Flux of Kilogram-sized Meteoroids from Lunar Impact Monitoring

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Routine lunar impact monitoring has harvested over 110 impacts in 2 years of observations using 0.25, 0.36 and 0.5 m telescopes and low-light-level video cameras. The night side of the lunar surface provides a large collecting area for detecting these impacts and allows estimation of the flux of meteoroids down to a limiting luminous energy. In order to determine the limiting mass for these observations, models of the sporadic meteoroid environment were used to determine the velocity distribution and new measurements of luminous efficiency were made at the Ames Vertical Gun Range. The flux of meteoroids in this size range has implications for Near Earth Object populations as well as for estimating impact ejecta risk for future lunar missions.

The Flux of Kilogram-sized Meteoroids from Lunar Impact Monitoring

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Abstract

Routine lunar impact monitoring has harvested over 150 impacts in just over 2 years of observations using 0.25, 0.36 and 0.5 m telescopes and low-light-level video cameras. The night side of the lunar surface provides a large collecting area for detecting these impacts and allows estimation of the flux of meteoroids down to a limiting luminous energy. In order to determine the limiting mass for these observations, models of the sporadic meteoroid environment were used to determine the velocity distribution and new measurements of luminous efficiency were made at the Ames Vertical Gun Range. The flux of meteoroids in this size range has implications for Near Earth Object populations as well as for estimating impact ejecta risk for future lunar missions.

Background

Measuring the flux of large meteoroids requires a large collecting area due to their relatively low flux. Large fireball networks use the atmosphere above them as the collecting area but the surface of the Moon provides a useful area when routinely monitored. Astronaut Harrison Schmidt saw an impact while orbiting the Moon on Apollo 17 in December of 1972 (NASA 1972). The Leonid storms of 1999 provided the first coordinated video observations of lunar meteoroid impacts (Dunham et al. 2000). In November 2005 a video recording of a lunar impact of a likely Taurid shower meteoroid from NASA's Marshall Space Flight Center led to the creation of a routine impact monitoring program which has recorded over 150 impacts in just over 2 years of operation. The primary purpose of this program is to improve the understanding of the lunar impact ejecta environment in support of the Constellation Program plans to return astronauts to the Moon. The flux of kilogram-sized meteoroids also has implications for the population of Near Earth Objects.

This poster describes the observational techniques and data analysis process used to record and catalog lunar impact flashes. In order to determine the limiting mass of the detection technique, the luminous efficiency (the fraction of impact kinetic energy converted to light in the camera spectral passband) and the velocity distribution of the impactors have to be considered.

$$E_{Earth} = \eta \; 1/2 \; m \; v^2 \; / \; f \; \pi \; R^2 \qquad (1)$$

Where E_{Earth} is the energy detected at Earth, η is the luminous efficiency, f is an asymmetry factor (2 for hemispherical emission and 4 for isotropic, we used 3 as in Bellot-Rubio (2000) and R is the distance to the Moon. The data from 147 nights of observation were reviewed and 72 nights comprising 162.7 observation hours were chosen for detailed analysis. In this time span 76 impact flashes were recorded in the field of view which covers approximately 9% of the total lunar surface.

Observation Procedure

Telescopes – correlated detections required to discriminate cosmic rays
- 0.5m RCOS
  - -MSFC (Huntsville, AL)
- 2x 0.34m Meade RCX
  - -MSFC and Chickamauga, GA (100 km separation to discriminate satellite/orbital debris sunglints)
- 0.25m f4.5 Newtonian – used for early observations
  - -MSFC

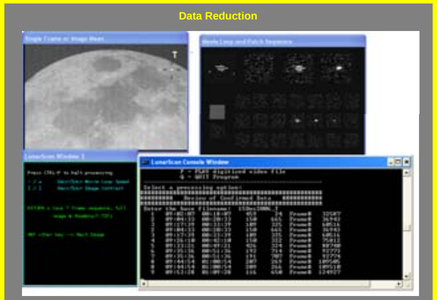
Focal reducers
- Positive lenses spaced to give approximately 1m focal length and 20 arcminute horizontal FOV for all telescopes

Cameras – all use Sony HAD EX chips, interleaved, 30 frame per second video rate
- StellaCam EX
- Watec Ultimate H2

Digitizer
-Sony GV-D800 digital 8 deck sends video data to PC where it is recorded.

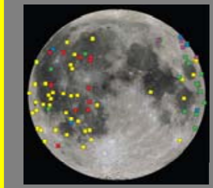
Moon is observed between 10% and 50% illumination which results in about 10 possible nights per month with observation periods between 1 and 5 hours per night.

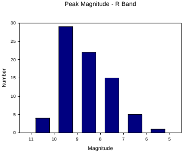
Data Reduction



LunarScan (Gural 2007) scans video file to find changes between frames which meet selectable signal-to-noise criteria.
Human reviews candidate flashes and deletes cosmic rays, aircraft, satellites, etc.
LunaCon (Swift et al., 2008) finds lunar edge and computes surface area searched, uses background stars to photometrically calibrate flashes, estimates data quality (passing clouds, lunar contrast) to allow exclusion of useless data, and calculates total energy for each flash in camera passband.

Impact Data and Determination of Flux





The image above shows the total lunar impacts used in the calculations reported here. Routine observations began in April 2006 and a second telescope came on-line in July 2006. A third telescope 100km away began operation in August 2007.
- Yellow points are likely sporadics
- Green – Geminids
- Blue – Leonids
- Red – Lyrids
- Purple - Quadrantids.

The asymmetry in sporadics is real and may be due to exposure to the higher velocity North and South Apex sporadics during evening observations (see Suggs et al., 2008).
- Of the 150 impacts recorded in the past 2 years, 76 were recorded under sufficiently good sky conditions to allow photometric calibration.
-The observing time under these uniform sky conditions was 162.7 hours.
- The average lunar surface area within the field of view was 3.43×10^6 km^2 or approximately 9% of the lunar surface.

Thus the flux of meteoroids down to our detection limit was

$$76 \; / \; (3.43 \times 10^6 \text{ km}^2 * 162.7 \text{ hr}) = 1.36 \times 10^{-7} \text{ impacts/km}^2 \text{ hr}$$

or $$1.19 \times 10^{-3} \text{ impacts/km}^2 \text{ yr.}$$

Determination of the Luminous Efficiency and Mass Limit

To determine the limiting mass for these observations we must first determine the luminous efficiency η. This was done using 2 different approaches:

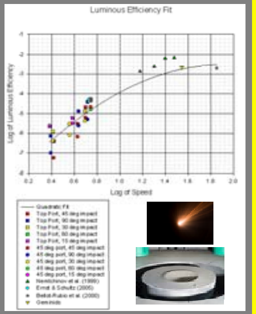
1) Hypervelocity shots of Pyrex spheres into JSC-1A lunar simulant were performed at the Ames Vertical Gun Range. The flashes were recorded with the same cameras used for impact monitoring but with neutral density filters and the fraction of the impact kinetic energy visible in the camera passband was calculated.

2) 12 Geminid shower impacts observed in 2006 were analyzed following the technique that Bellot-Rubio et al. (2000) used for the 1999 Leonids.

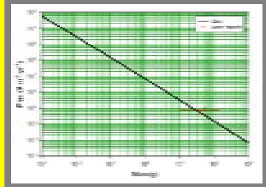
The resulting η as a function of impact speed was fitted including the Bello-Rubio Leonid value and the results appear to the right. Points from Ernst and Schultz (2005) and Nemtchinov et al. (1999) are included on the plot but not in the fit. Note that the Nemtchinov points lie above the fit due to the fact that they represent estimates based on hydrocode modeling and have not been adjusted for the spectral response of the cameras as the other points were.

The luminous efficiency as a function of speed was then convolved with the speed distribution of the sporadics from MEM (McNamara et al. 2004) and identified shower meteoroids in the 76 impacts to determine a limiting mass.

Determination of shower mass is easily accomplished using equation 1, as showers are mono-velocity. The masses of the sporadics are determined by substitution of the expectation value of v2 using the MEM (McNamara 2004) velocity distribution.



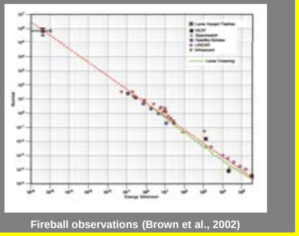
Comparison with Other Flux Determinations



Grün Model (Grün et al., 1985)

A comparison of the derived mass flux with that of Grün (1985) shows good agreement within the margin of error although there is a suggestion that the flux may be higher due to a significant shower contribution at these sizes.

The plot of number versus energy shows good agreement with that of Brown (2000) despite the significant difference in energies. This calls into question the results of Ortiz et al. (2006) as we find no significant deviation from previous results.



Fireball observations (Brown et al., 2002)

Plans and References

Near-term plans:
- Continue impact monitoring
- Reprocess existing video data using more sensitive version of LunarScan software
When funding is available:
- Perform additional impact testing at Ames Vertical Gun Range to determine ejecta characteristics (size, speed, flux)
- Perform crater modeling for impacts in observable size range and calibrate with AVGR tests
- Incorporate results into engineering model to use for design requirements and risk assessments for Constellation Program elements

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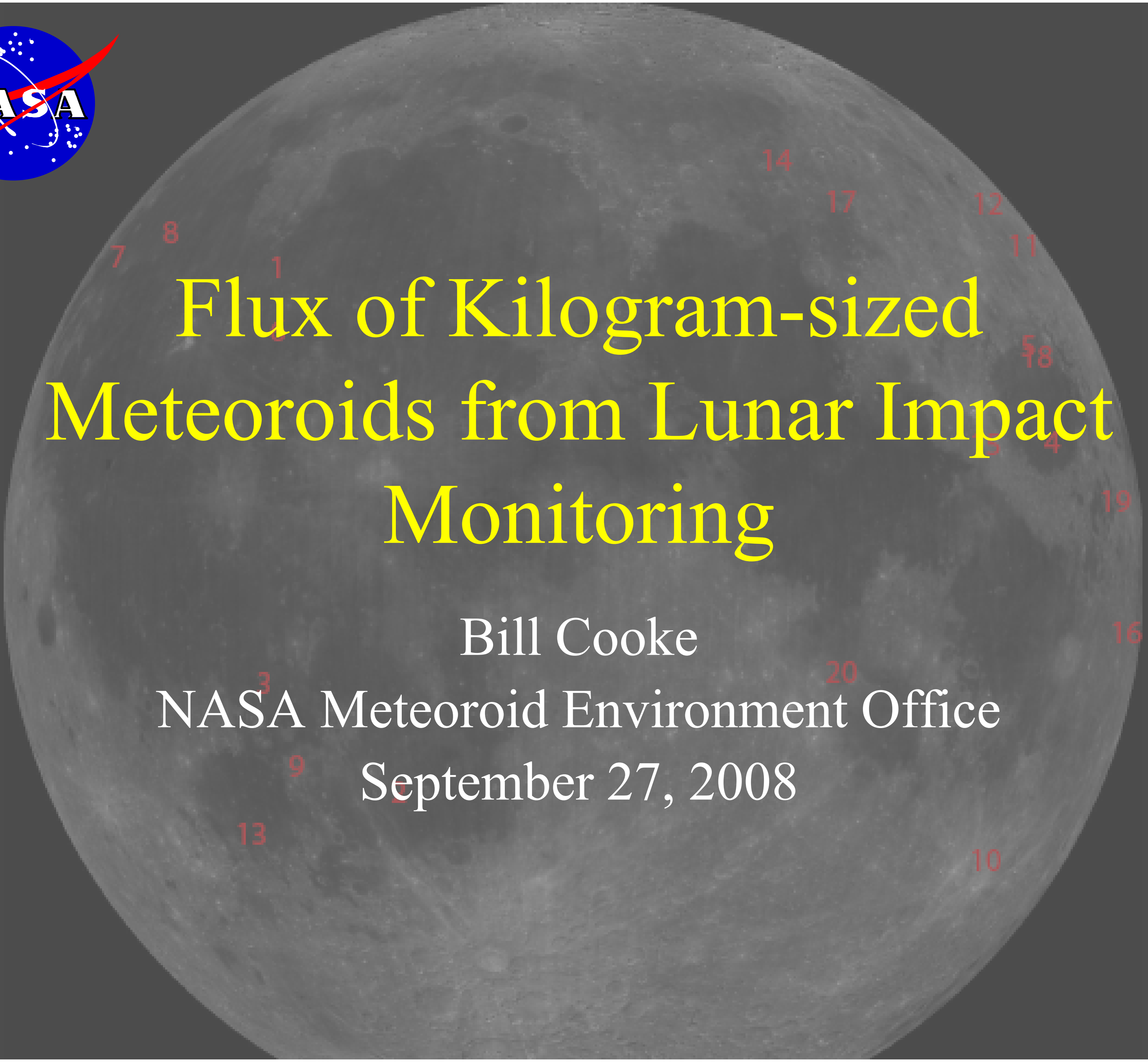


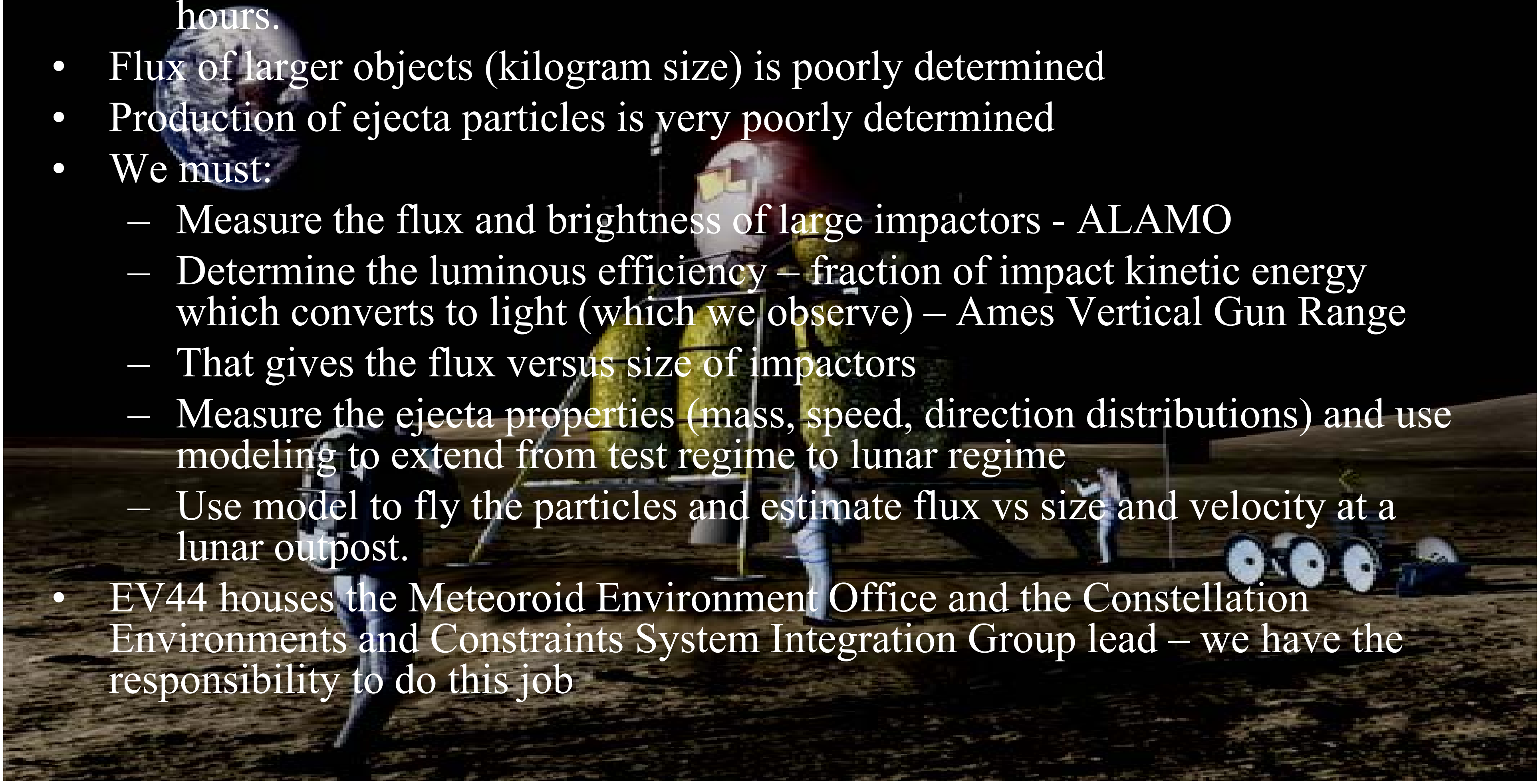
Flux of Kilogram-sized Meteoroids from Lunar Impact Monitoring

Bill Cooke
NASA Meteoroid Environment Office
September 27, 2008

Why Lunar Impact Monitoring is Useful

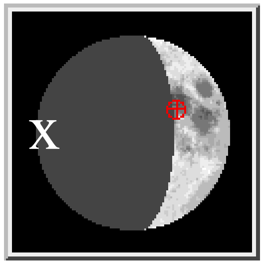
- We started this work in earnest 2 years ago to provide a better estimate of the ejecta environment for Constellation lunar elements.
- It turns out that it is also useful for calibration of MEM for large (kg) masses.

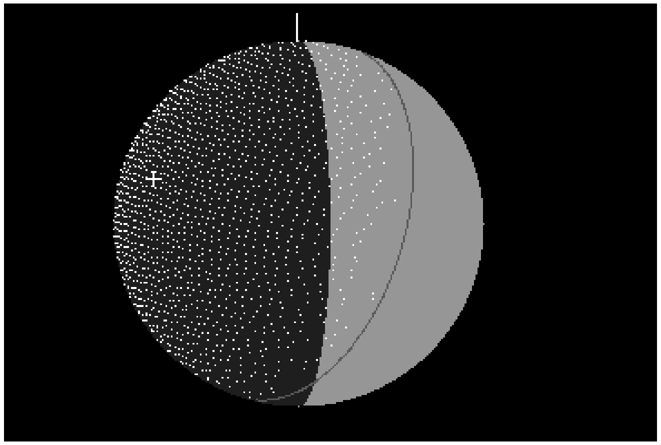
Why are lunar impact monitoring and hypervelocity impact testing necessary for Constellation?



- Constellation Program needs a specification for lunar impact ejecta
  - Existing spec is for Apollo – circa 1969
  - Astronauts will be exposed to this environment for months as opposed to hours.
- Flux of larger objects (kilogram size) is poorly determined
- Production of ejecta particles is very poorly determined
- We must:
  - Measure the flux and brightness of large impactors - ALAMO
  - Determine the luminous efficiency – fraction of impact kinetic energy which converts to light (which we observe) – Ames Vertical Gun Range
  - That gives the flux versus size of impactors
  - Measure the ejecta properties (mass, speed, direction distributions) and use modeling to extend from test regime to lunar regime
  - Use model to fly the particles and estimate flux vs size and velocity at a lunar outpost.
- EV44 houses the Meteoroid Environment Office and the Constellation Environments and Constraints System Integration Group lead – we have the responsibility to do this job

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):
----
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.

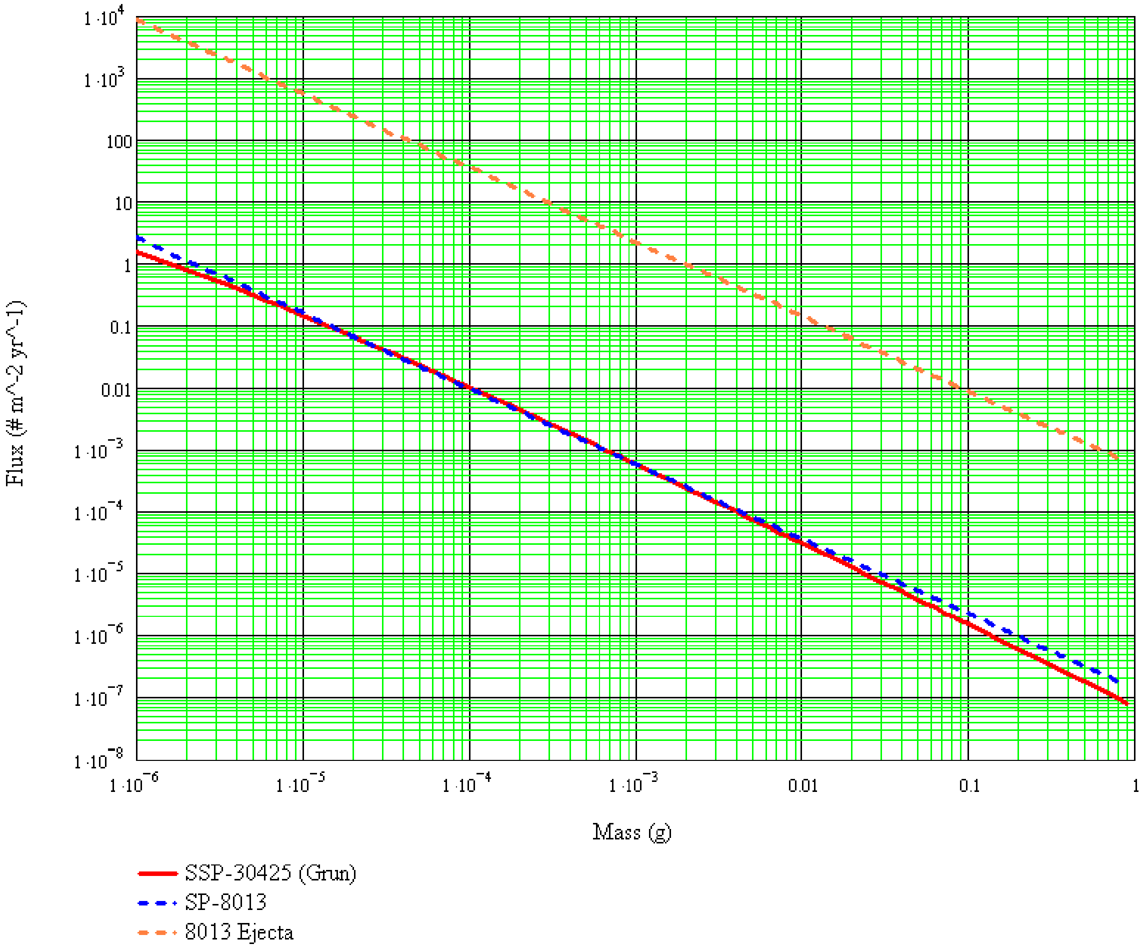
CC Okay. We'll check.

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....

Current (1969) Ejecta Model from SP-8013



Ejecta

Primaries

Ejecta particles are 10,000 times as abundant as primaries!
This curve is unphysical.

Impact Observation Technique

- Dark (not sunlit) side only
  - Earthshine illuminates lunar features
- Crescent and quarter phases – 0.1 to 0.5 solar illumination
  - 5 nights waxing (evening)
  - 5 nights waning (morning)
- 4-6 nights of data a month, weather dependent
- 3 telescopes
  - 20 inch (0.5m) and 2 x 14 inch (0.35m)
  - StellaCam EX and Watec H2 cameras
- Observing procedure
  - Aim scope at Moon
  - Record video to harddrive
    - CCD camera → Digital 8 recorder → hard drive
  - Wait and reposition

Automated Lunar and Meteor Observatory

0.5m in dome on left, 0.35m in tower

20 inch (0.5m) RCOS

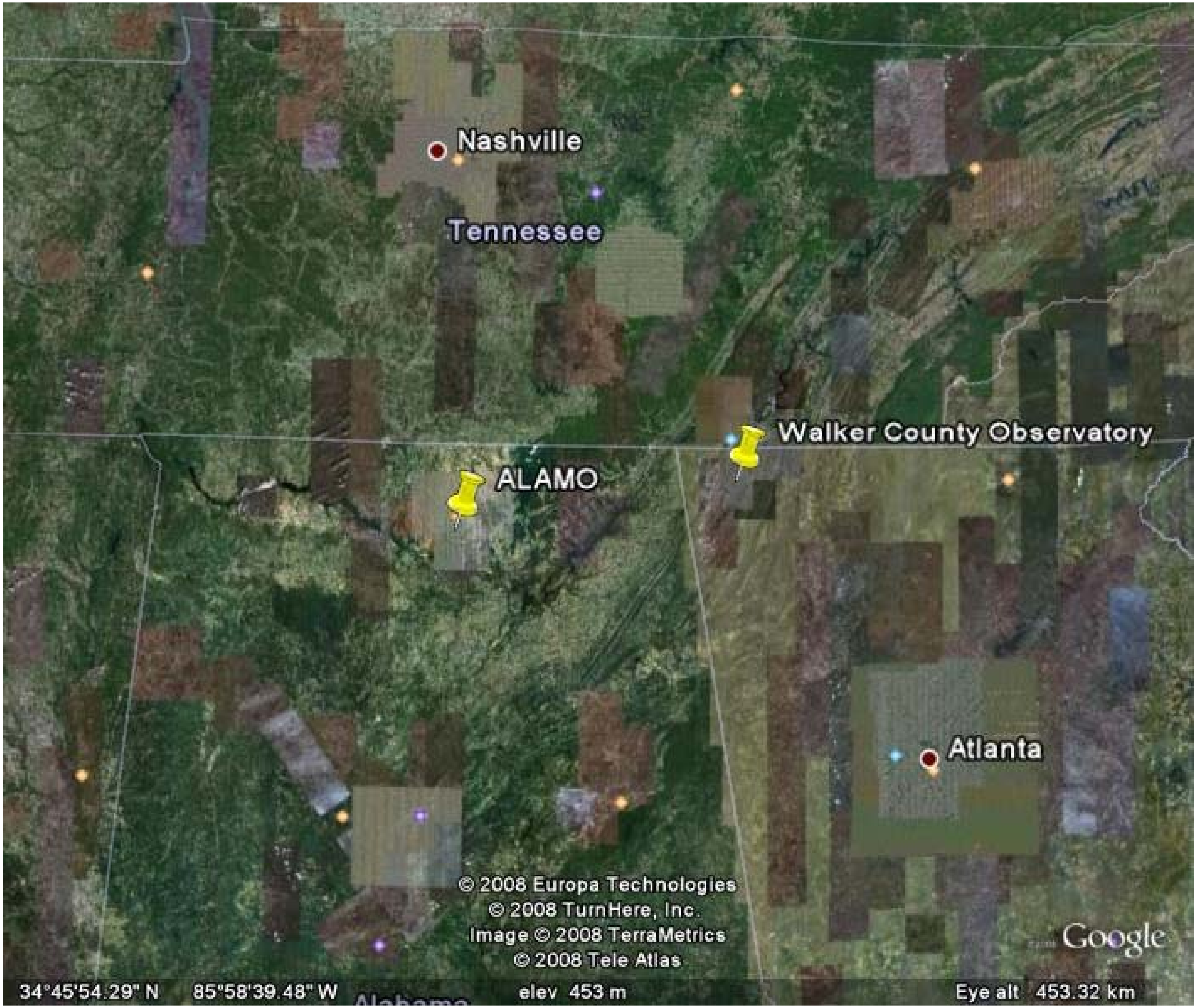

Nashville
Tennessee
Walker County Observatory
ALAMO
Atlanta
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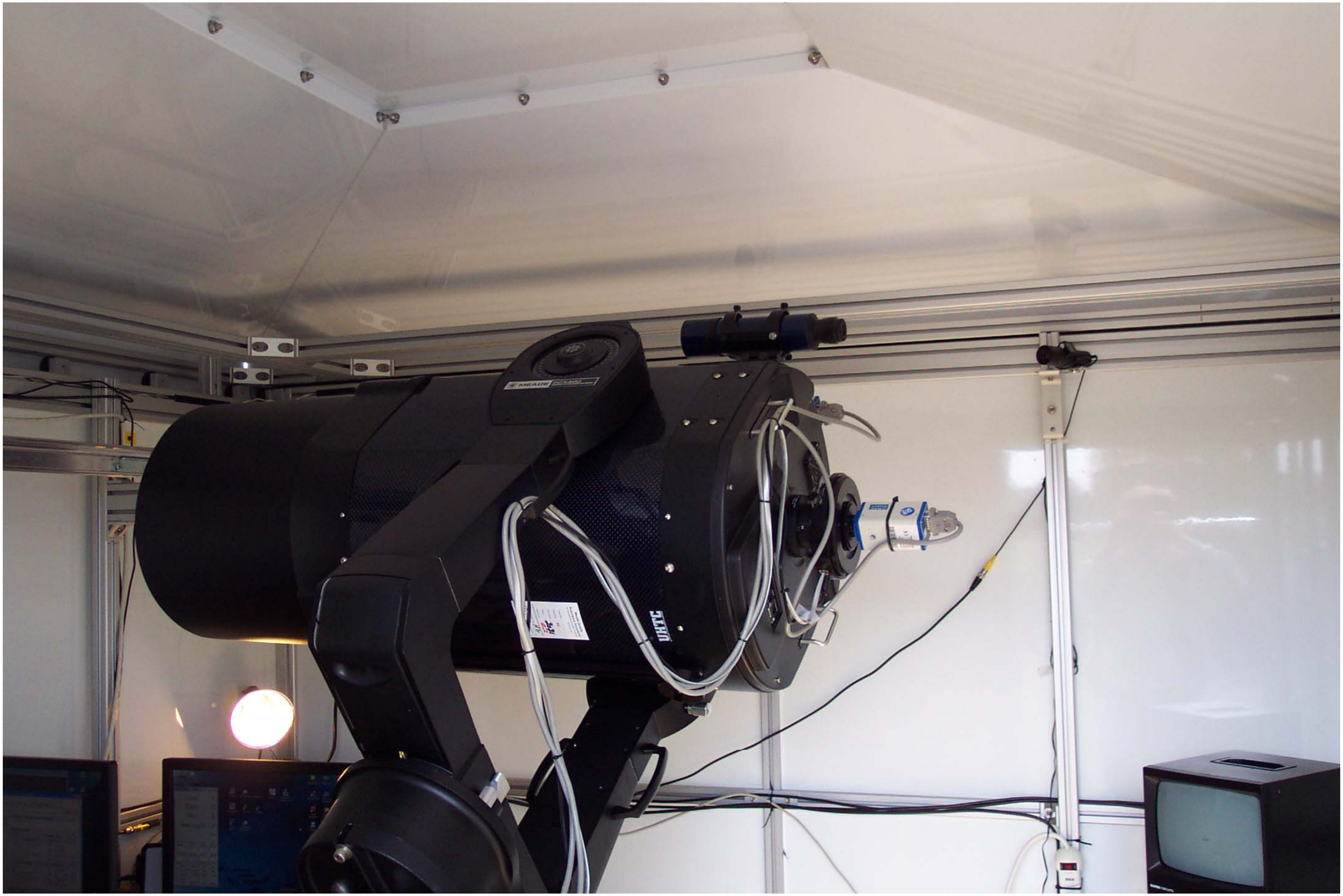
Image © 2008 TerraMetrics
© 2008 Tele Atlas
Google
34°45'54.29" N
85°58'39.48" W
Alabama
elev 453 m
Eye alt 453.32 km

Walker County Observatory

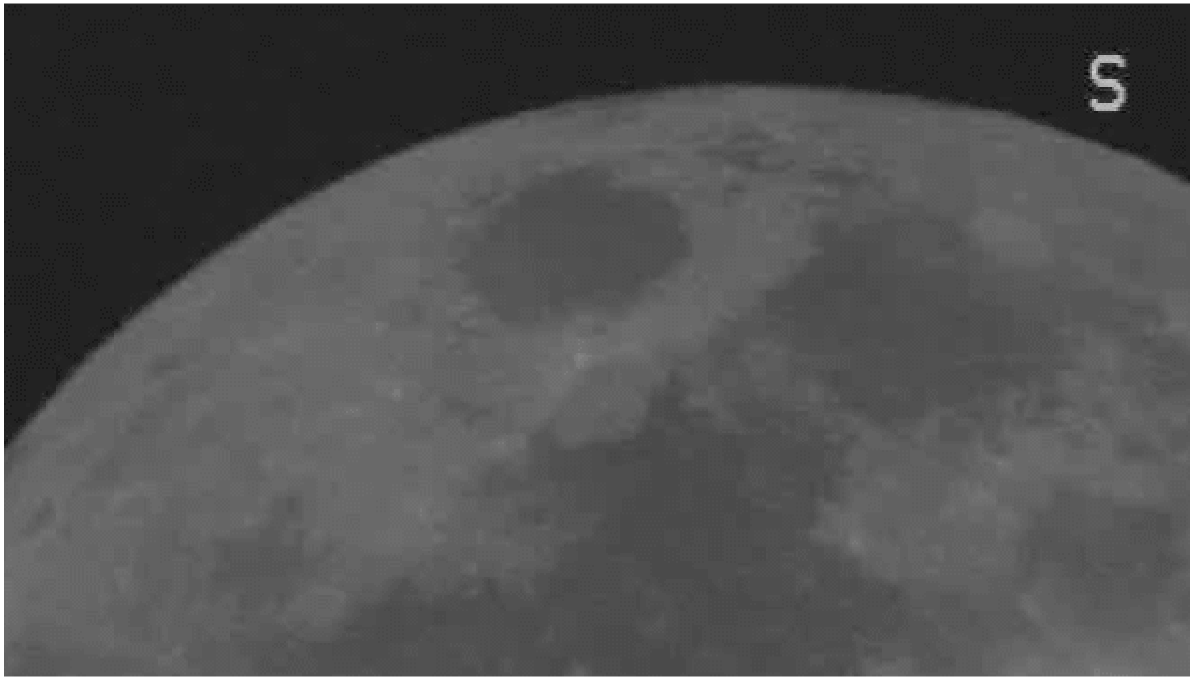
Meade 14 in (0.35m)



Control Room

Operator position

Probable Leonid Impact
November 17, 2006

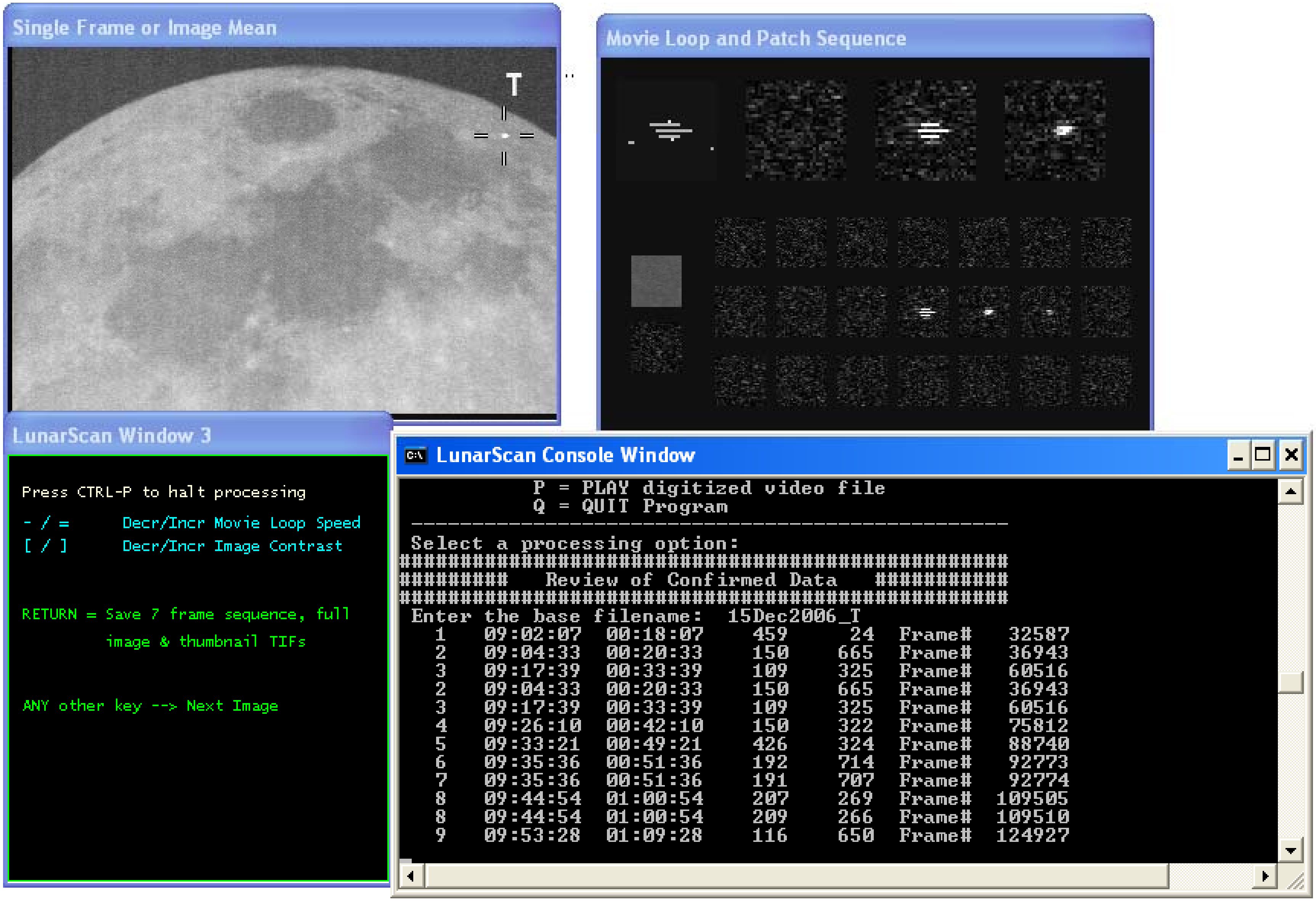


Video is slowed by a factor of 7

Video of multiple impacts

LunarScan (Gural)

Impact 15 Dec 2006



```
Press CTRL-P to halt processing
- / =      Decr/Incr Movie Loop Speed
[ / ]      Decr/Incr Image Contrast

RETURN = Save 7 frame sequence, full
         image & thumbnail TIFs

ANY other key --> Next Image
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```
           P = PLAY digitized video file
           Q = QUIT Program
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 Select a processing option:
##################################################
#########   Review of Confirmed Data   ###########
##################################################
 Enter the base filename:  15Dec2006_T
   1   09:02:07  00:18:07    459     24  Frame#   32587
   2   09:04:33  00:20:33    150    665  Frame#   36943
   3   09:17:39  00:33:39    109    325  Frame#   60516
   2   09:04:33  00:20:33    150    665  Frame#   36943
   3   09:17:39  00:33:39    109    325  Frame#   60516
   4   09:26:10  00:42:10    150    322  Frame#   75812
   5   09:33:21  00:49:21    426    324  Frame#   88740
   6   09:35:36  00:51:36    192    714  Frame#   92773
   7   09:35:36  00:51:36    191    707  Frame#   92774
   8   09:44:54  01:00:54    207    269  Frame#  109505
   8   09:44:54  01:00:54    209    266  Frame#  109510
   9   09:53:28  01:09:28    116    650  Frame#  124927
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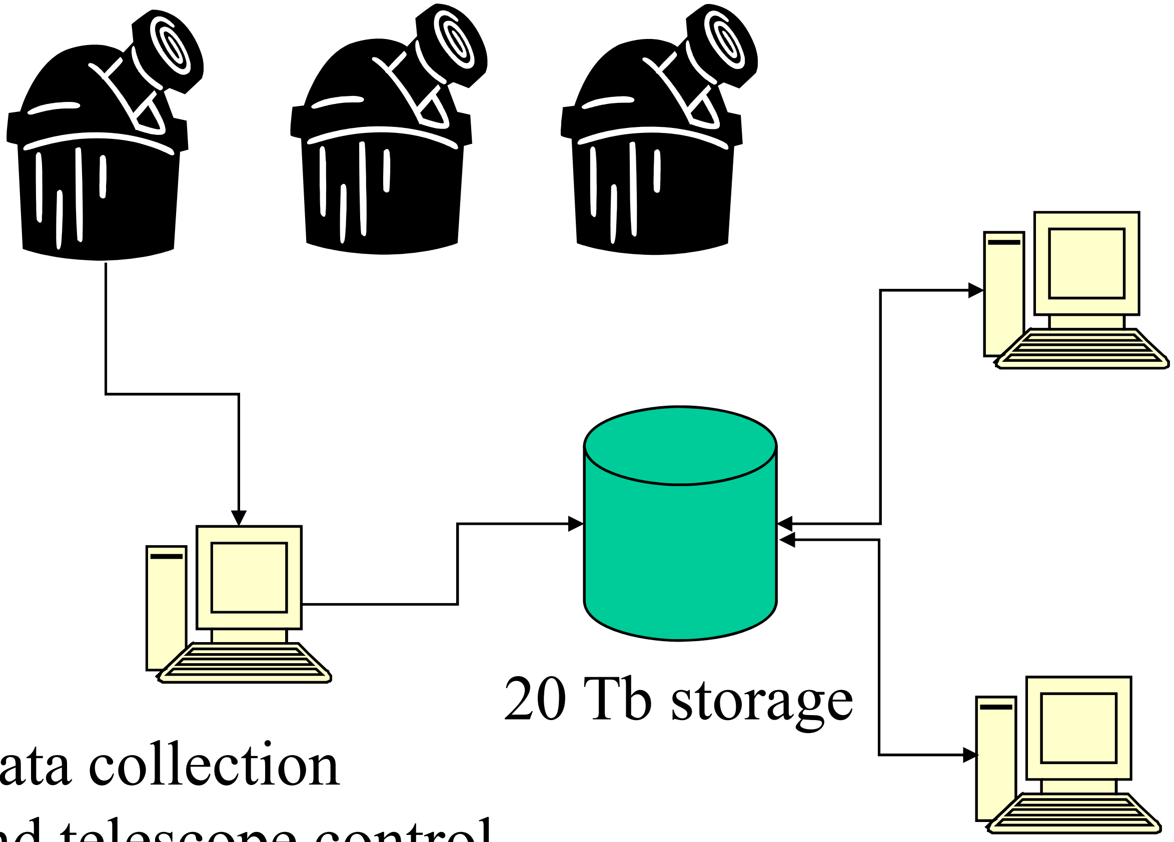
Data Analysis Pipeline



LunarScan
finds flashes

20 Tb storage

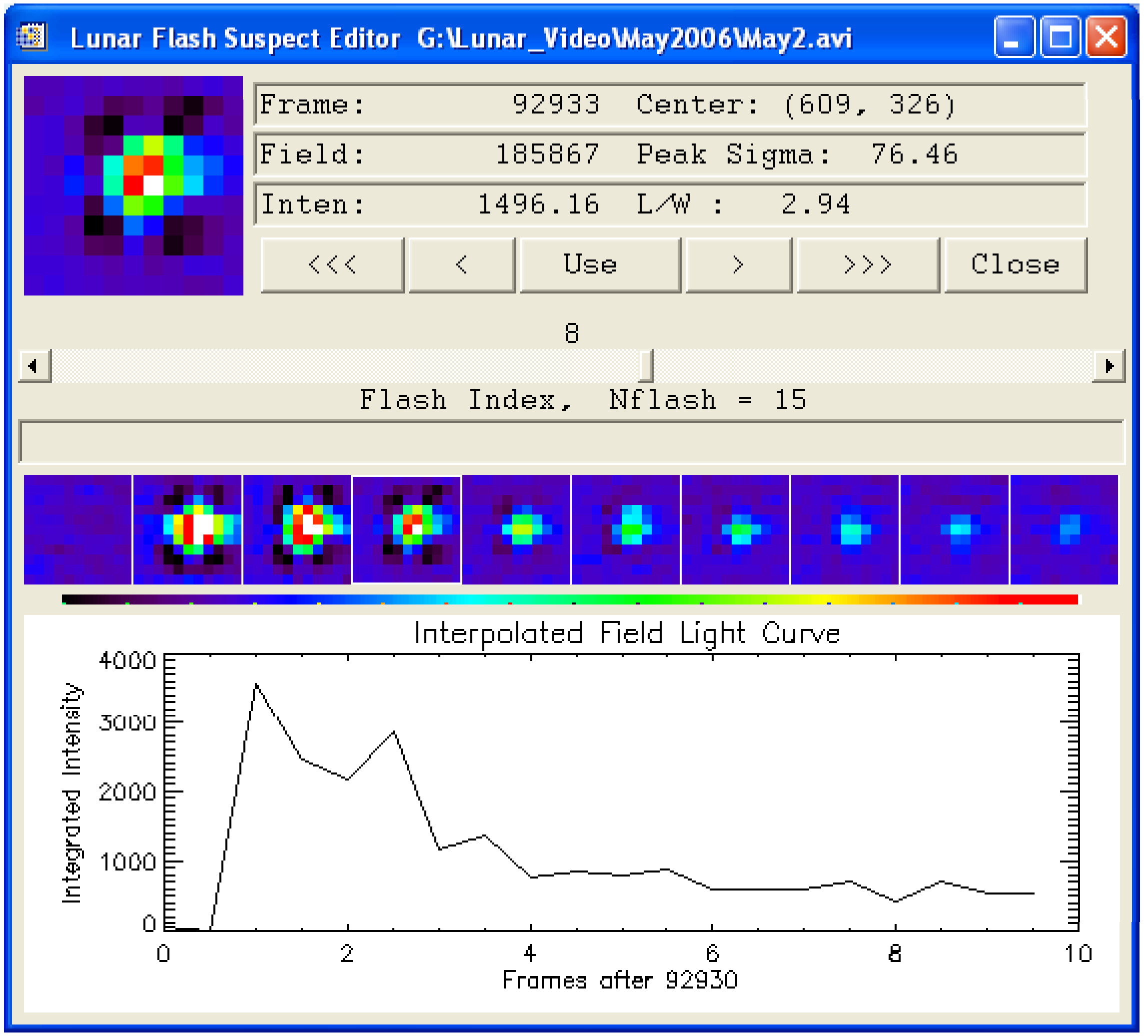
Data collection
and telescope control

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

Must detect flash in all operating telescopes

The Usual Suspects

- Noise
- Boundaries
- Stars
- Satellite glints
- Impacts
- Established WCO site to discriminate faint glints from orbital debris



Frame: 92933 Center: (609, 326)

Field: 185867 Peak Sigma: 76.46

Inten: 1496.16 L/W : 2.94

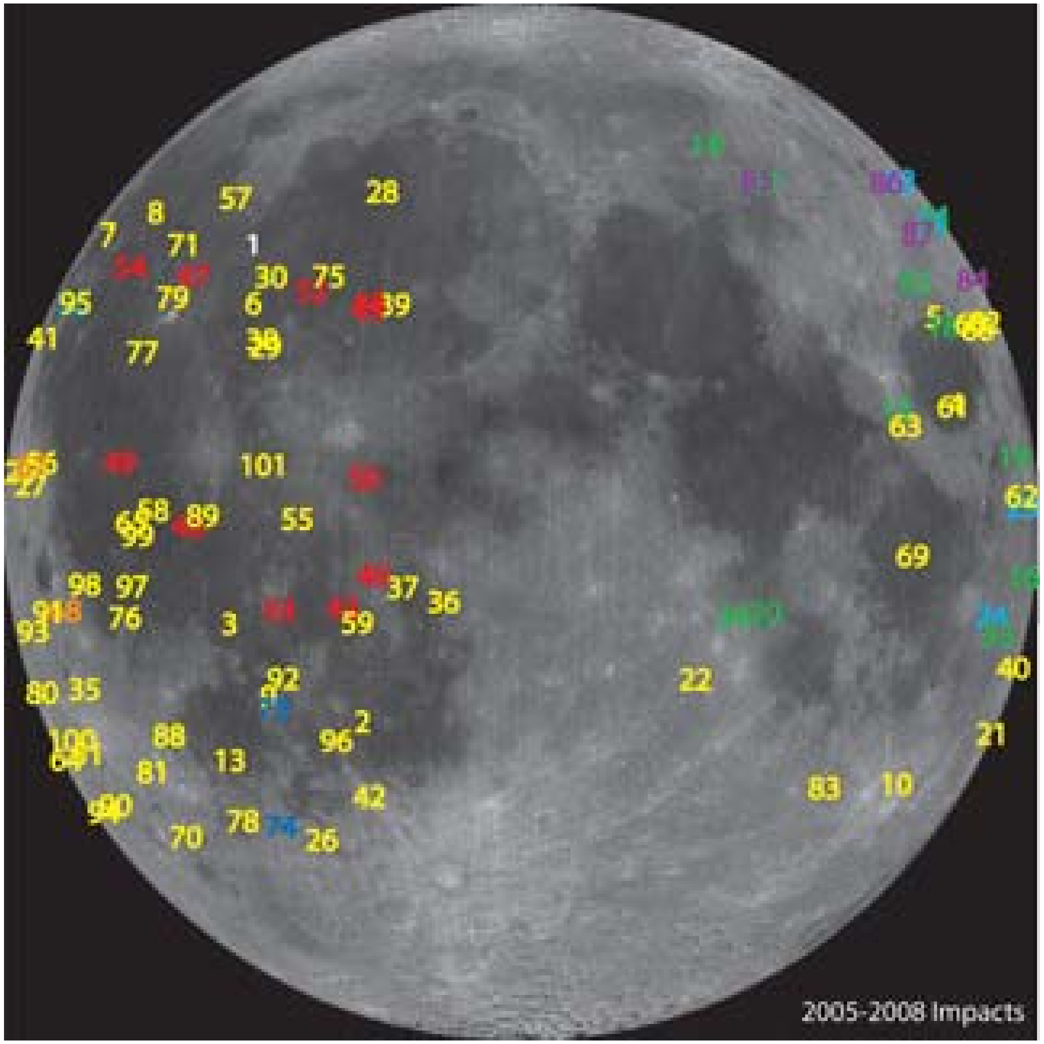
Flash Index, Nflash = 15

Atlas-Centaur Debris

16 Dec. 2006

Half real-time

Impact Candidates – over 100 now



Yellows are sporadic meteoroids
Other colors are probable shower meteoroids

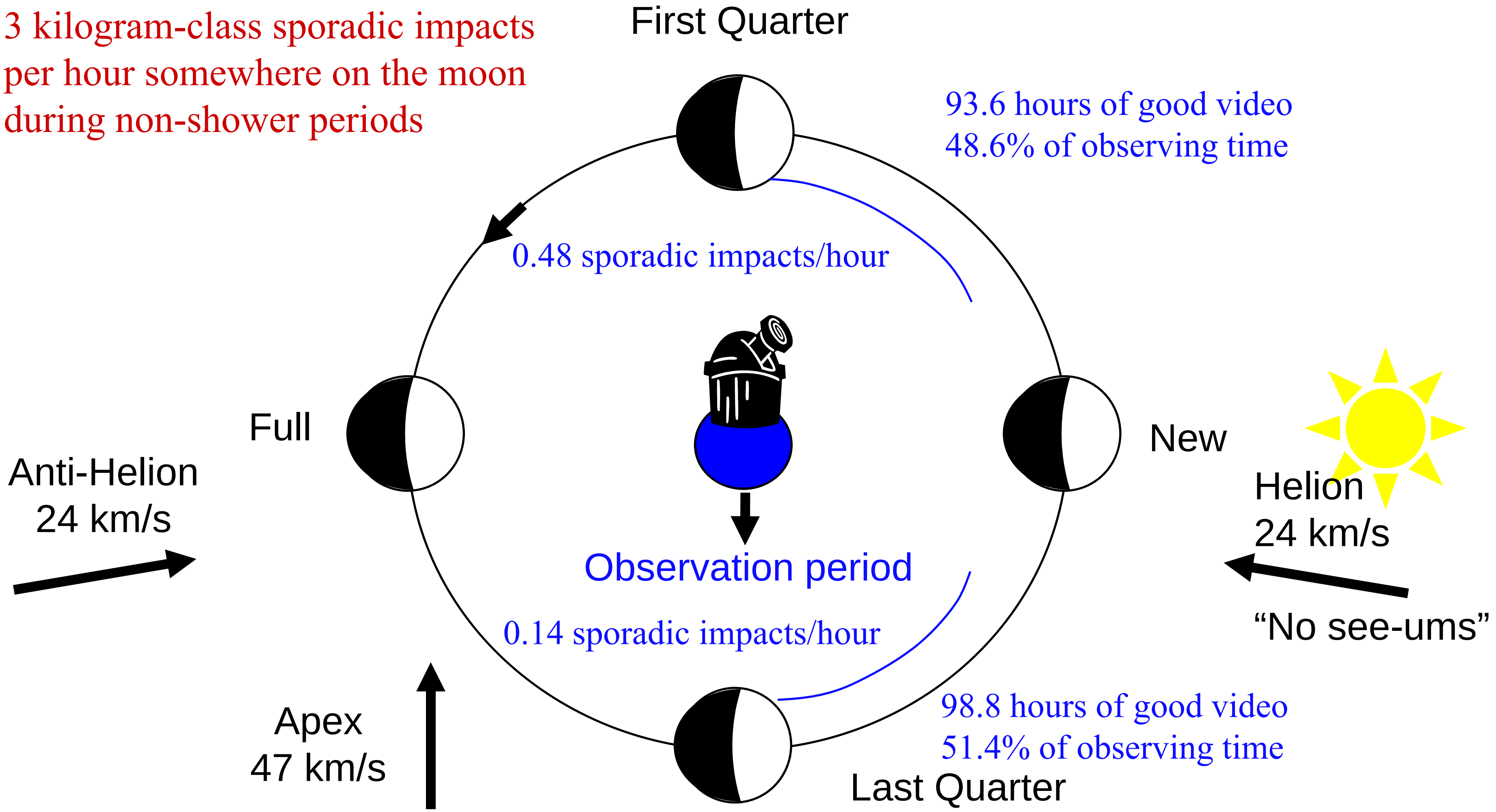
Sporadics Only thru March 08

Evening obs
45 impacts
in approx.
93 hours

Morning obs
14 impacts
in approx.
99 hours

Lunar Viewing and Impact Geometry from 3 In-plane Sporadic Sources

Implies an average of more than 3 kilogram-class sporadic impacts per hour somewhere on the moon during non-shower periods



First Quarter

93.6 hours of good video
48.6% of observing time

0.48 sporadic impacts/hour

Full

New

Anti-Helion
24 km/s

Helion
24 km/s

"No see-ums"

Observation period

0.14 sporadic impacts/hour

Apex
47 km/s

98.8 hours of good video
51.4% of observing time

Last Quarter

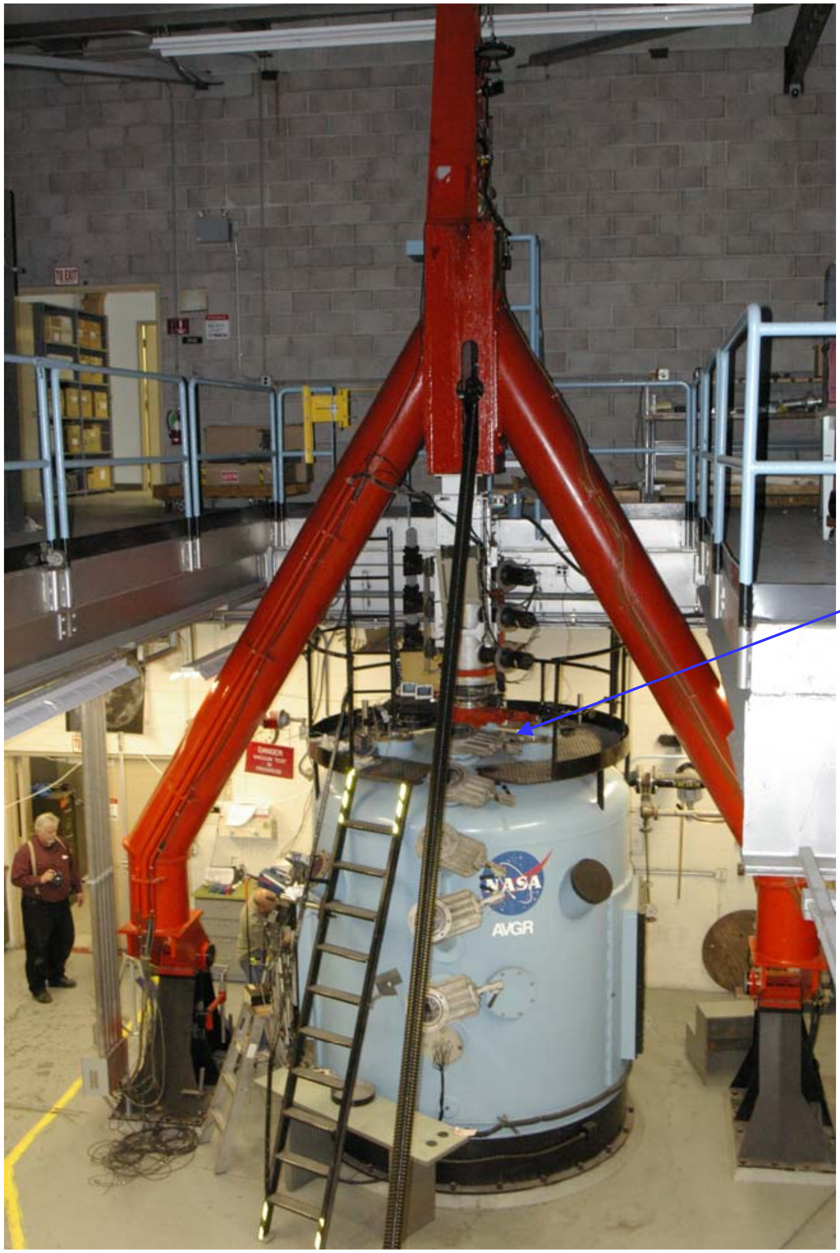
Example of a Moderate-Sized Impactor - May 2, 2006

Duration of flash:	~500 ms
Estimated peak magnitude:	6.86
Peak power flux reaching detector:	$4.94 * 10^{-11}$ W/m^2
Total energy flux reaching detector:	$4.58 * 10^{-12}$ J/m^2
Detected energy generated by impact:	$3.394 * 10^7$ J
Estimated kinetic energy of impactor:	$1.6974 * 10^{10}$ J (4.06 tons of TNT)
Estimated mass of impactor:	17.5 kg
Estimated diameter of impactor:	32 cm ($\rho = 1$ g/cm^3)
Estimated crater diameter:	13.5 m

Ames Hypervelocity Impact Testing

- Purposes
  - Determine impact luminous efficiency – fraction of kinetic energy converted to light (completed 2 sessions of tests for this)
  - Determine size and velocity distributions of ejecta produced in cratering process
- 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 using JSC-1A simulant

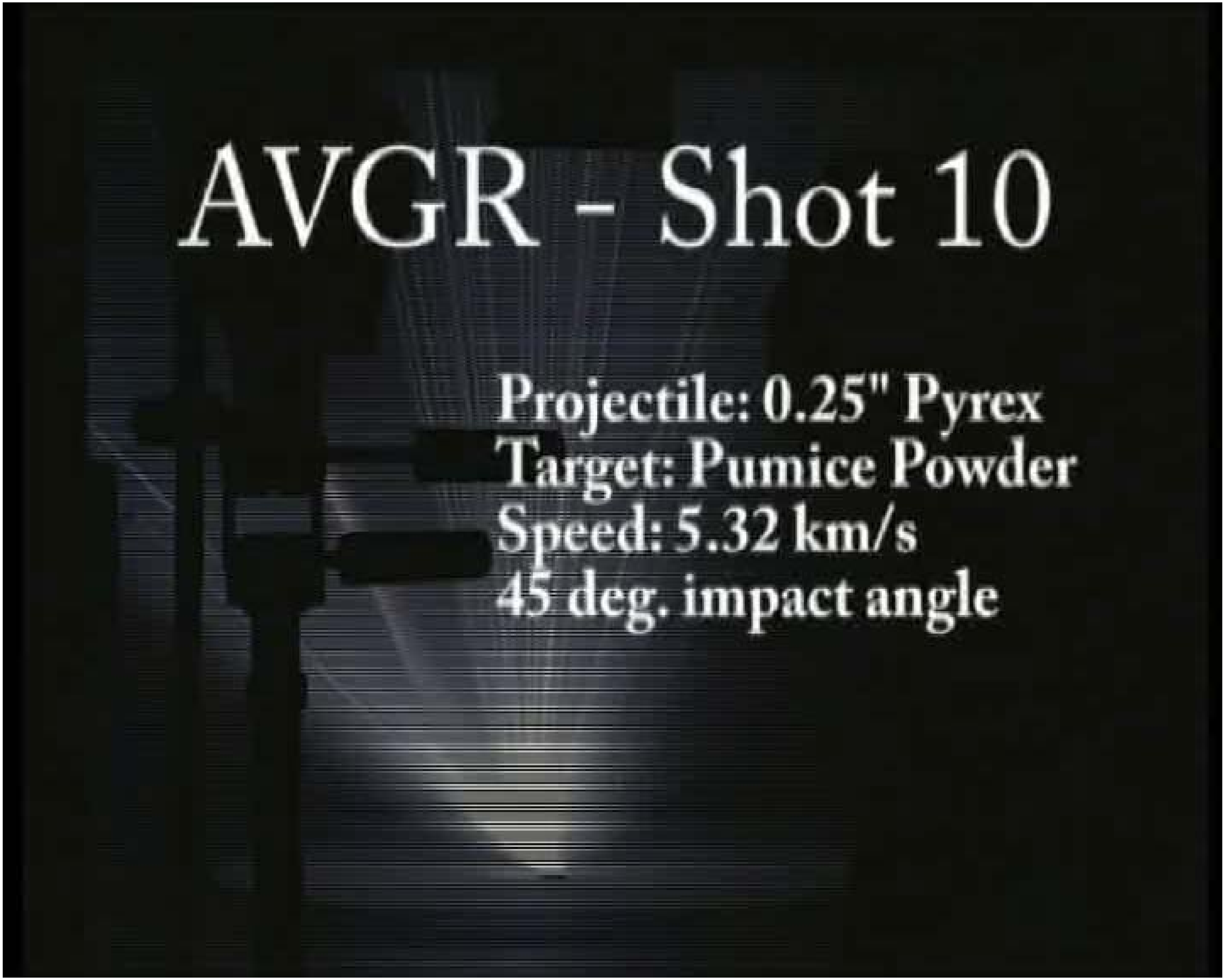
Ames Vertical Gun Range



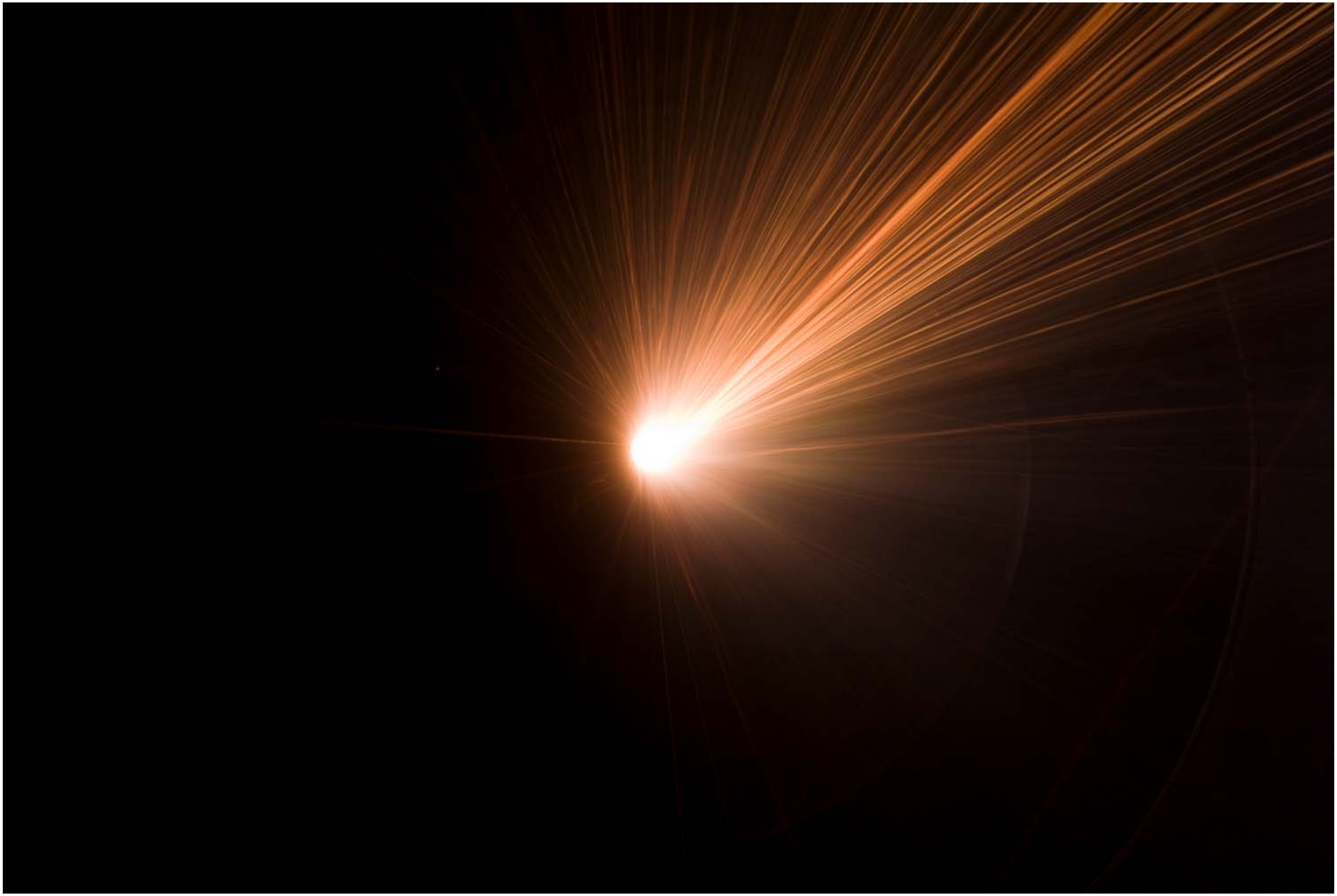
Camera ports


BK 7
BK 7

AVGR - Shot 10



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

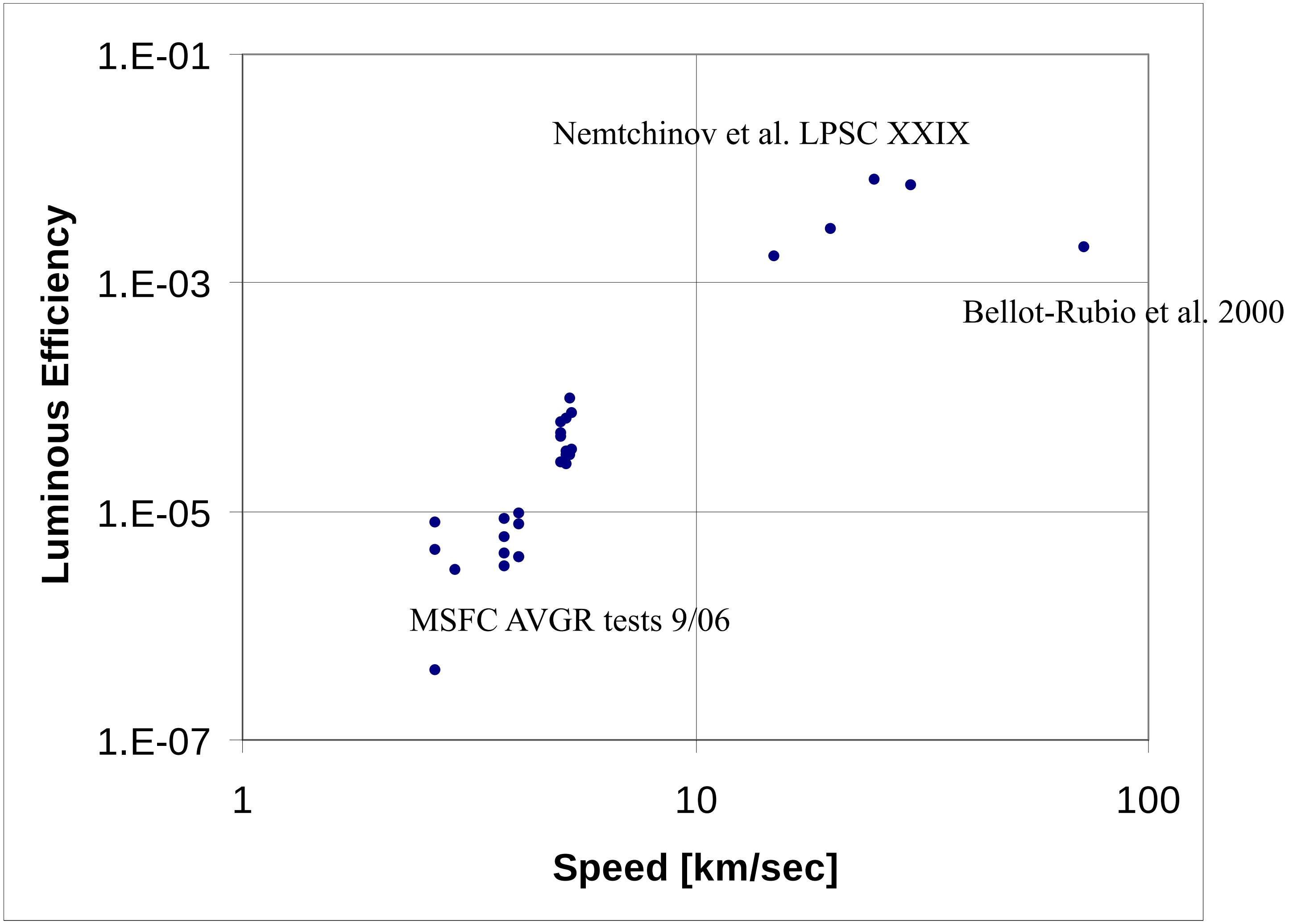


AVGR Run 070823

Crater in JSC-1A Simulant

Preliminary Results

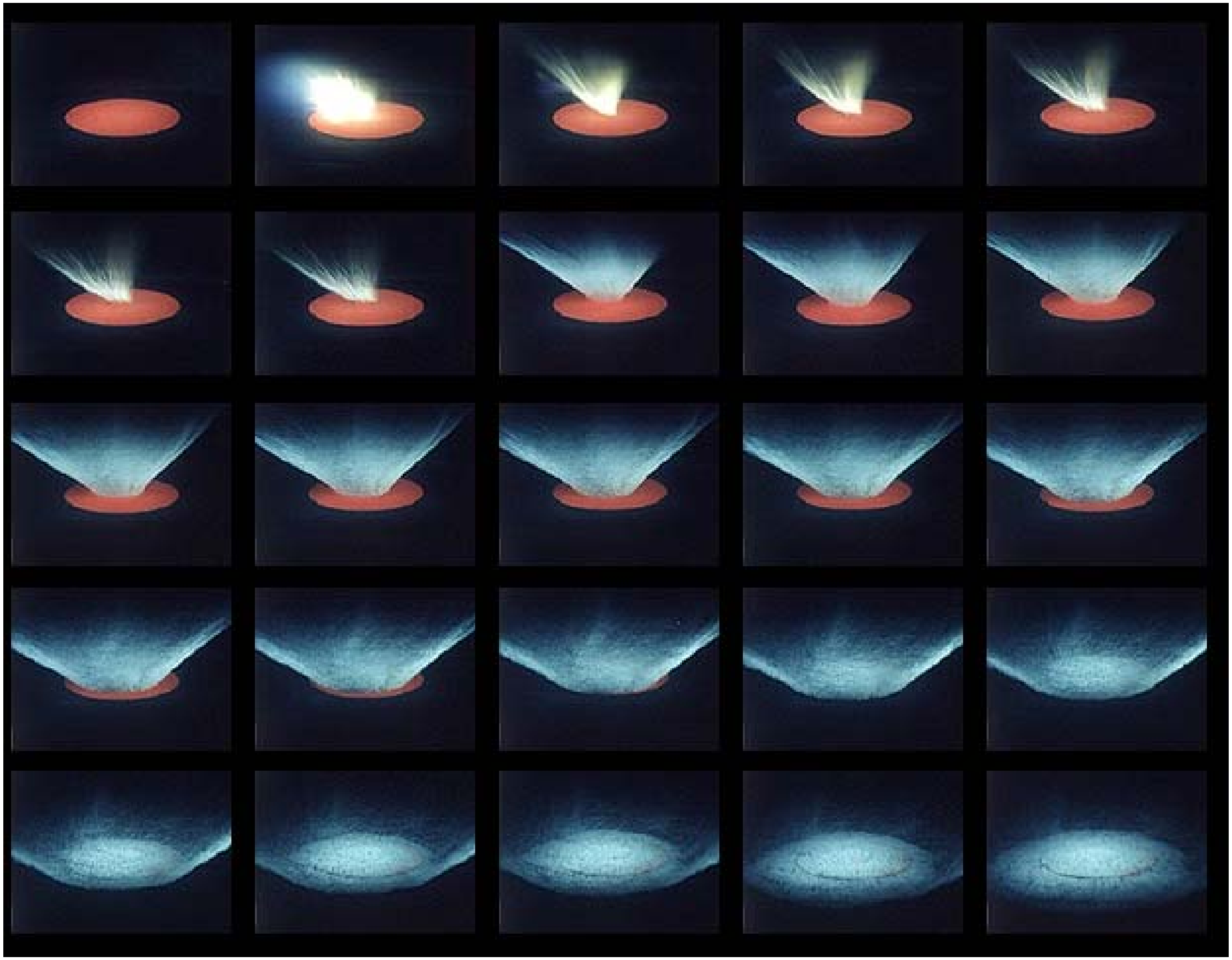
using “not so neutral” density filters



Next Step – Measure Ejecta Properties

- Designers need speed, size, and direction distributions to optimize meteoroid shielding designs
- Very high speed camera or sheet laser measurements of hypervelocity shots are needed to determine these characteristics
- Modeling to scale from AVGR tests to lunar sizes and velocities

Stopping time: watching craters grow
170 millionths of second

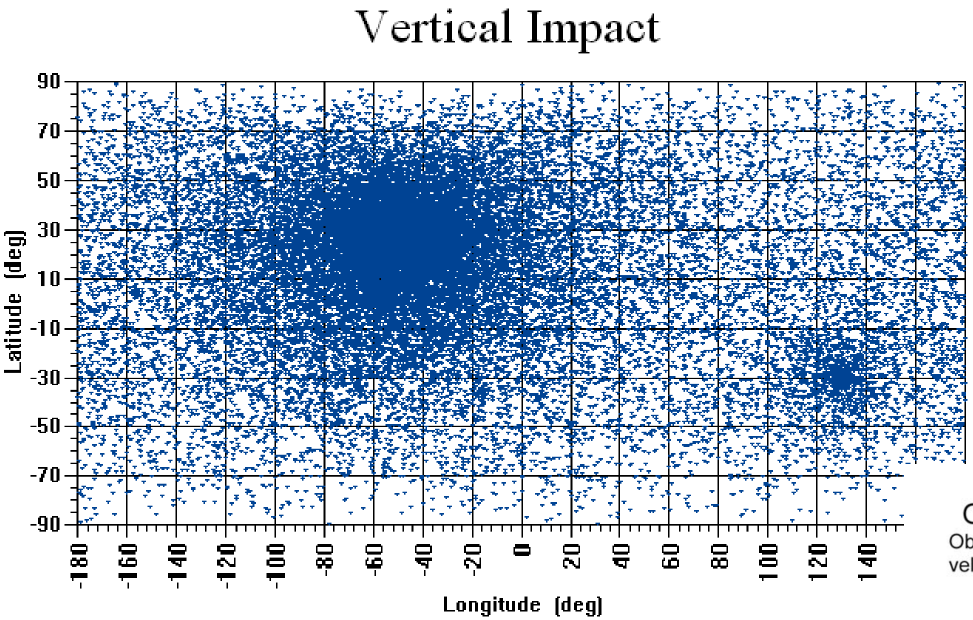


Schultz, et al.

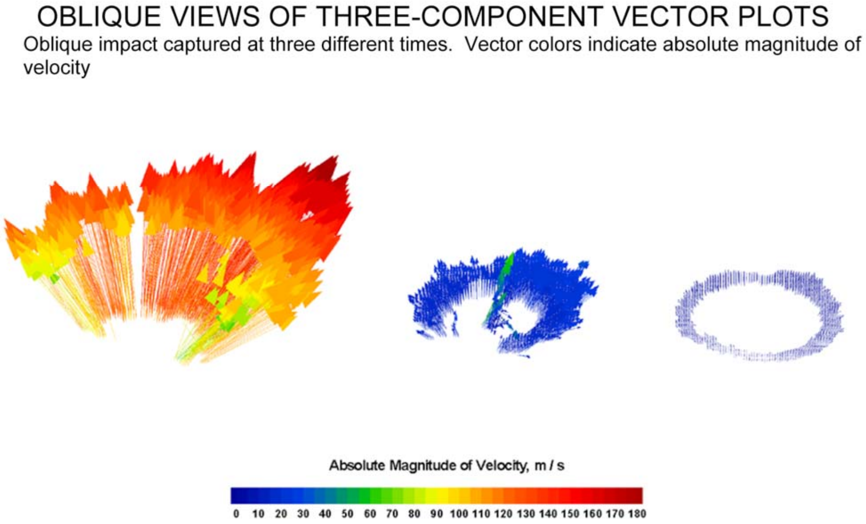
Ejecta Flight Model

Very Preliminary Model Test Results

Simple assumed ejecta distribution



Vertical Impact



OBLIQUE VIEWS OF THREE-COMPONENT VECTOR PLOTS

Oblique impact captured at three different times. Vector colors indicate absolute magnitude of velocity

From Schultz et al. (2000)

Plans

- Continue impact monitoring into the foreseeable future
  - Perhaps add an infrared camera since flashes peak redward of 1 micron
- Observe LCROSS impact from Apache Point Observatory
  - 3.5m and one of our 14 inch scopes to measure ejecta plume
- Complete analysis of observational data and present at DPS this October
- Analyze latest AVGR photometric data to determine luminous efficiency at low speed/size
  - Previous data was taken with "non-neutral" neutral density filters
- If/when Constellation funding becomes available, begin ejecta characterization and modeling tasks and develop engineering model of the ejecta environment

Summary

- We have a fruitful observing program underway which has significantly increased the number of lunar impacts observed
- We have done initial test shots at the Ames Vertical Gun Range – obtained preliminary luminous efficiency values
- More shots and better diagnostics are needed to determine ejecta properties
- We are working to have a more accurate ejecta environment definition to support lunar lander, habitat, and EVA design
- Data also useful for validation of sporadic model at large size range

Useful Links

- MEO http://meo.nasa.gov
- Impacts

  http://www.nasa.gov/centers/marshall/news/lunar/index.html