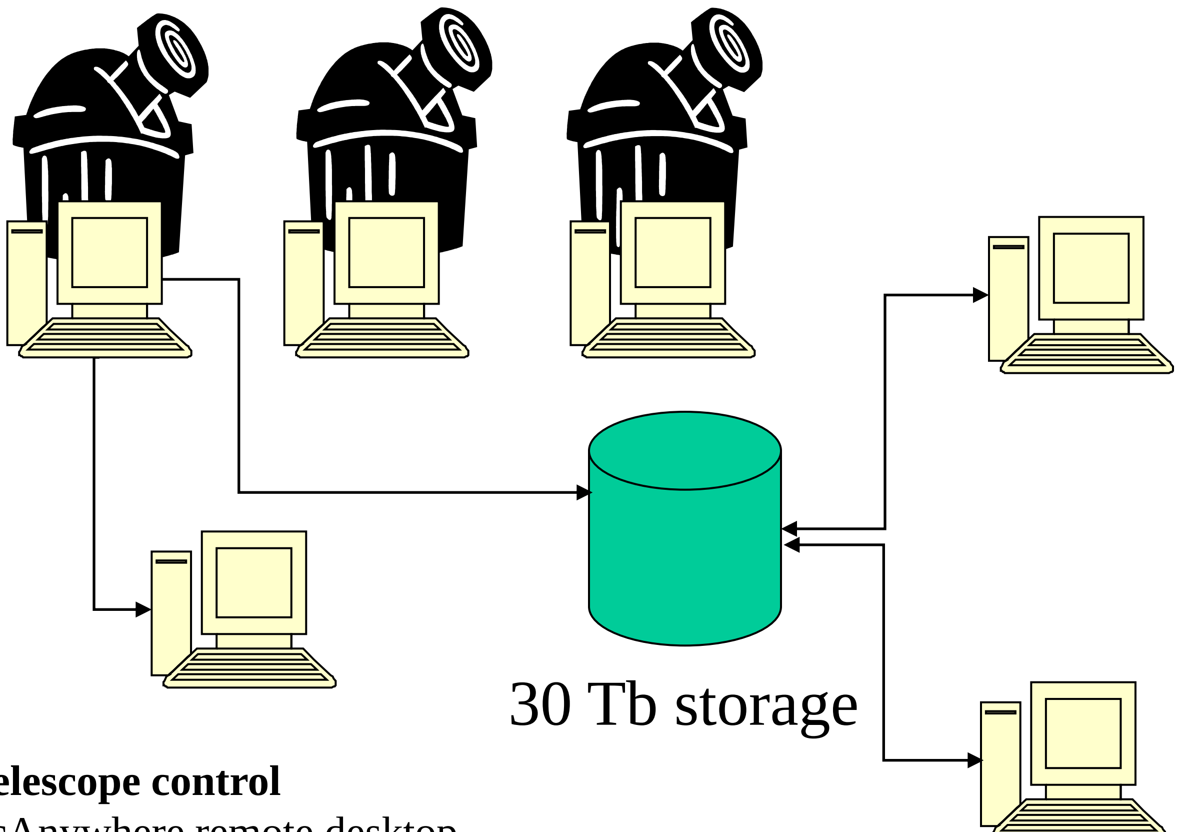




Telescope Control and Recording

TheSky 6 (Paramount/C14)
or Autostar (Meade)
WinDV to record via
 Firewire from Sony DV deck/digitizer
Kiwi GPS time stamper
Pyxis rotator control
Finger Lakes focuser control
DDW dome control
DLI power control

Data Pipeline



LunarScan
finds flashes

VirtualDub
video review

LunaCon (custom)
flash photometry
collecting area,
detection limit,
time on target of all video

Telescope control
pcAnywhere remote desktop

Must detect flash in all operating telescopes to discriminate cosmic rays and orbital debris unless flash is multiple fields with no apparent motion

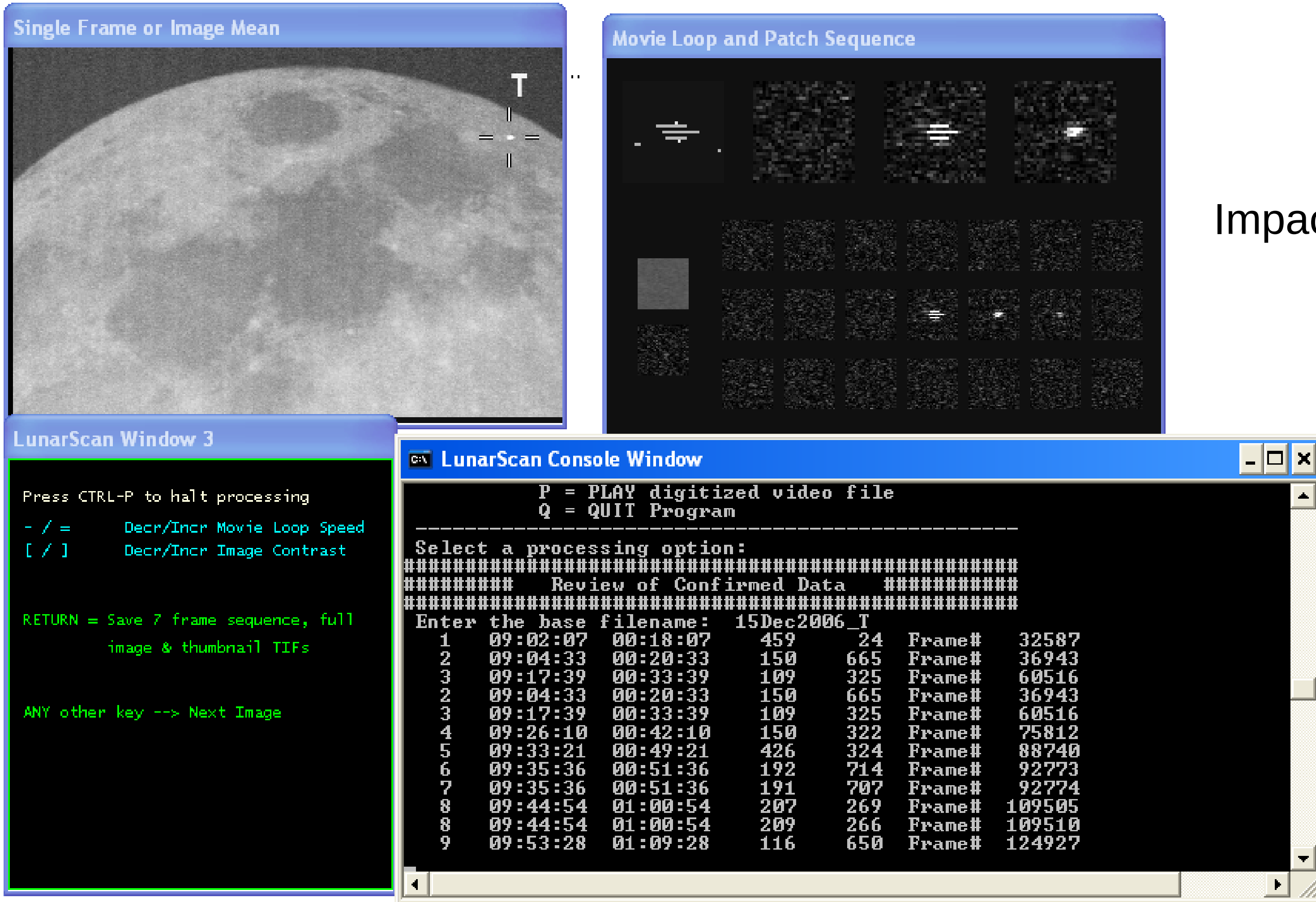
Control Room

Operator position

Probable Leonid Impact
November 17, 2006

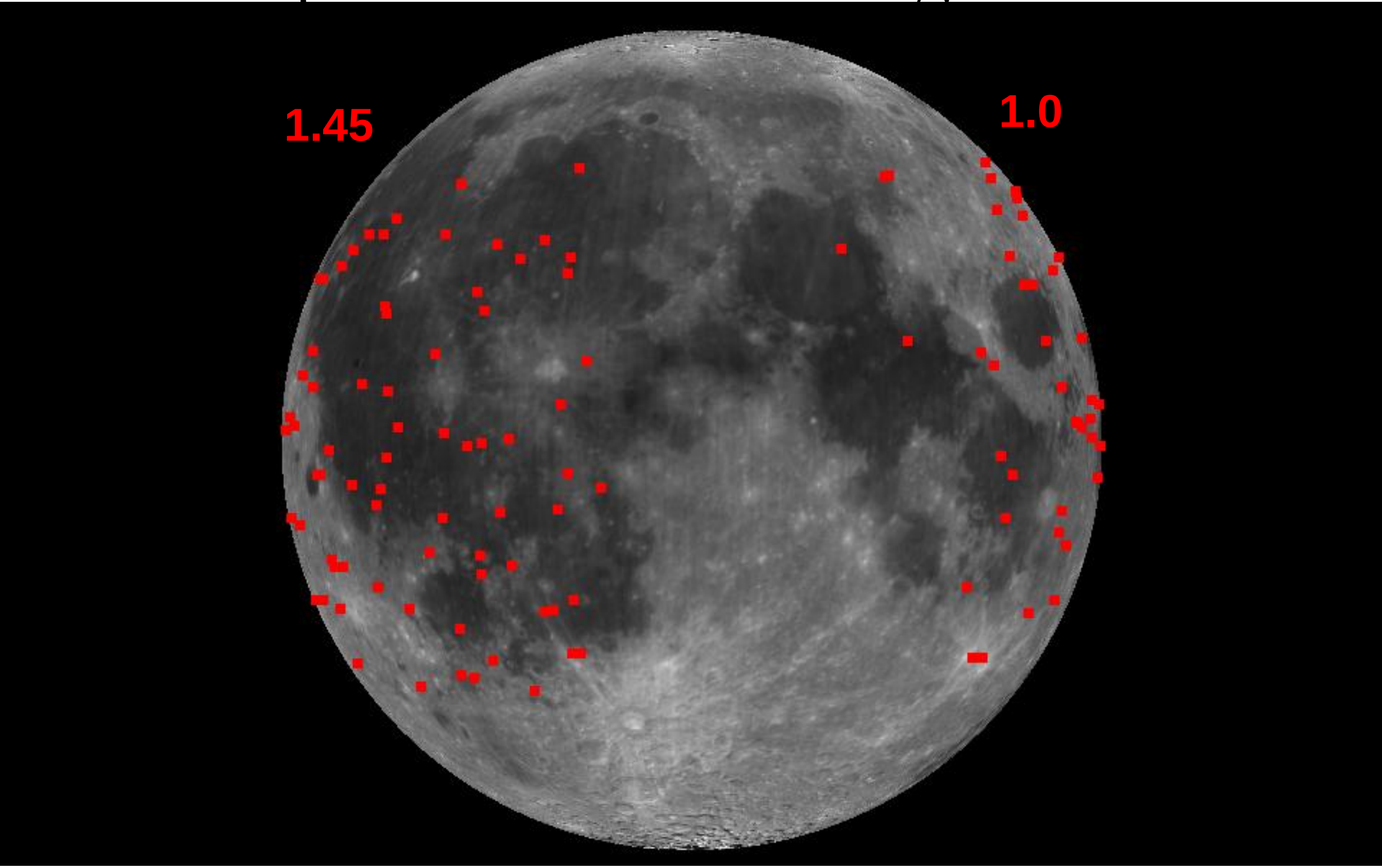
Video is slowed by a factor of 7

LunarScan (Gural)



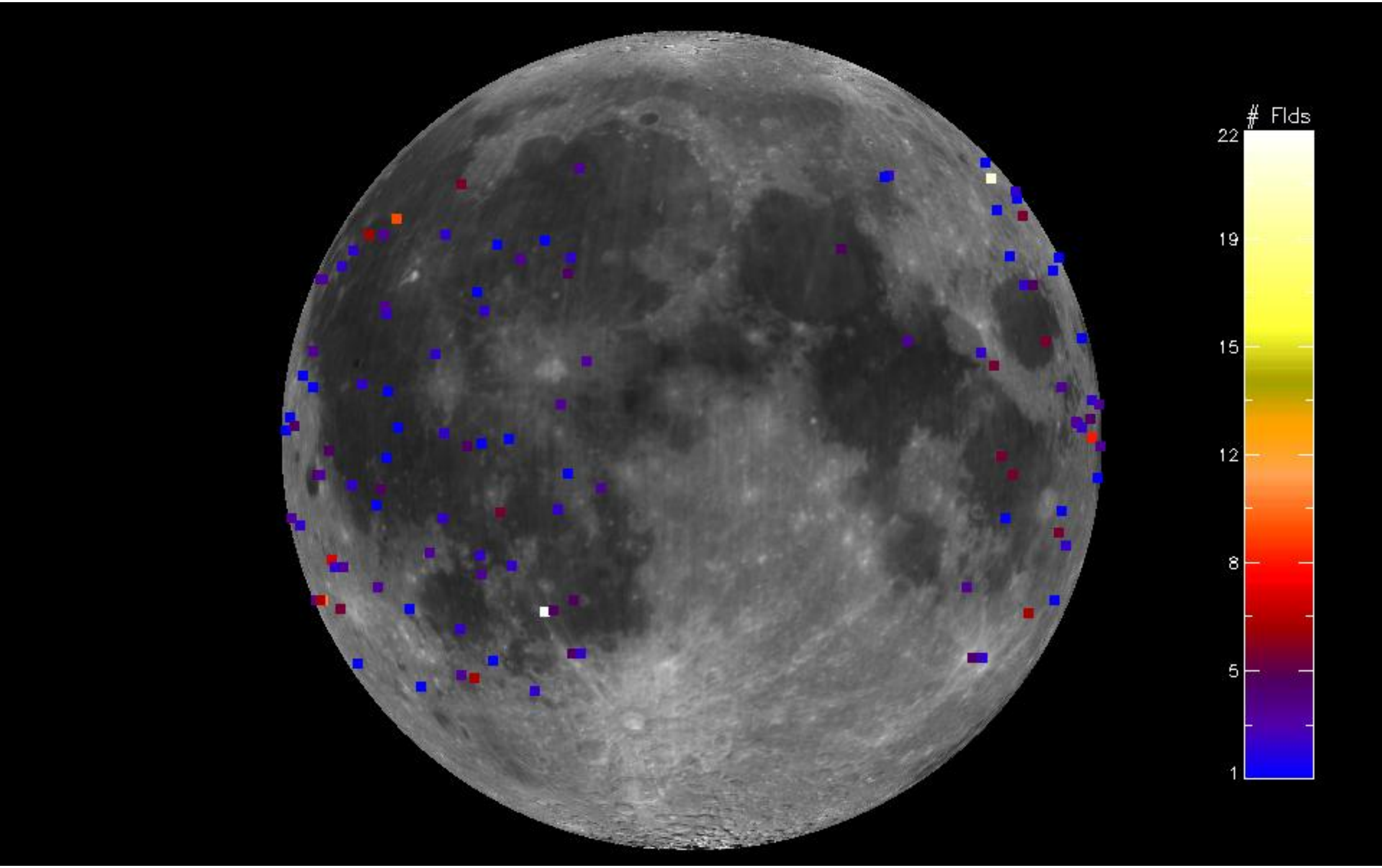
Impact 15 Dec 2006

108 Impacts used in this study, 212 hours

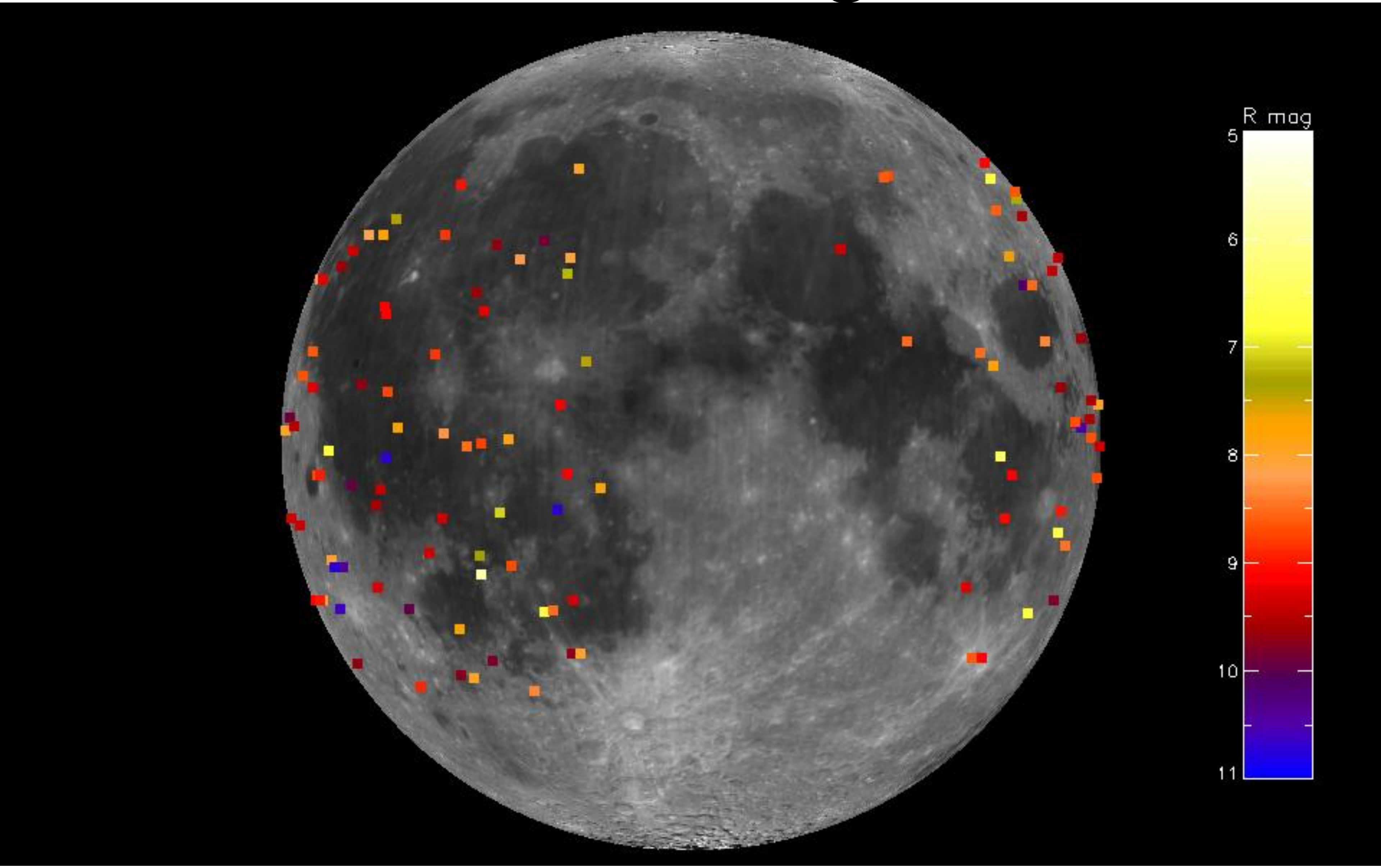


Flux asymmetry – 1.55×10^{-7} evening (left), 1.07×10^{-7} morning (#/km^2/hr)

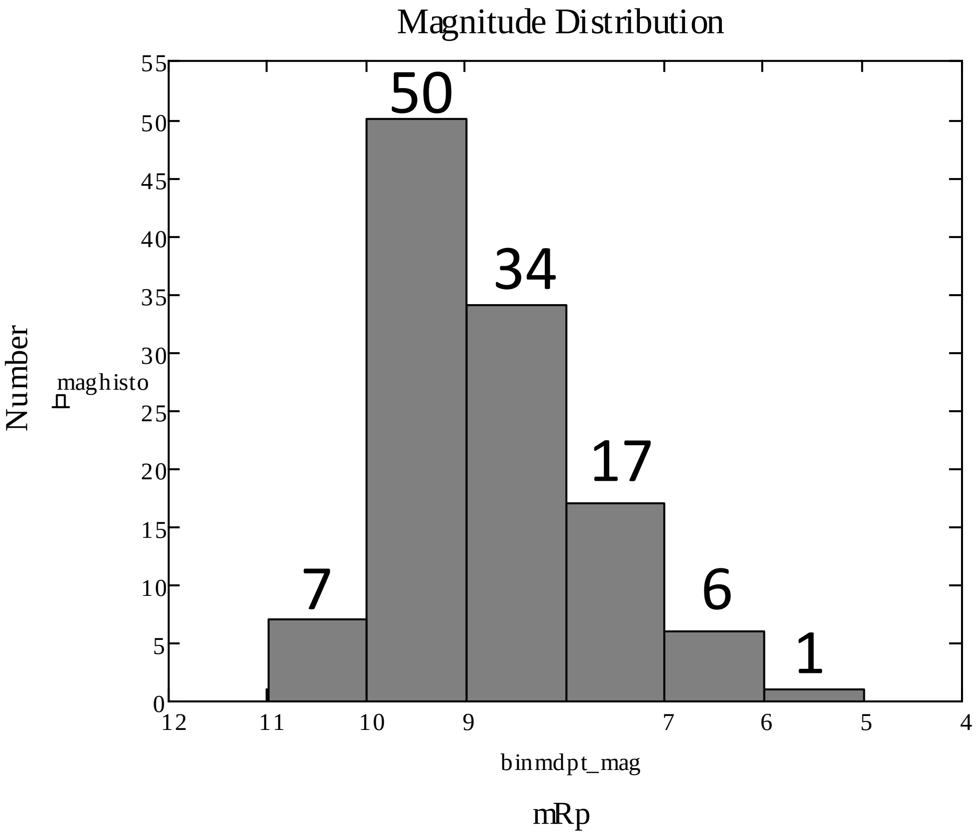
Flash Duration – Video Fields



Peak Flash Magnitude



Magnitude Distribution – first 3 years



- Complete to 10th magnitude, approximately 100g for average shower meteoroid (25 km/s)

Results

Flux is 1.34×10^{-7} km^{-2} hr^{-1}

- Approximate detectable mass limit is 100g
- Ratio of leading to trailing edge is 1.45:1

- 212.4 total observing hours (photometric quality)
- 115 total impacts in this period, 108 to our completeness limit (~ 10th mag.)
- 3.8×10^{6} km^{2} average collecting area

Note: flux determination depends on accurate estimate of observing time, limiting magnitude, and collecting area

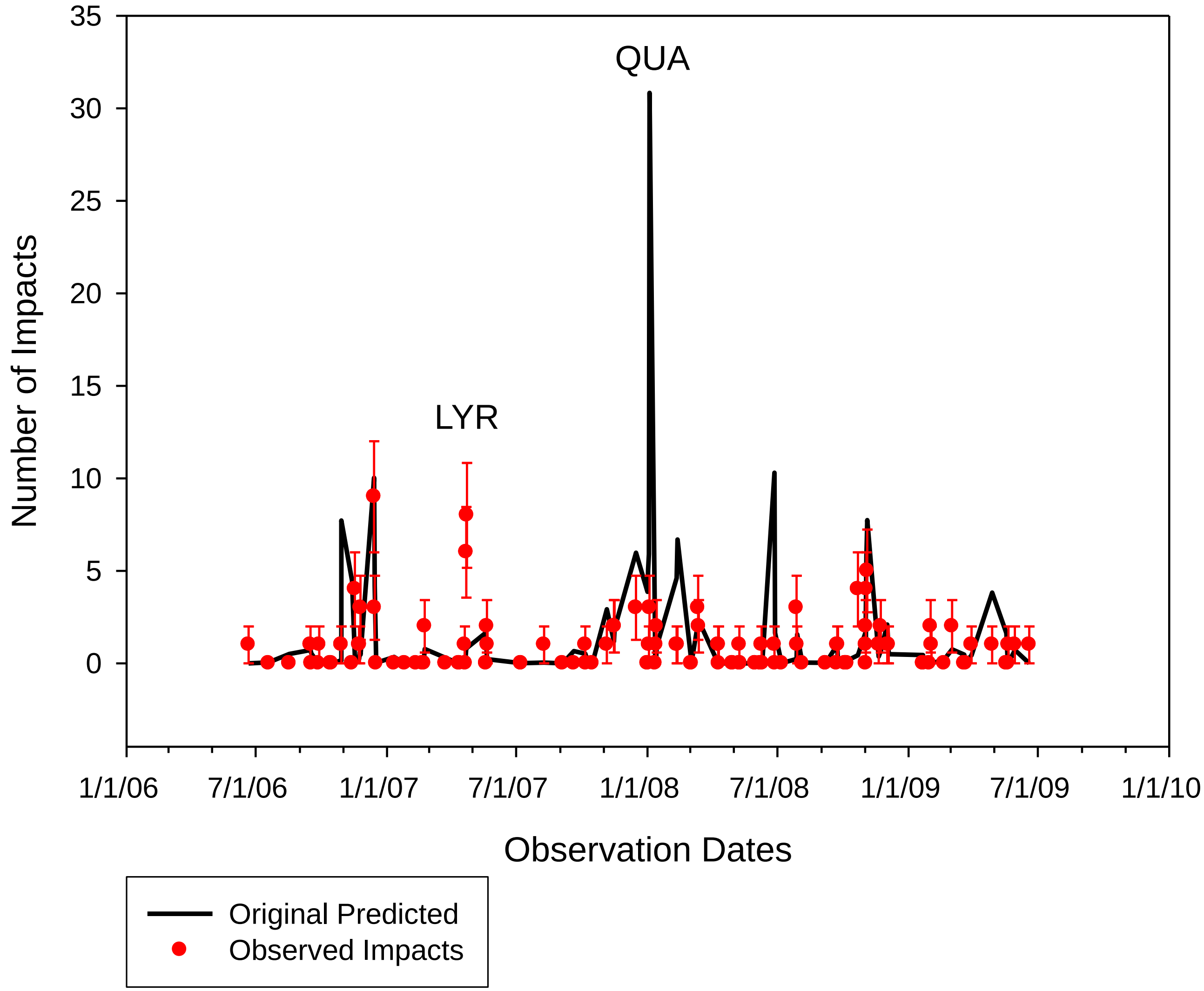
Sporadic Modeling Results

- Used Meteoroid Engineering Model to attempt to reproduce the morning/evening flux asymmetry
  - Hypothesis was that Apex + Antihelion impacts visible in evening, Antihelion only in morning explained asymmetry
- Modeled ratio is 1.02:1 versus observed ratio of 1.45:1
- But, since sporadic population indices are steeper (more small particles) than showers, the showers should dominate at larger particle sizes…

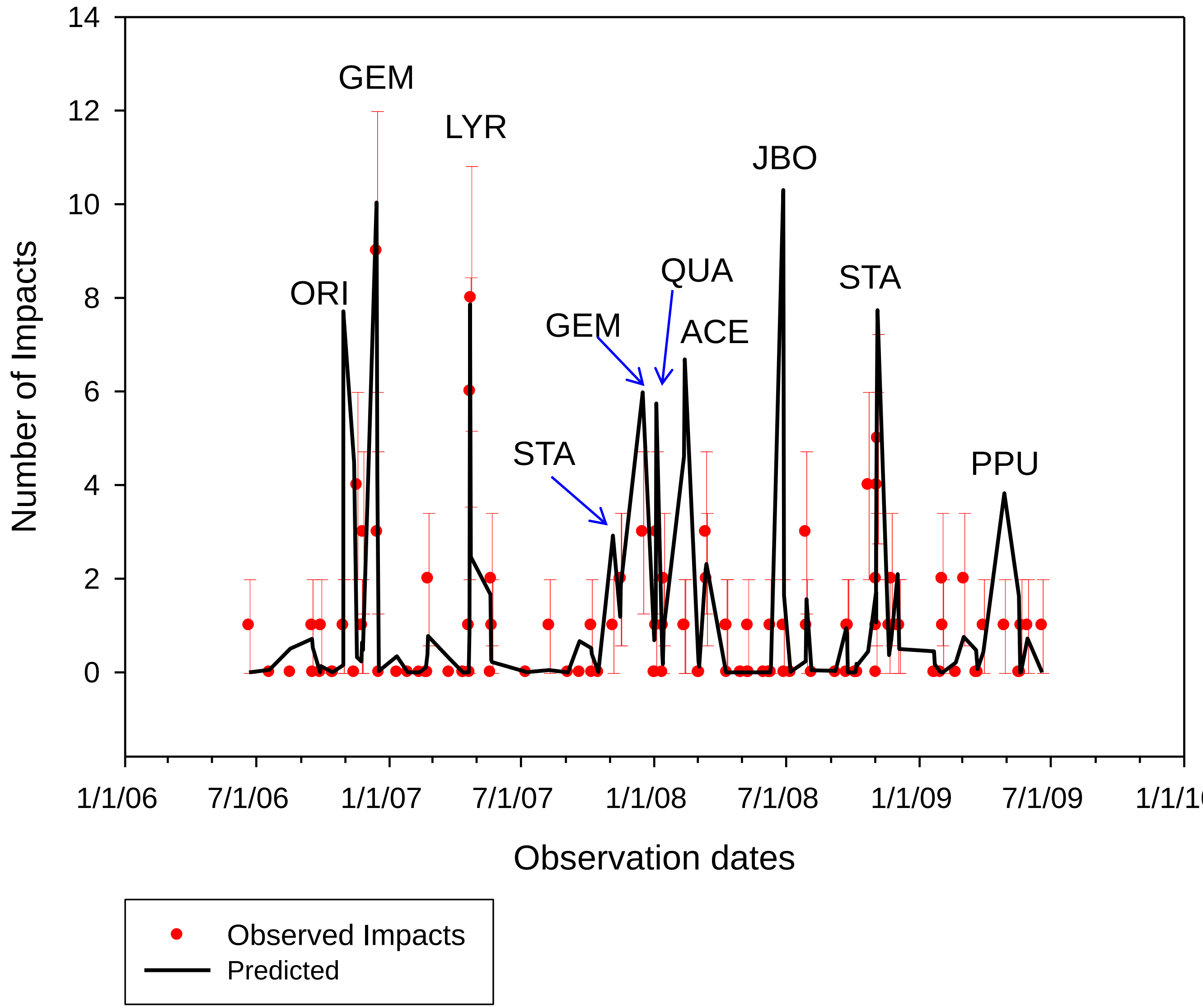
Shower Modeling Results

- Determined radiant visibility for the FOV of each night of observations
- Computed an expected flash rate using
  - Reported ZHR at time of observations from International Meteor Organization (corrected for location of the Moon and FOV visibility of radiant)
  - Population index from IMO
  - Shower speed
  - Luminous efficiency vs. speed from Swift, et al. 2010 , and Moser, et al. 2010
- Had to adjust population index for Lyrids and Quadrantids to match observed rates
  - Modeled 2007 Lyrids were too weak
    - Initial 2.9, better fit with 2.5,2.3, 2.6 (4/21-23/2007)
  - Modeled 2008 Quadrantids were too intense (30 impacts vs 3)
    - Initial 2.1, better fit with 2.6
- Computed evening/morning ratio is 1.57 compared to observed of 1.45

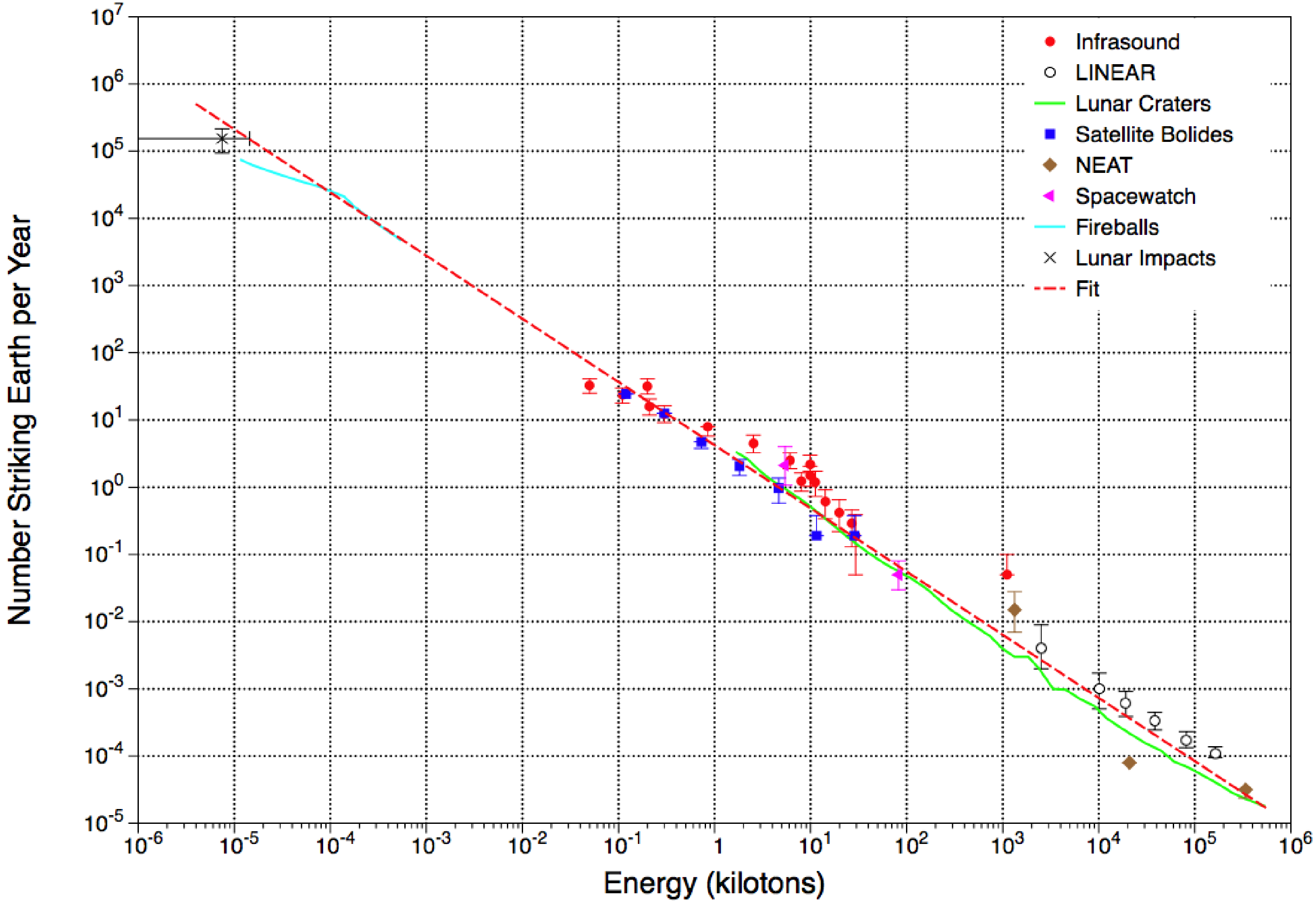
Meteor Shower Correlation
Predicted and Observed – IMO Population Indices



Meteor Shower Correlation
Predicted and Observed – Adjusted Population Indices



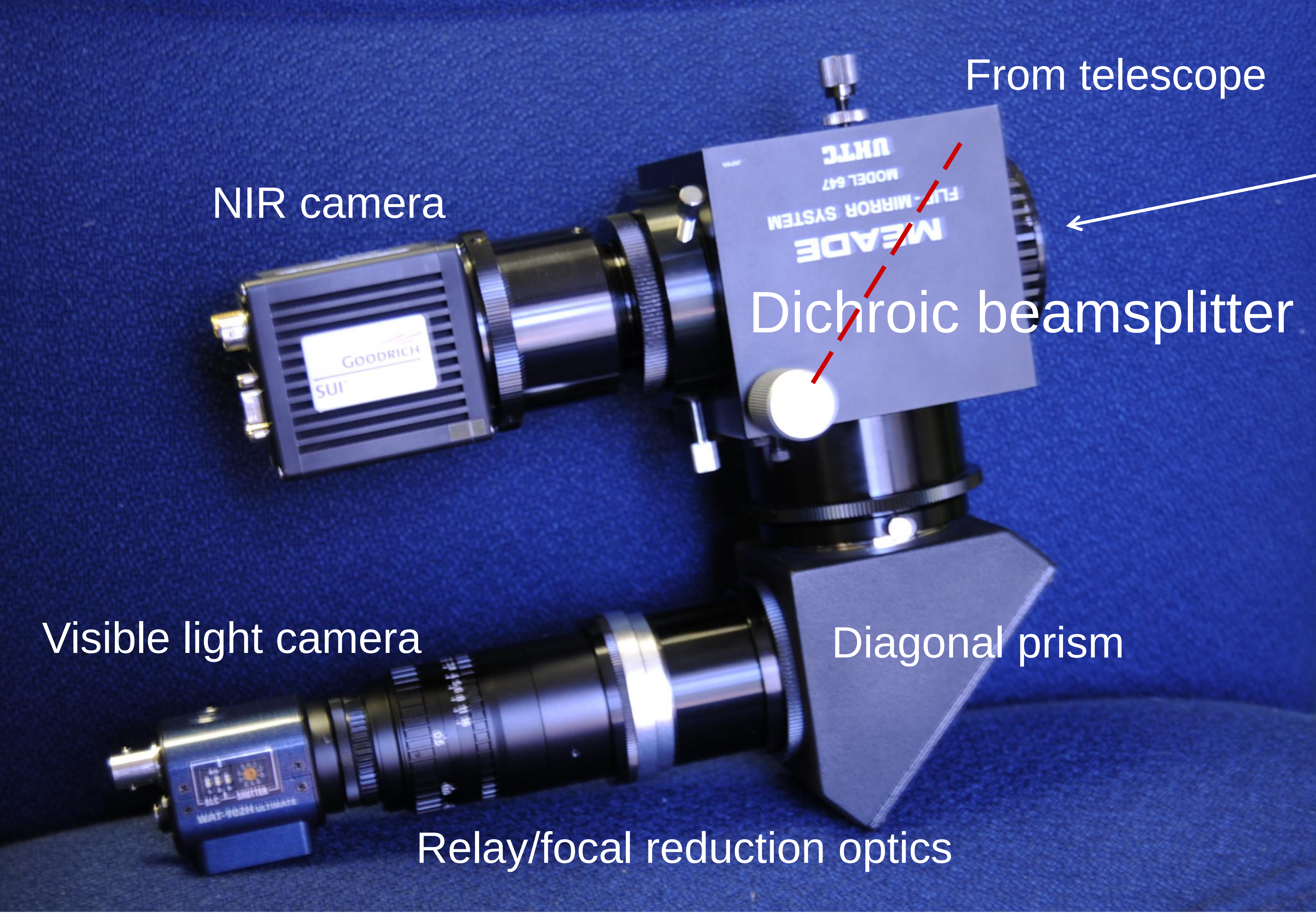
Flux Comparison with Other Measurements

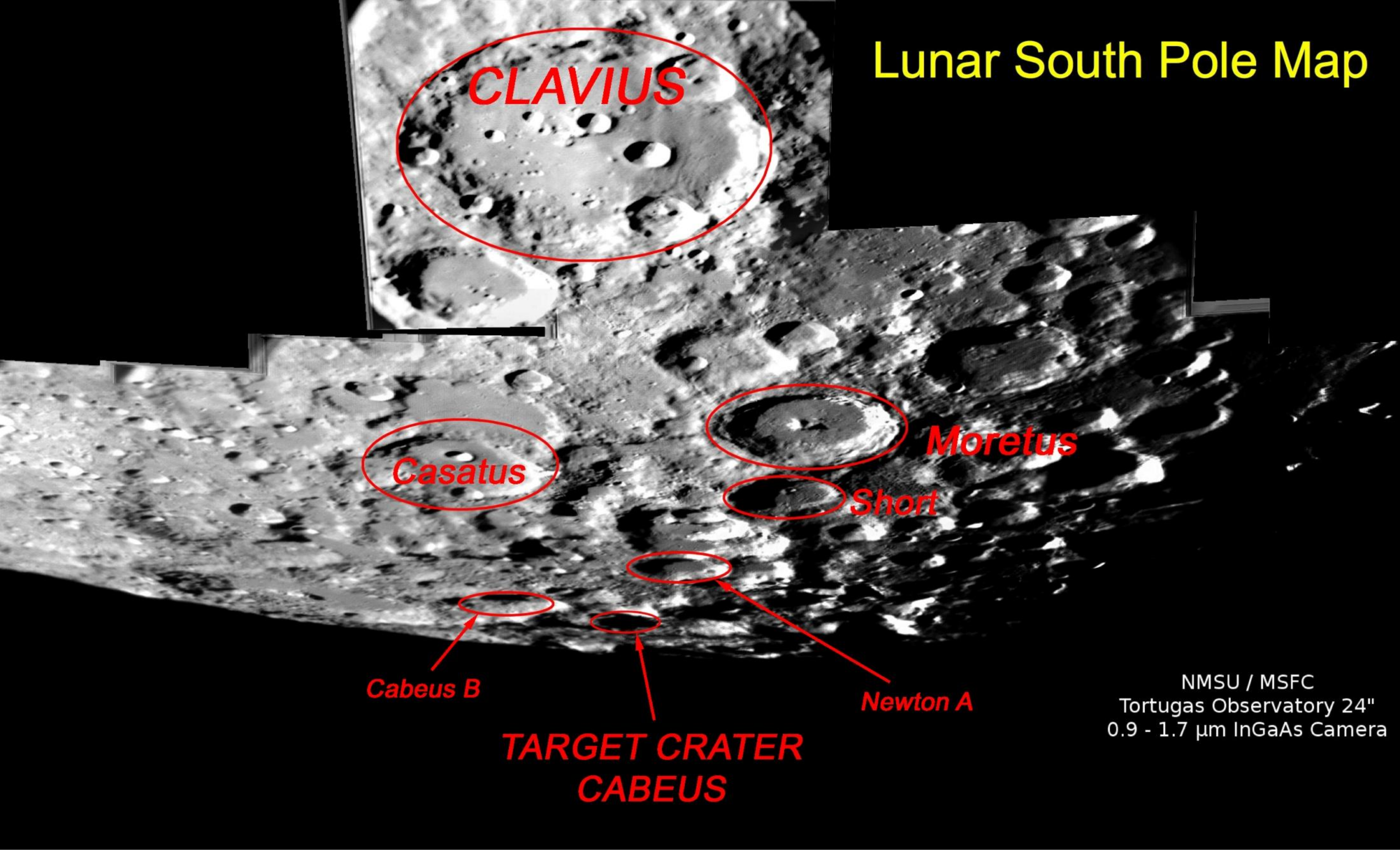


After Silber, ReVelle, Brown, and Edwards, 2009, JGR, 114, E08006

Future Equipment and Site

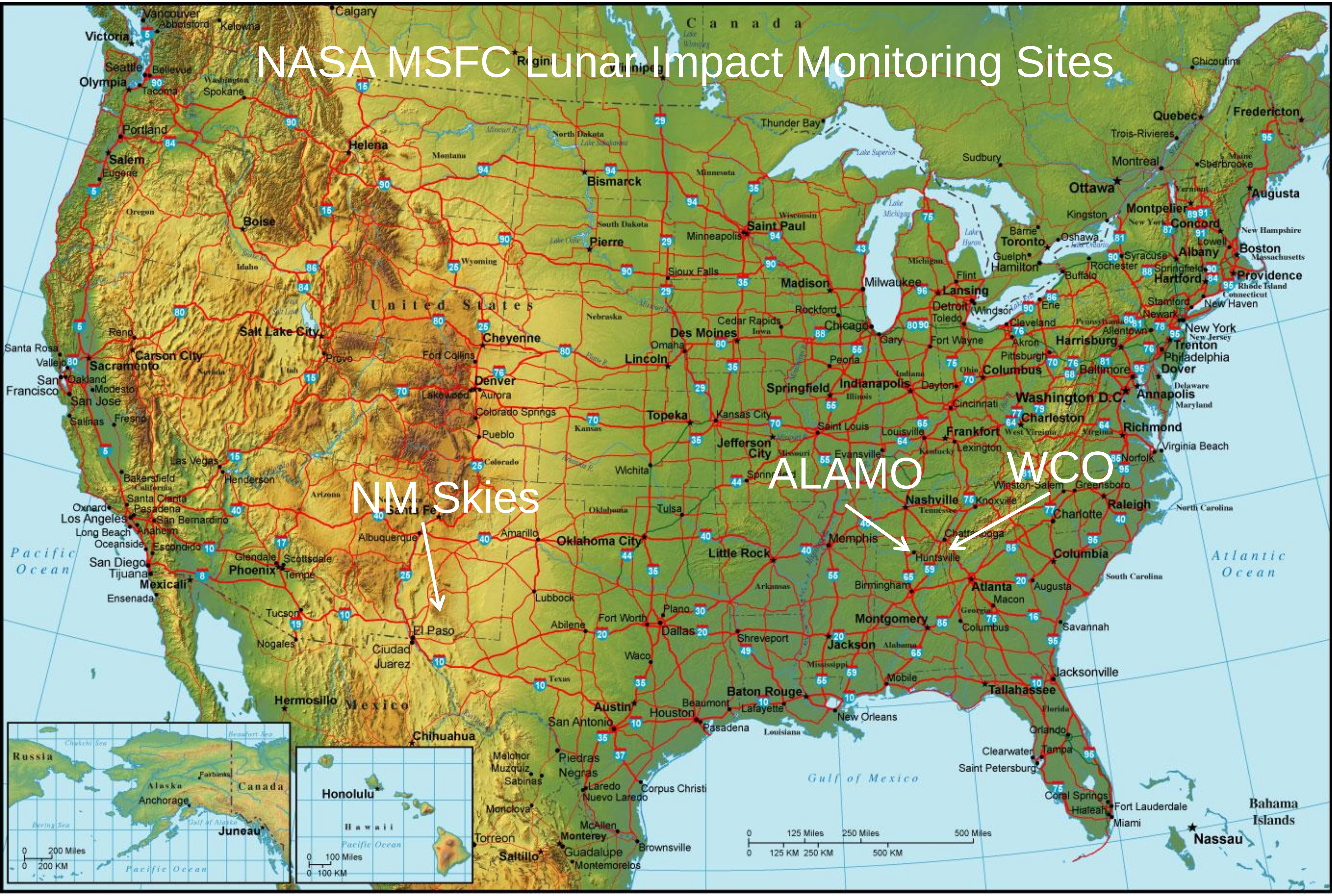
- Dichroic beamsplitter allows simultaneous observations with near-infrared (0.9 – 1.7 micron) and visible light cameras on one telescope
  - Expected plume temperature is 3000K which has blackbody peak at 1 micron
- Site in New Mexico extends longitude coverage and improves weather prospects


From telescope
NIR camera
Dichroic beamsplitter
Visible light camera
Diagonal prism
Relay/focal reduction optics
MEADE
FLIP-MIRROR SYSTEM
MODEL 647
UHTC
GOODRICH
SUI

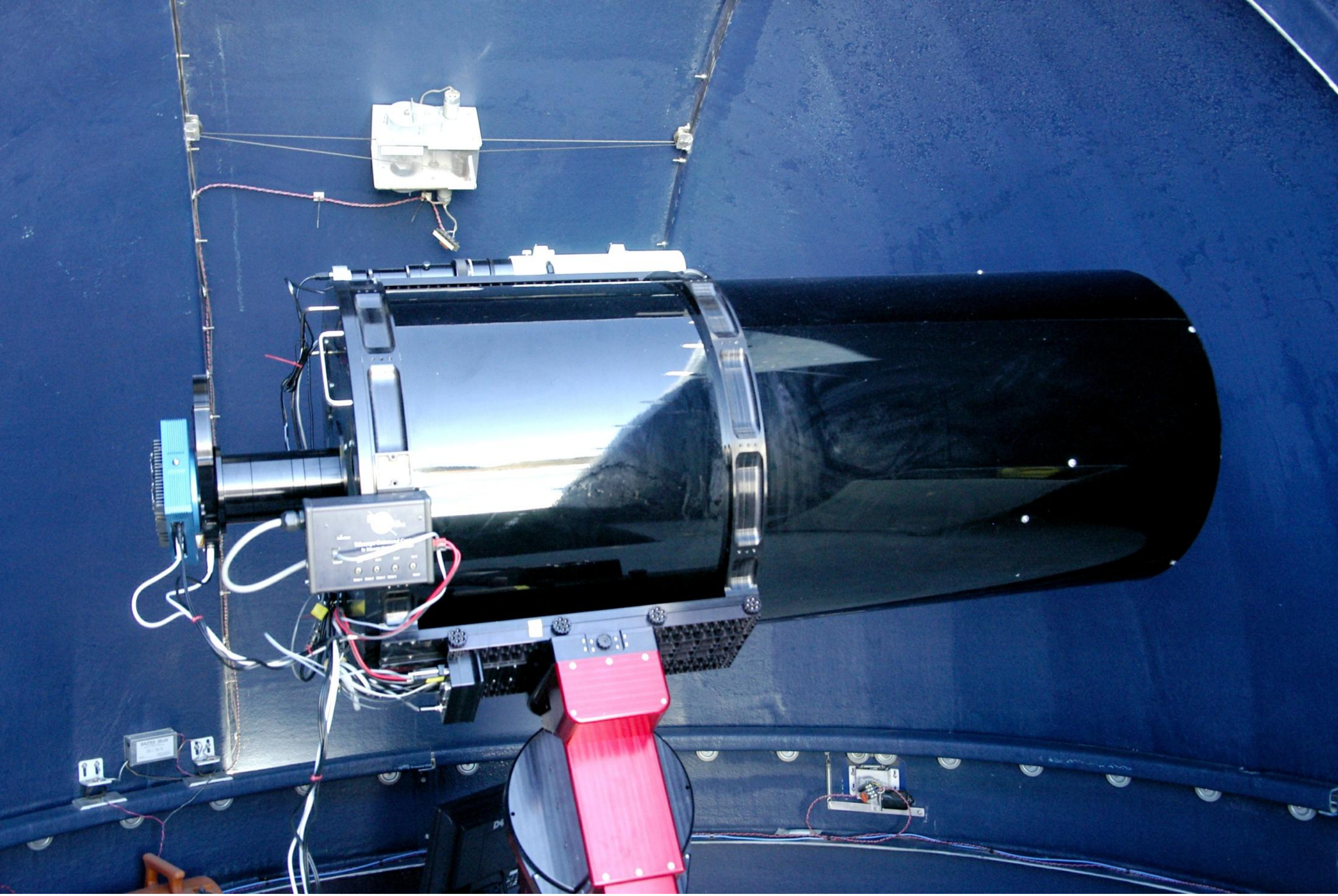


Video from MSFC’s near-infrared camera, selected and stacked with Registax
Astronomy Picture of the Day just before LCROSS impact

NASA MSFC Lunar Impact Monitoring Sites



New Mexico Skies
MSFC 0.5m



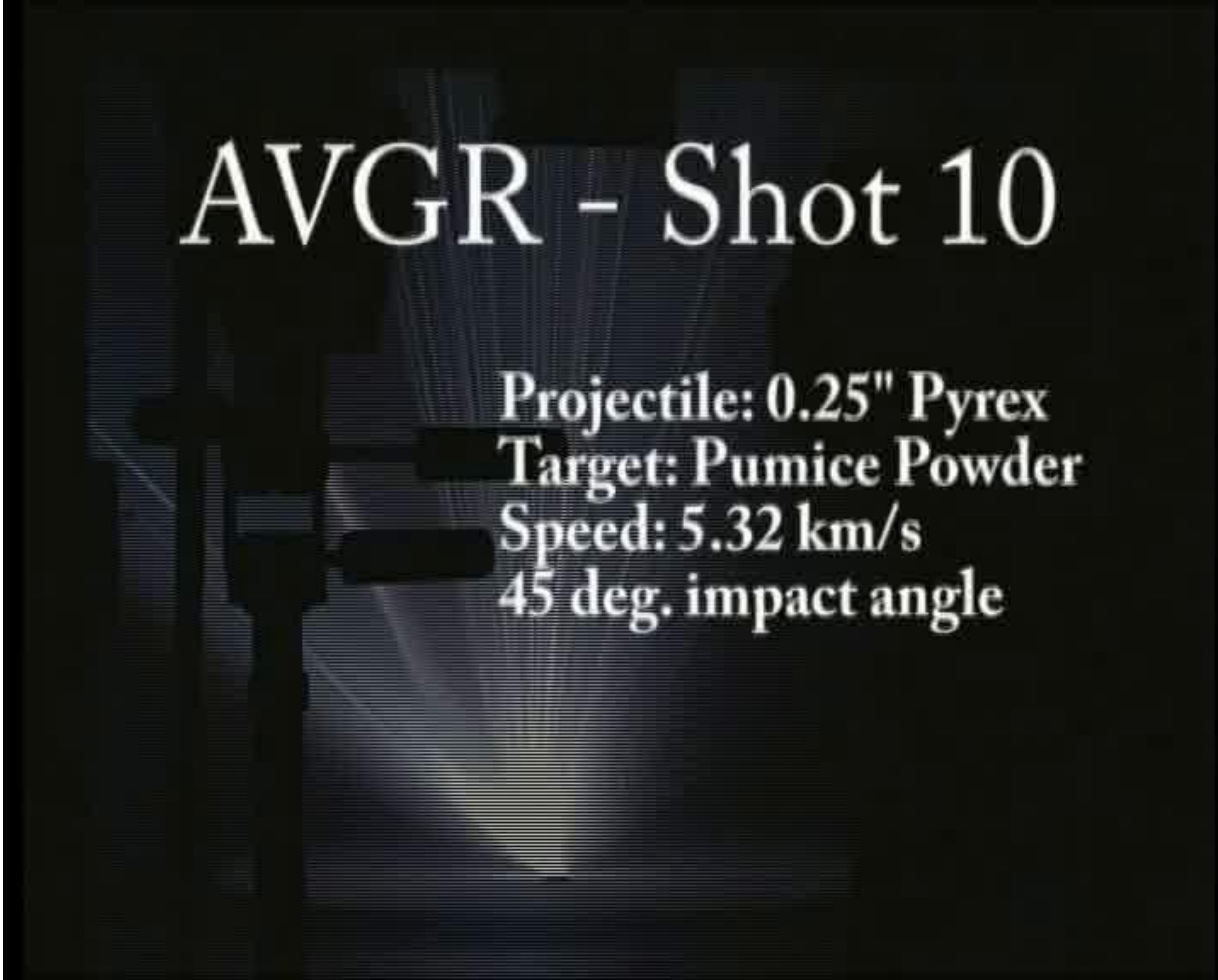
Luminous Efficiency (low velocity) from Ames Hypervelocity Impact Testing

- Purposes
  - Determine impact luminous efficiency – fraction of kinetic energy converted to light (completed 2 sessions of tests for this)
- Fired pyrex projectiles into pulverized pumice and JSC-1A simulant at various speeds and angles
- Preliminary testing completed in October ‘06
  - Recorded impacts with our video cameras and Schultz’s high speed photometer using ground pumice
- Second test sequence completed August ’07
  - True neutral density filters on our video cameras and JSC-1A simulant

Ames Vertical Gun Range

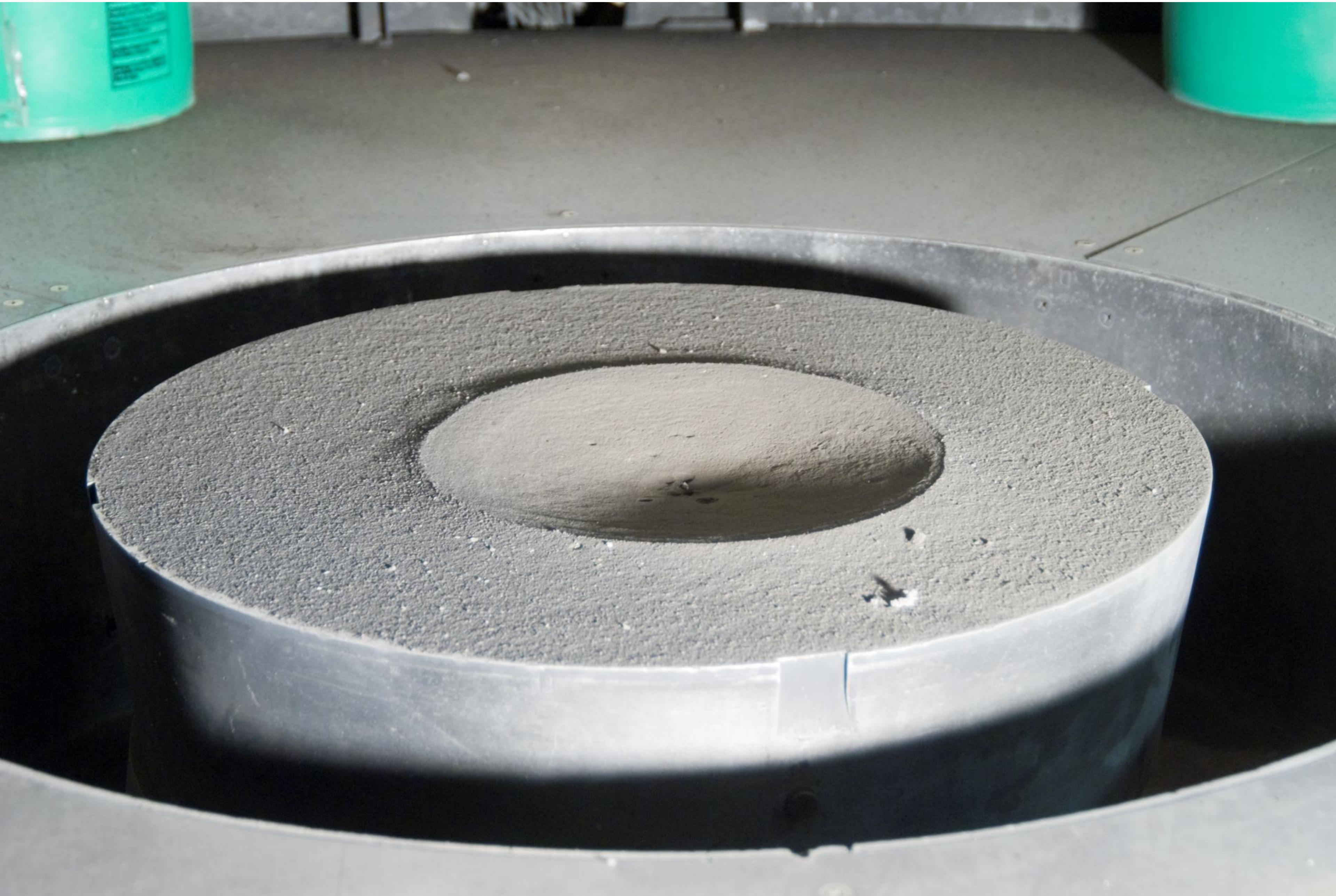
Camera ports


SONY
SONY
SONY
SONY
SONY

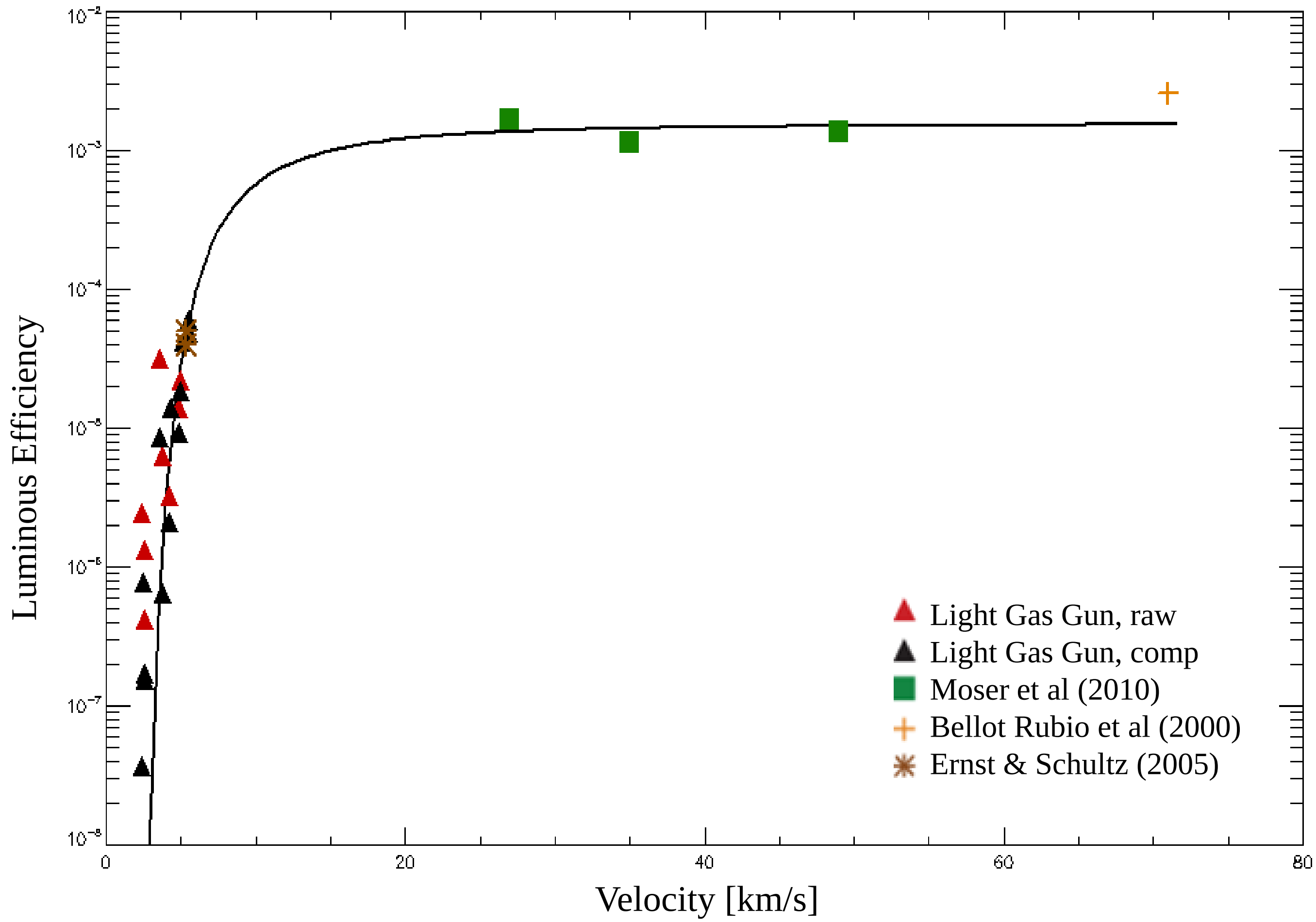

AVGR - Shot 10
Projectile: 0.25" Pyrex
Target: Pumice Powder
Speed: 5.32 km/s
45 deg. impact angle

AVGR Run 070823

Crater in JSC-1A Simulant



Luminous Efficiency from Swift et al. 2010



$$\eta_{cam} = 1.5x10^{-3}\, e^{-\left(\frac{9.3}{v}\right)^2}$$

- Fits both *Lunar Impact and Light Gas Gun data*

Summary

- Measured flux of meteoroids in the 100g to kilograms range is consistent with other observations
- Meteor showers dominate the environment in this size range and explain the evening/morning flux asymmetry of 1.5:1
- With sufficient numbers of impacts, this technique can help determine the population index for some showers
- We have a fruitful observing program underway which has significantly increased the number of lunar impacts observed
  - Over 200 impacts have been recorded in about 4 years
  - This analysis reports on the 115 impacts taken under photometric conditions during the first 3 full years of operation.
- We plan to continue for the foreseeable future
  - Run detailed model to try explain the concentration near the trailing limb
  - Build up statistics to better understand the meteor shower environment
  - Provide support for robotic seismometers and dust missions
  - Deploy near-infrared and visible cameras with dichroic beamsplitter to 0.5m telescope in New Mexico to observe during meteor showers

The authors thank the Meteoroid Environment Office and the MSFC Engineering Directorate for support of this project