Electrostatic dust transport and its instrumentation on the lunar surface

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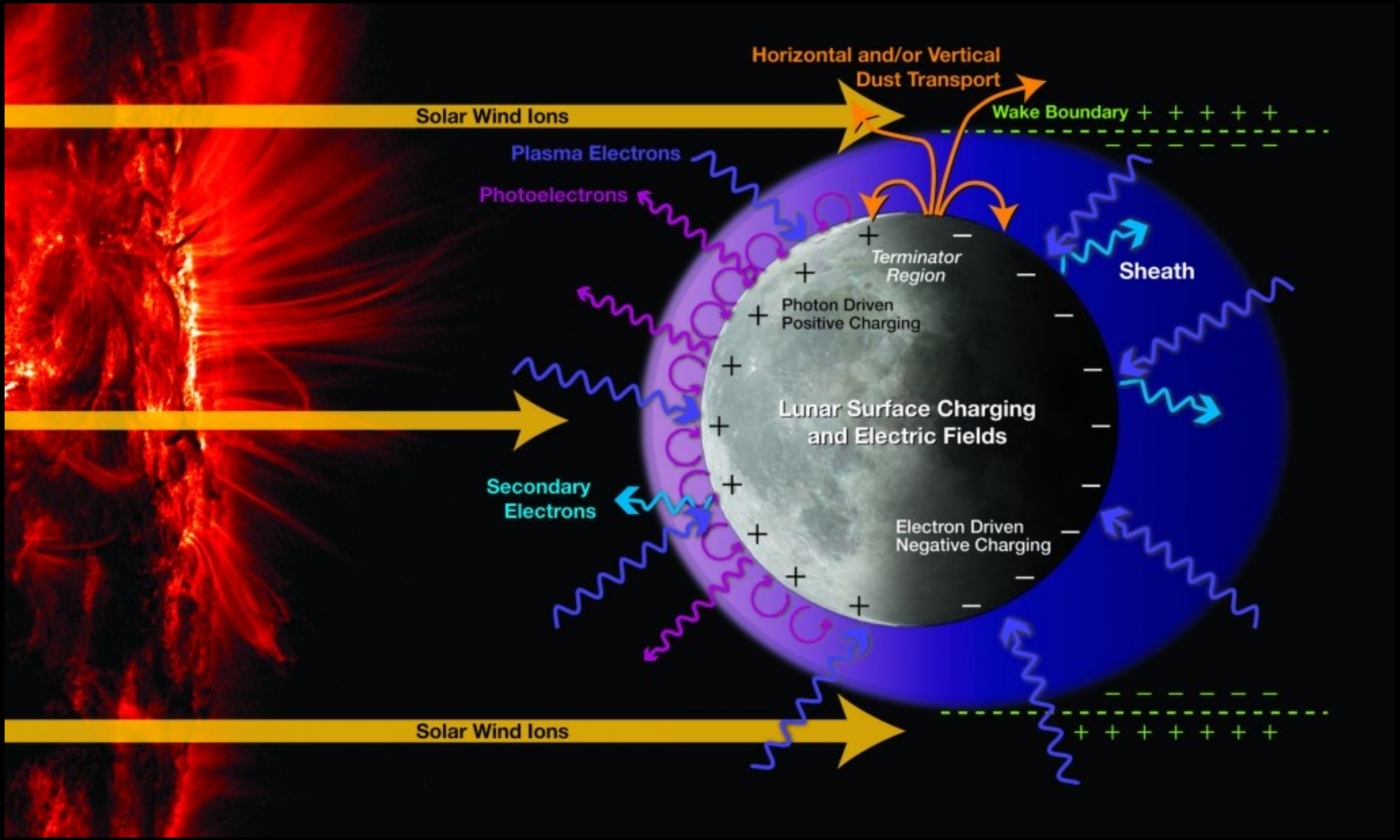
The DAP Meeting
June 5 - 6, 2023

IMPACT

LASP

Lunar Dust and Plasma Environment

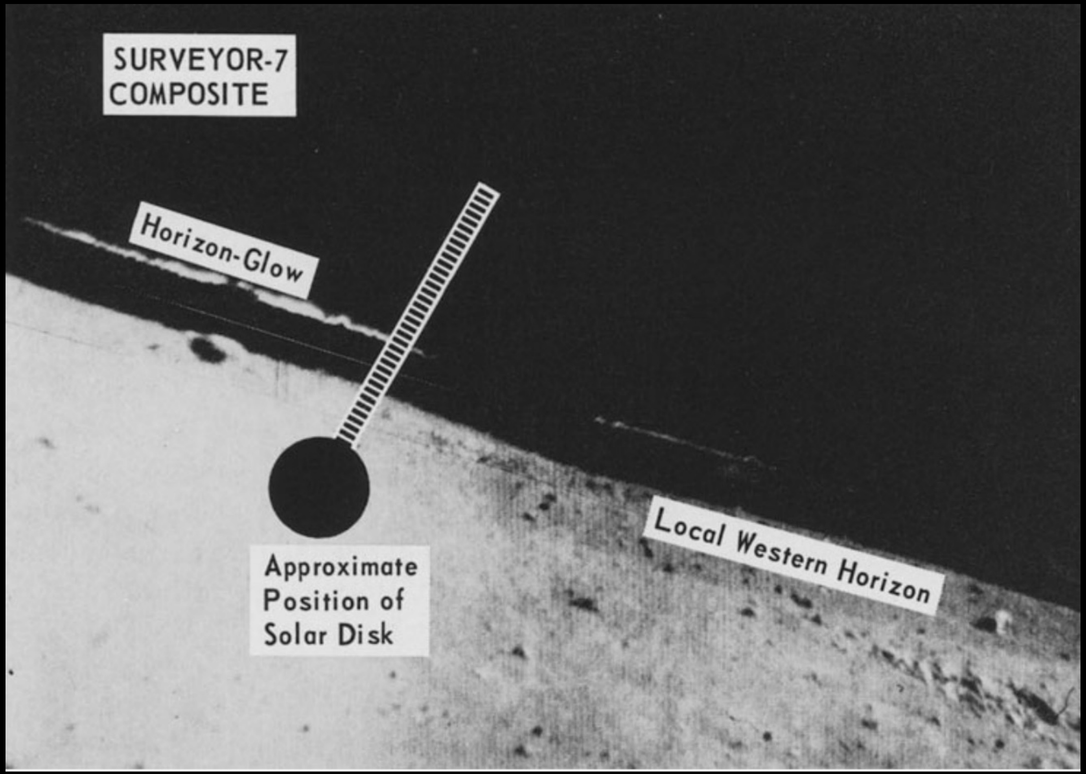


Halekas et al

Hypothesis: Dust particles on the regolith surface of the Moon are charged and may be lofted or mobilized due to electrostatic forces.

Apollo Observations

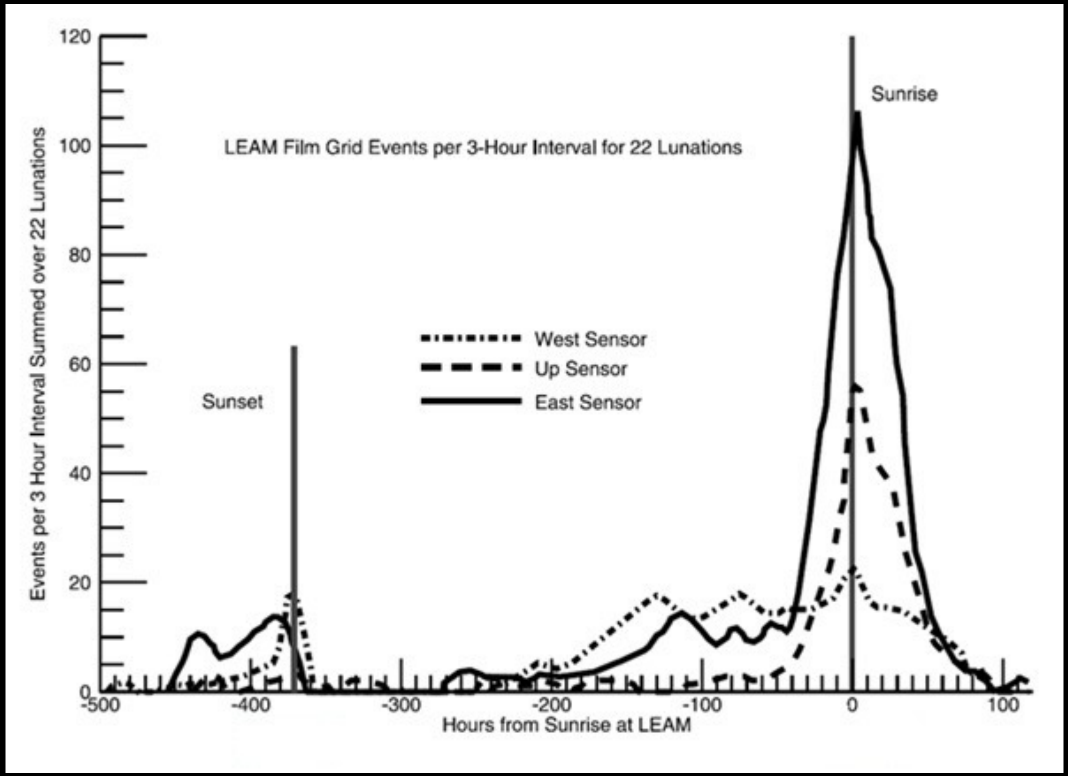
Lunar Horizon Glow (LHG)



Criswell. 1973

Lofted or levitated dust particles ~10 μm in diameter at height <30 cm

Low-Speed Dust Detections across Terminator



Berg et al., 1976

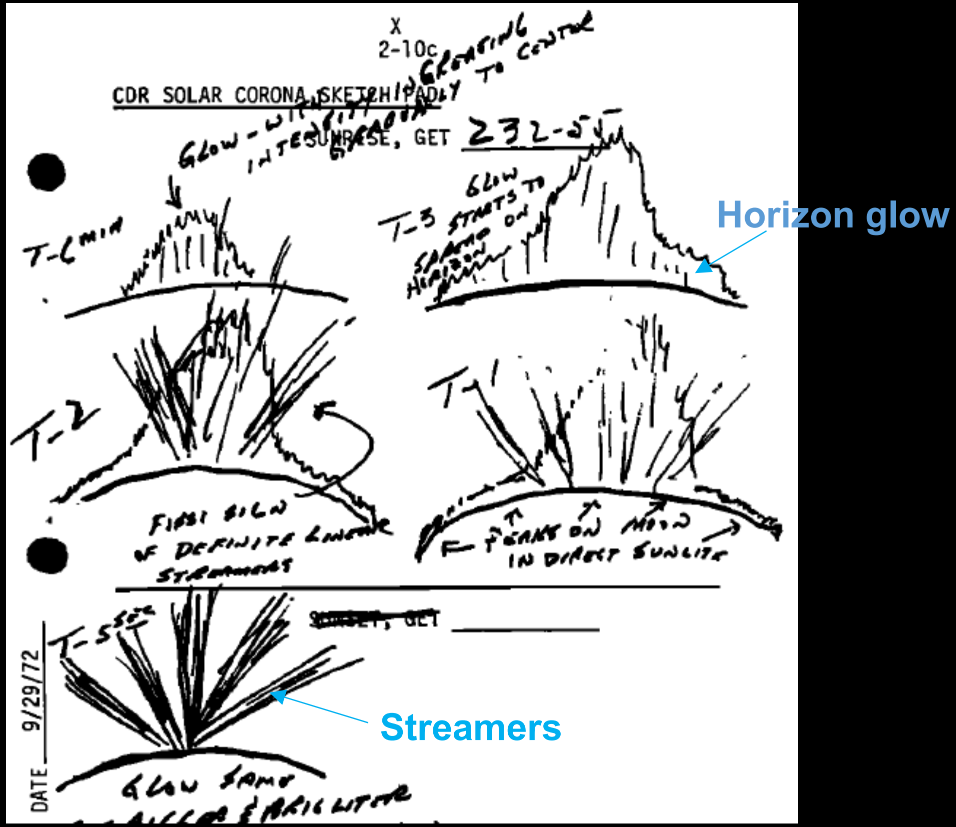
However, later work analyzing different LEAM datasets (Grün and Horányi, 2013) found no significant rate enhancement during terminator crossings.

Enhanced electric field across lunar terminator due to differential charging has been thought to enhance dust lofting.

Apollo Observations

High-altitude LHG and Streamers

(Apollo 17 astronaut E.A. Cernan's sketches)



McCoy and Criswell, 1974

High-altitude streamers are thought to be nm-sized dust particles electrostatically lofted near the terminator (McCoy and Criswell, 1974; Zook & McCoy, 1991).

However, there are contradictory results:

High-altitude dust was indicated from the Apollo observations (McCoy, 1976; Glenar et al., 2011) and LADEE/UVS (Wooden et al., 2016) but not detected by Clementine (Glenar et al., 2014), LRO/LAMP (Feldman et al., 2014), and the in-situ measurements by LADEE/LDEX (Szalay and Horányi, 2015).

Dust Impact on Human Exploration

- Charged dust sticks to all exploration system surfaces, causing various issues:
  - Damage to spacesuits
  - Degradation of thermal radiators and optical components
  - Failure of mechanisms
  - Health risks for astronauts

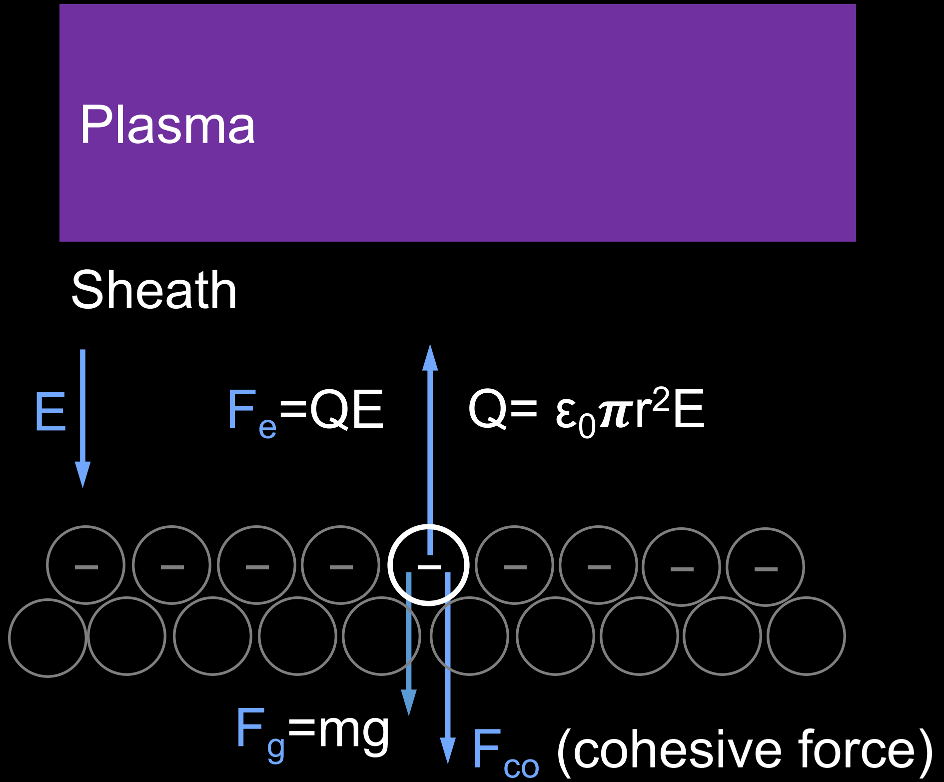
- Understanding of electrostatic dust charging and transport is critical and imperative for assessing its impact on Artemis missions and future long-term, sustainable human exploration on the lunar surface.

A Long-standing Question

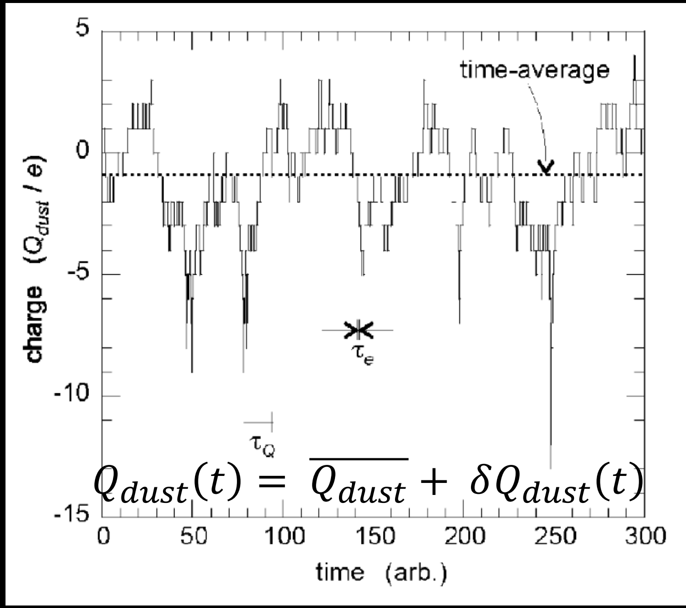
How do dust particles obtain enough charge to be electrostatically lofted from the regolith surface?

Macroscale Charging Models

Shared Charge Model



Charge Fluctuation Theory (Stochastic process)



Flanagan and Goree, 2006

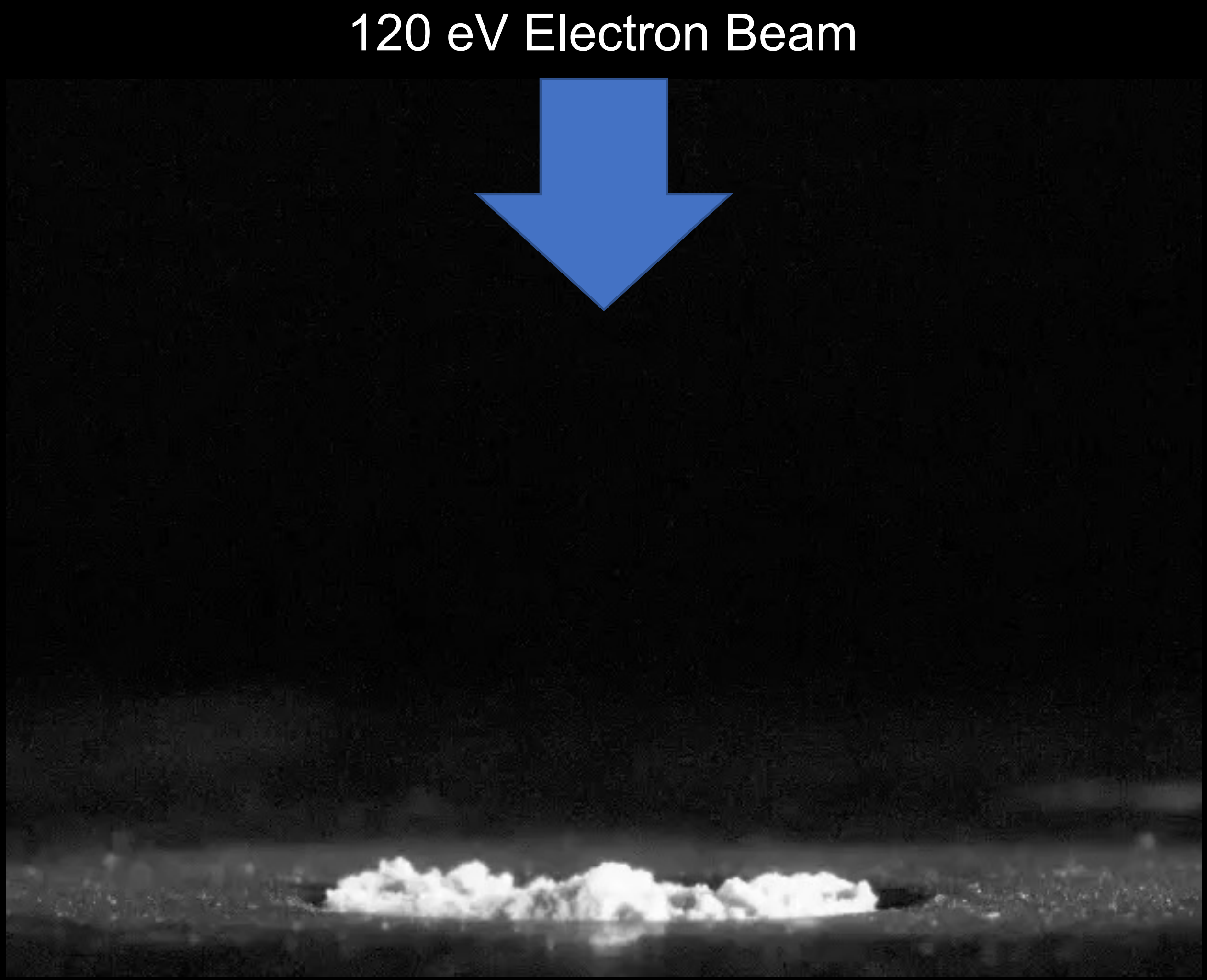
Charge fluctuation magnitude is estimated as following

$$\frac{\delta Q_{dust}^{rms}}{e} = \sqrt{\frac{CT_e}{e}}$$

Sheridan and Hayes, 2011

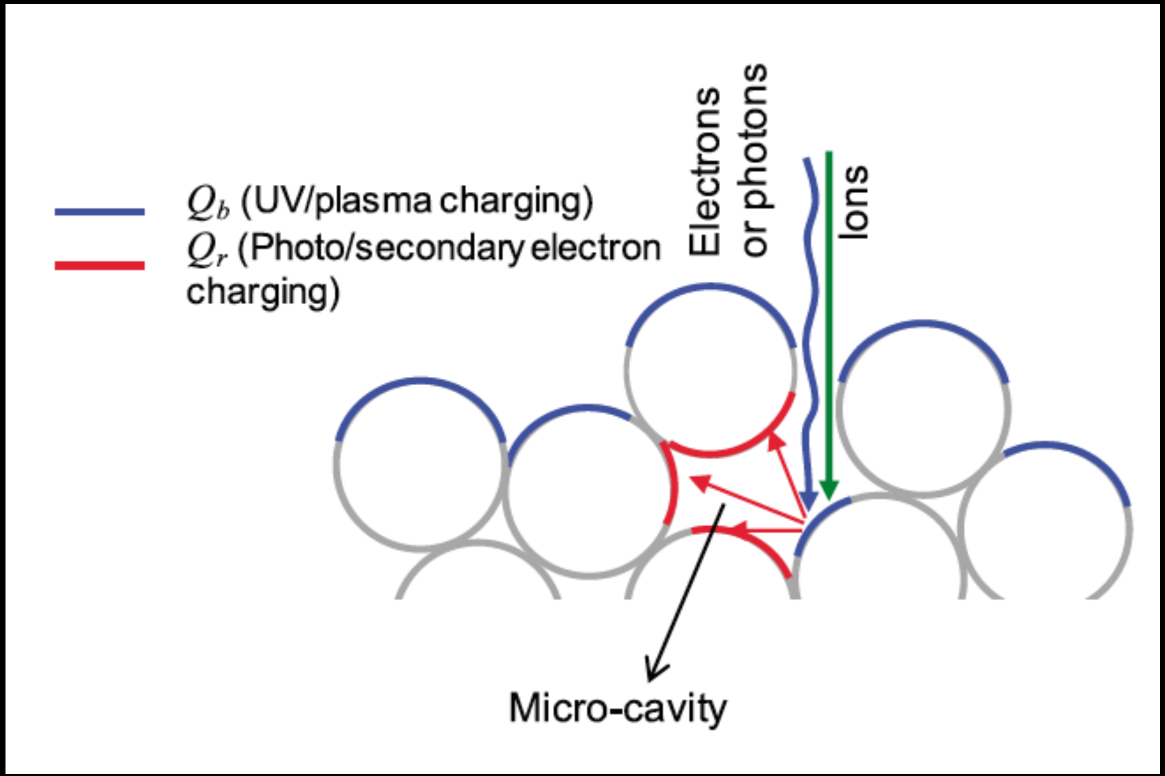
These models ***cannot*** fully explain dust lofting on the lunar surface

Dust Lofting Experiments in the Laboratory



38μm JSC-1A Lunar Simulant

Novel "Patched Charge Model" (Microscale)



Wang et al., 2016

According to Gauss's law

$Q_b \propto (\phi_b - \phi_p) / \lambda_{De}$

$Q_r \propto (\phi_r - \phi_b) / r$

$Q_r >> Q_b$ due to $r << \lambda_{De}$

$Q \approx Q_r \approx -0.5C(\eta T_{ee}/e)$,

where, $C = 4\pi\varepsilon_0 r$

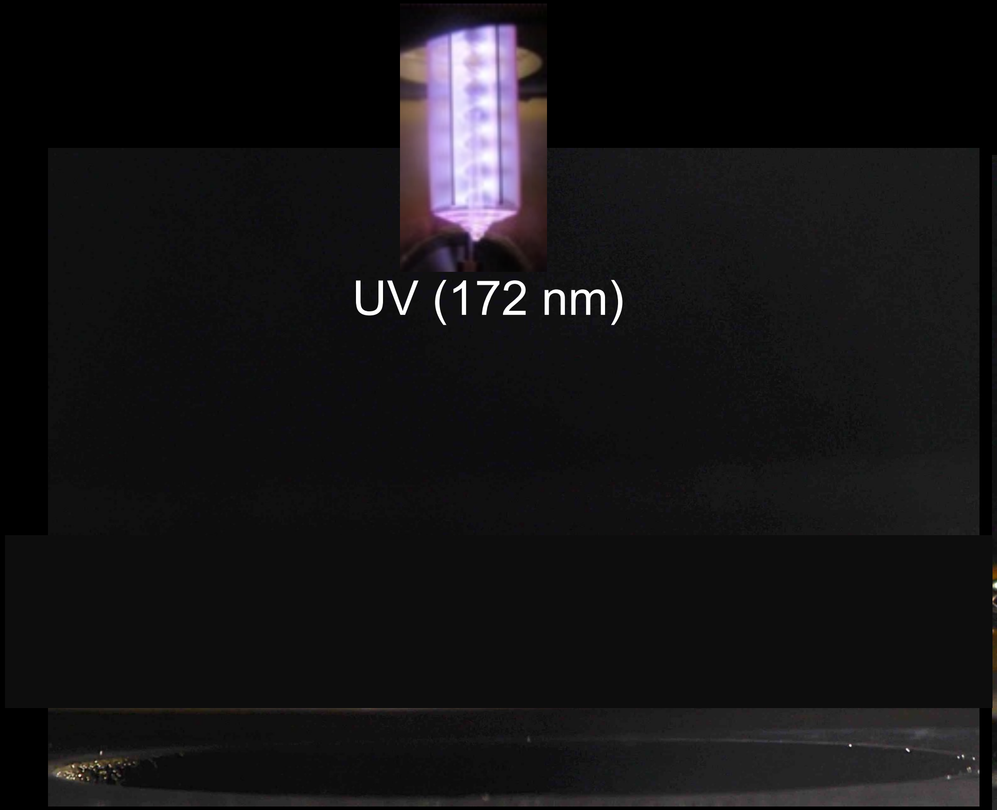
T_{ee} is the emitted electron temperature in eV.

ηT_{ee} represents high-energy tail electrons.

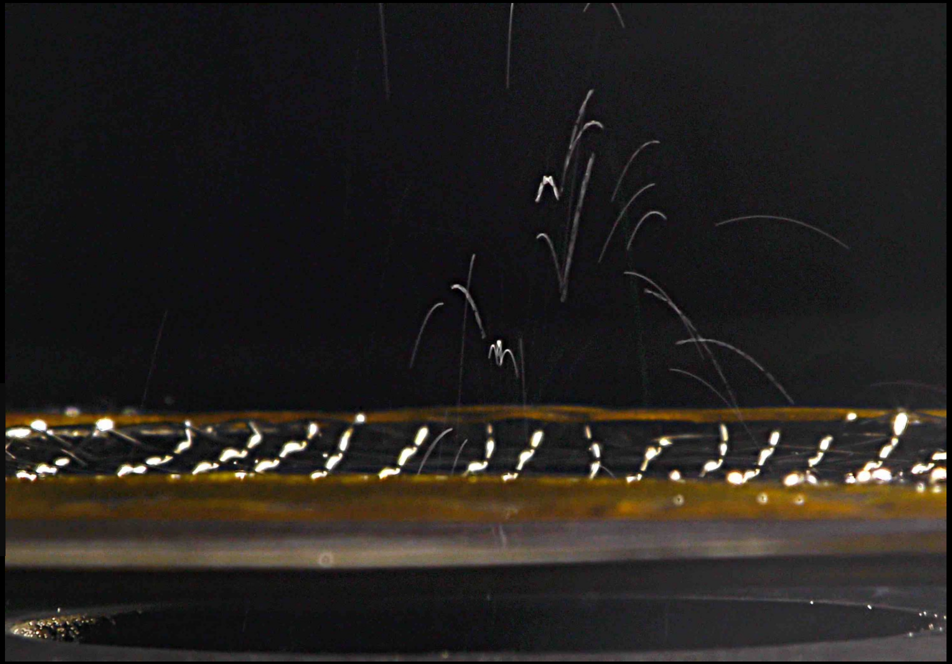
η: 4 ~ 10, empirical constant determined from experiments.

- **Photo- or secondary electrons** are absorbed within **microcavities** and collected by the surrounding dust particles, resulting in **substantial negative charges** on their surfaces.
- **Repulsive forces** between the negatively charged particles cause them to be lofted from the surface.

Charge Measurements (Polarity)



Negative voltage (-3 kV) grid



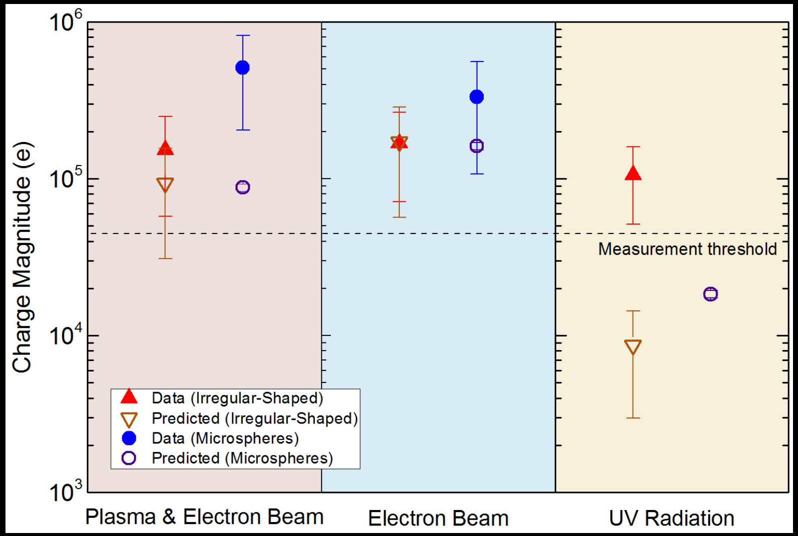
Positive voltage (+0.5 kV) grid

Schwan et al., 2017

All lofted dust particles are charged negatively, even under UV radiation. This is contrary to the generally expected positive charge due to photoemission but agrees with the Patched Charge Model.

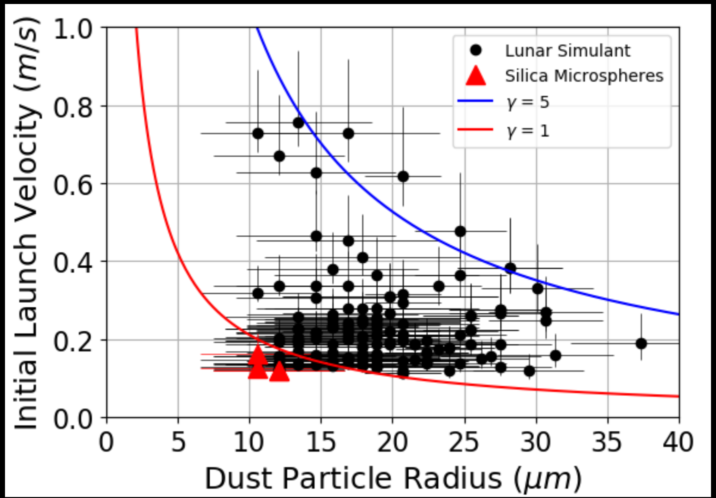
Characteristics of Lofted Dust Particles

Charge Magnitudes



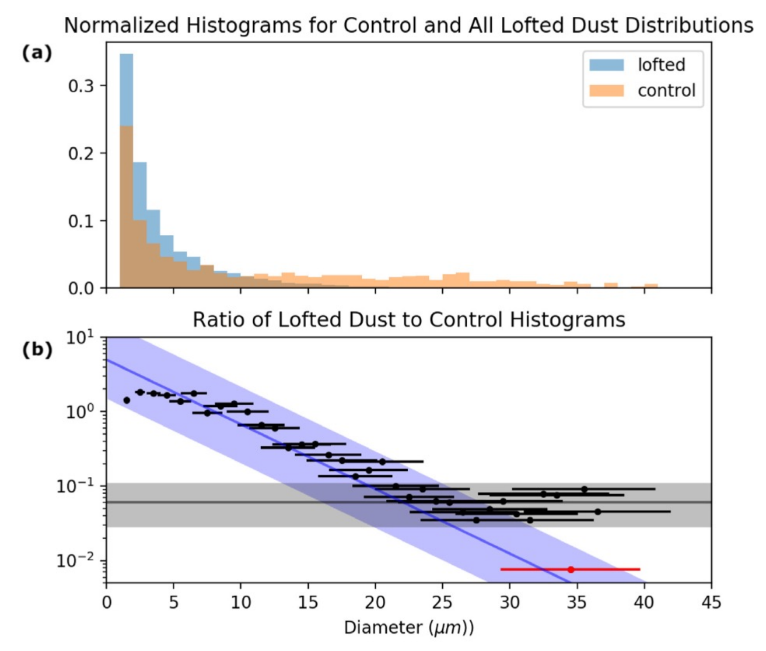
Schwan et al., 2017

Initial Velocities



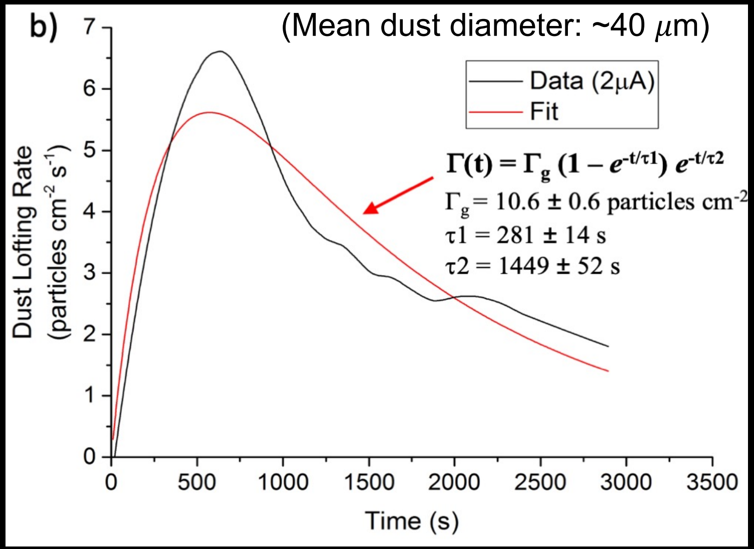
Carroll et al., 2020

Size Distributions



Hood et al., 2022

Lofting Rates

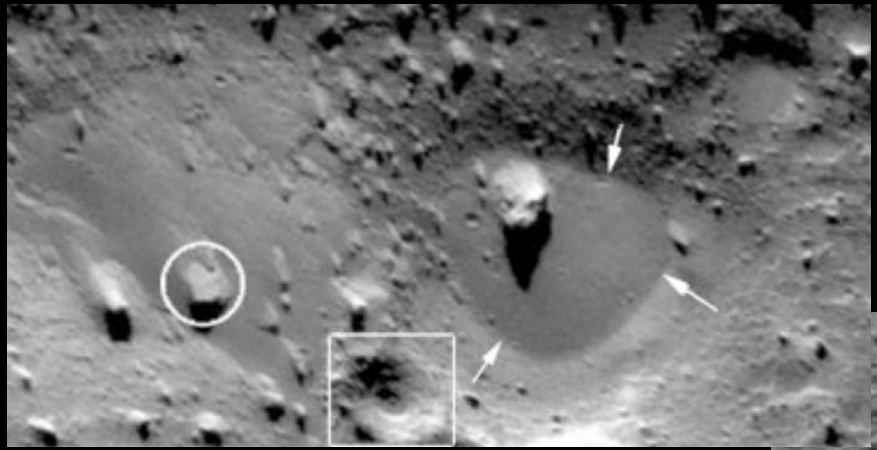


Hood et al., 2018

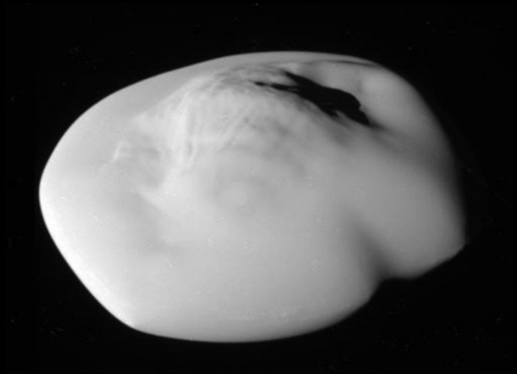
It is time to find ground truth about electrostatic dust charging and transport on the Moon

Findings on the Moon will help understand electrostatic dust transport and its role in surface evolution on other airless bodies in the solar system

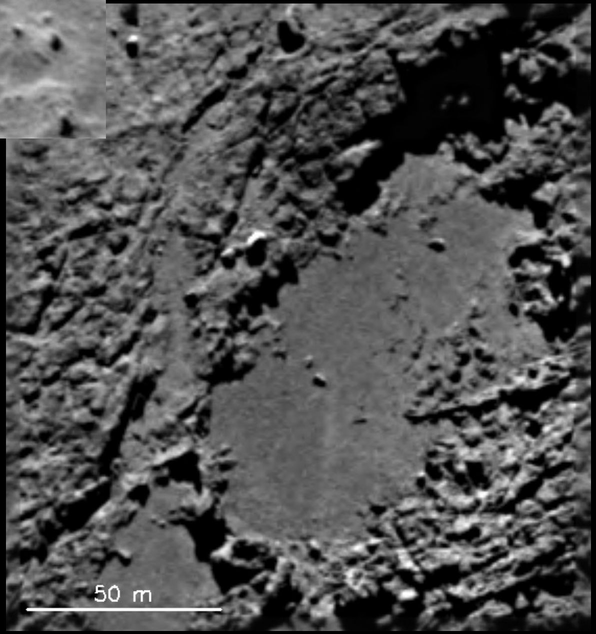
Radial ‘spokes’ in Saturn’s rings
(Smith et al., 1981)



Dust ponds on asteroid Eros
(Robinson et al., 2001)



Saturn’s icy moon Atlas (Hirata and Miyamoto, 2012)

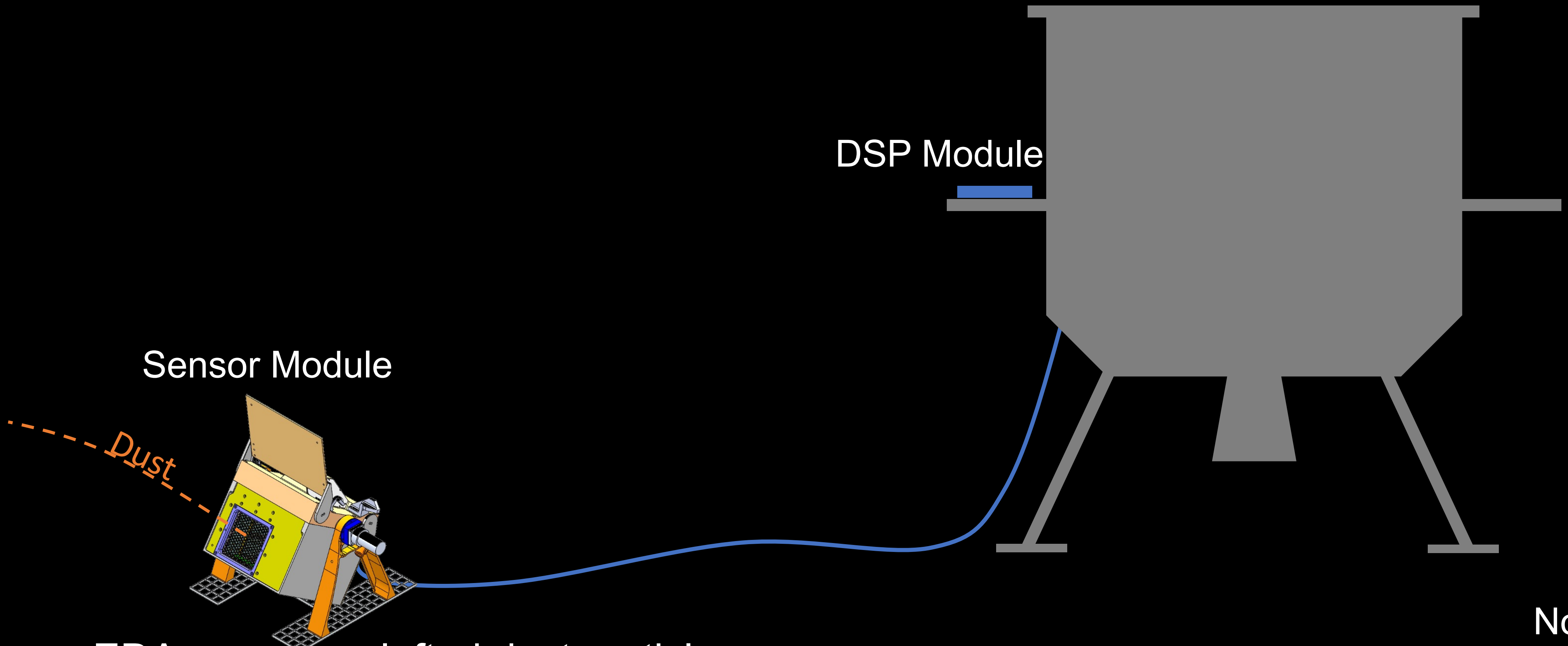


Ponded dust deposits in Khepry on comet 67P (Thomas et al., 2015)

Electrostatic Dust Analyzer (EDA) to measure dust transport on the lunar surface

(NASA – DALI: Development and Advancement of Lunar Instrumentation)

A Notional Measurement Configuration



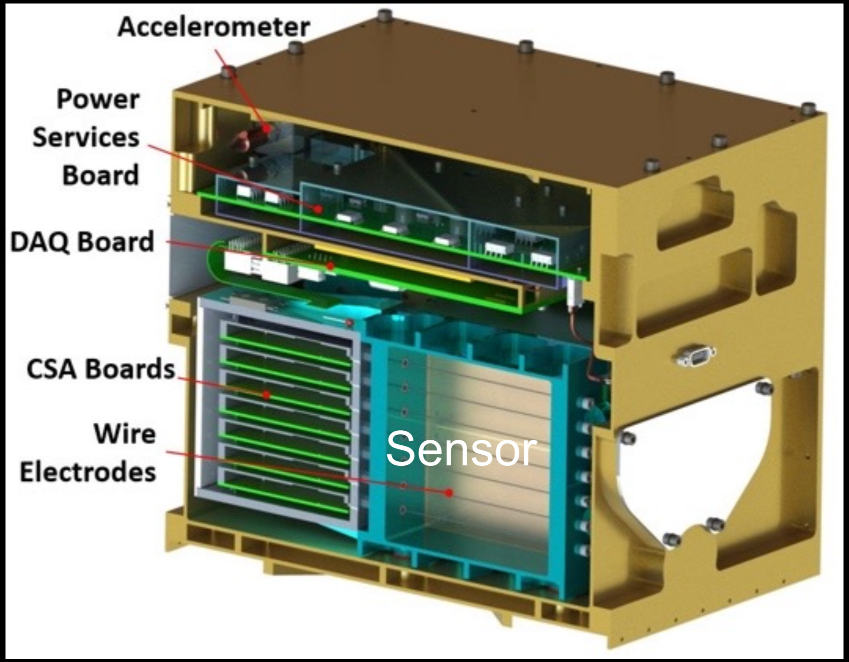
Not-to-scale

EDA measures lofted dust particles
that fall back to the lunar surface

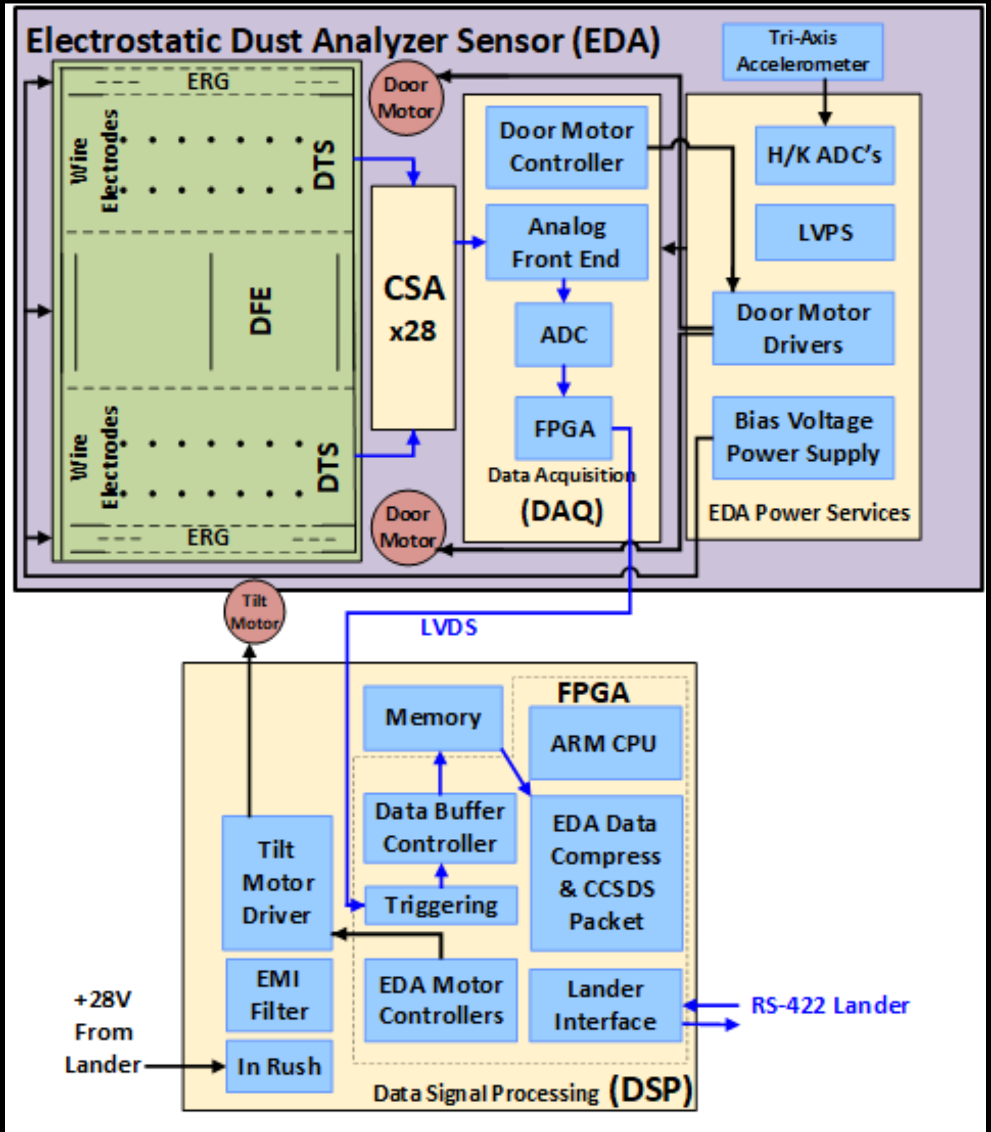
EDA is inherited from Electrostatic Lunar Dust Analyzer (ELDA, Duncan et al., 2011)

Electrostatic Dust Analyzer (EDA)

Sensor Module

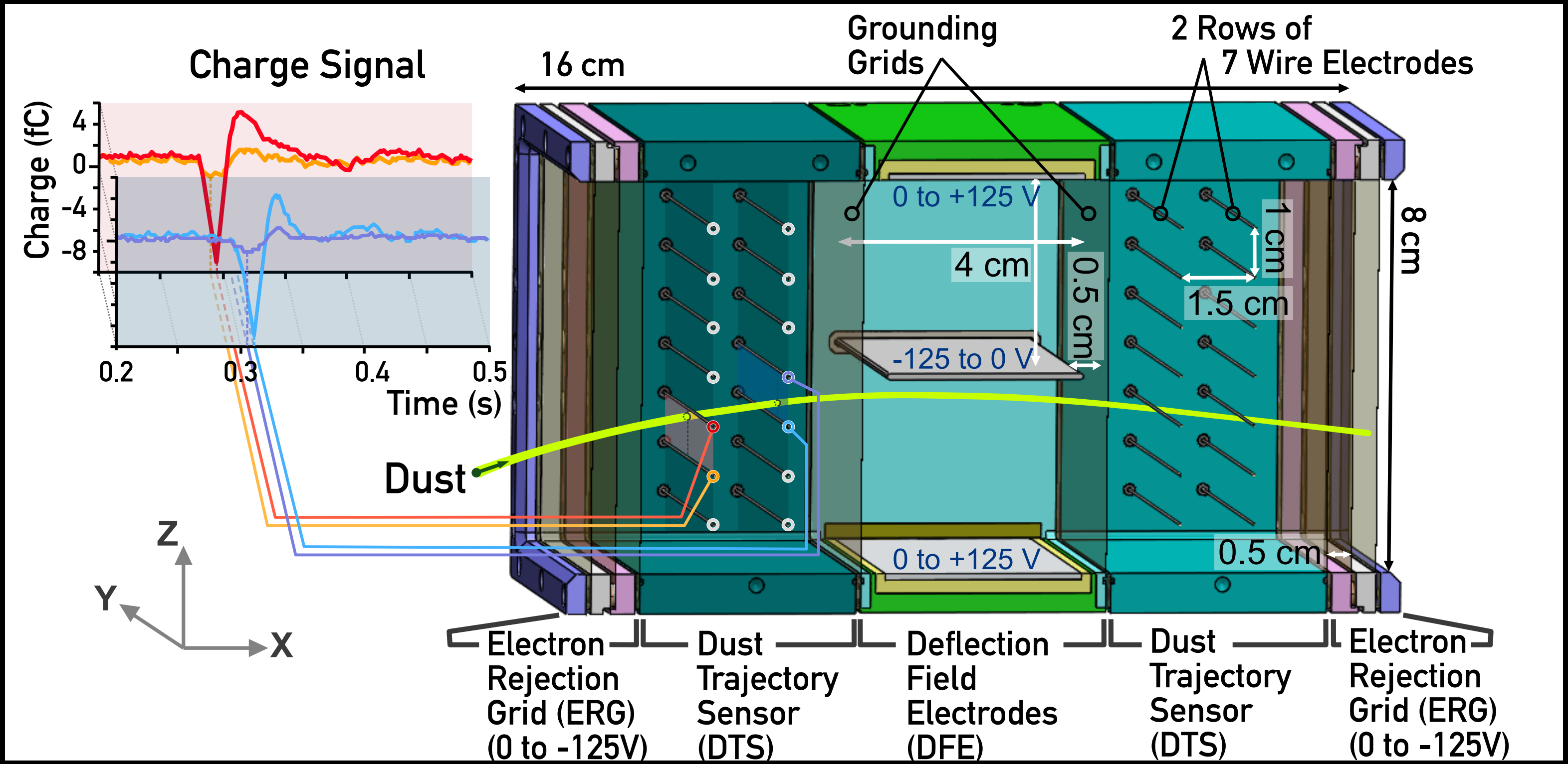


Functional Block Diagram



Dimensions	Sensor Module: 21.6 cm X 17.0 cm X 17.9 cm DSP Module: 14.6 cm X 13.3 cm X 2.5 cm
Mass	5.5 kg
Power	7.5 W

EDA - Sensor



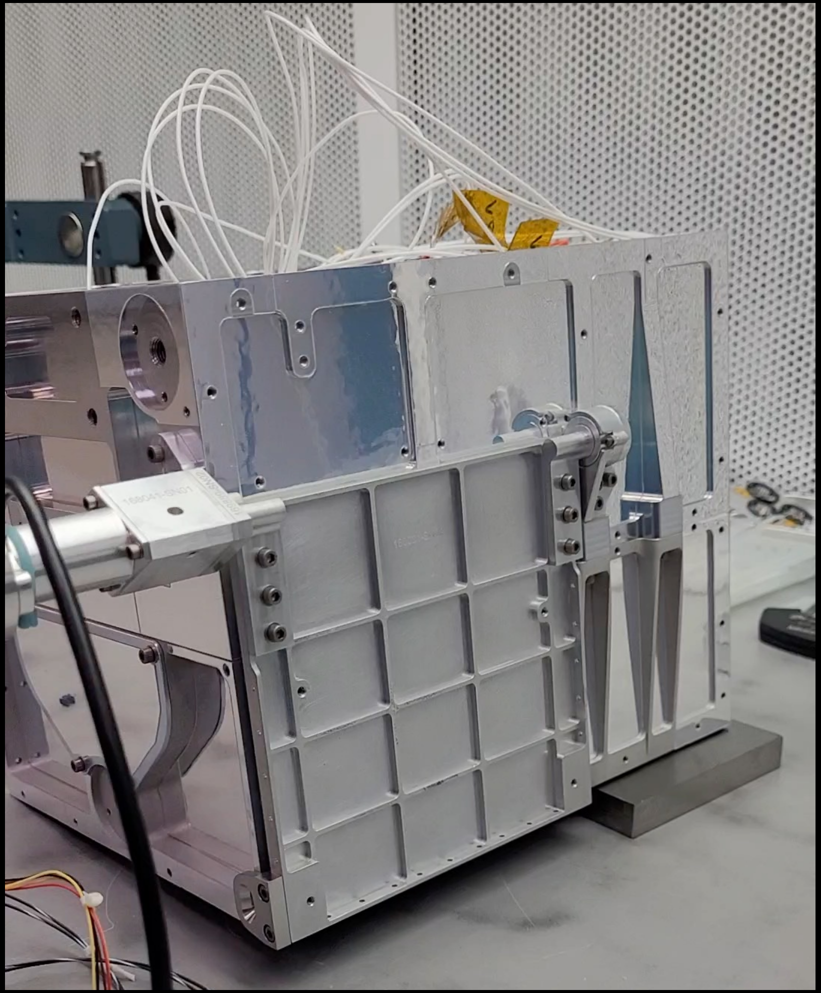
Measurement Quantities

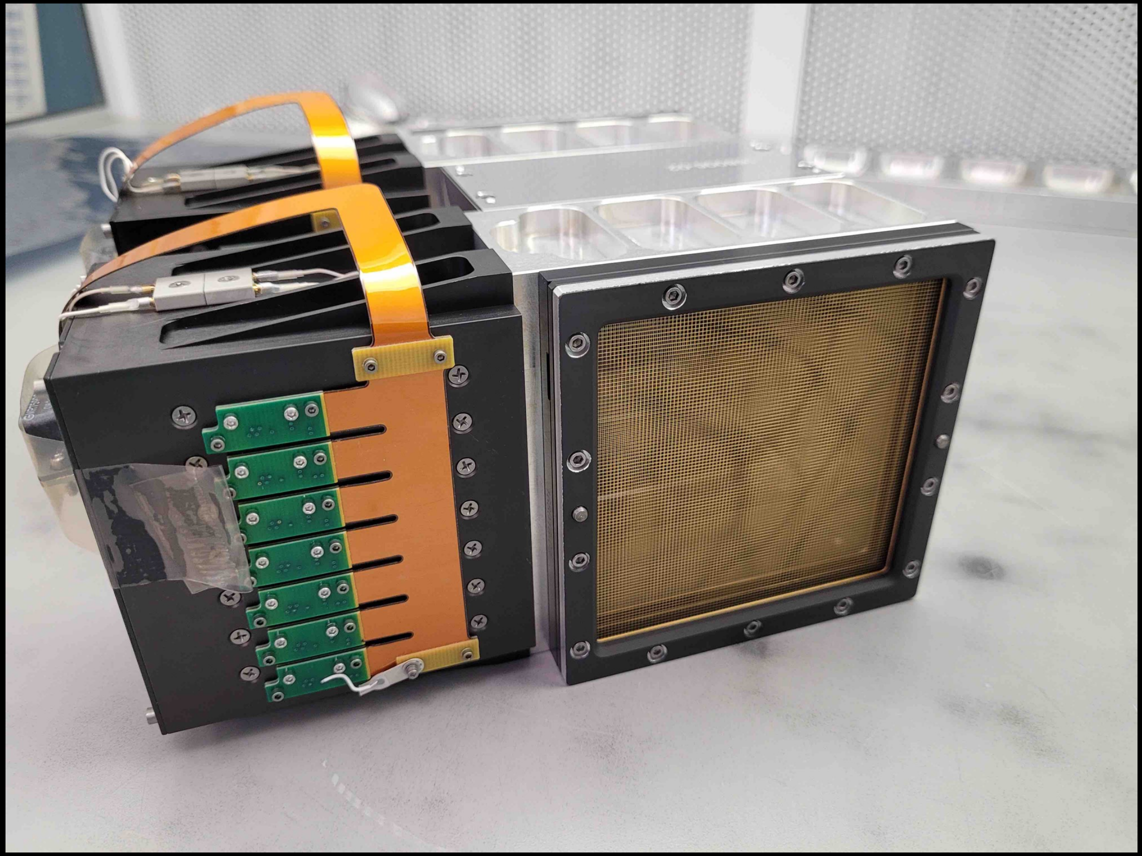
Dust size accuracy	1 < r < 20 μm 15%
Velocity accuracy	0.8 < v < 20 m/s 15%
Charge accuracy polarity	1.2 < Q < 64 fC 20% positive/negative
Flux accuracy cadence	0 < F < 1.7 particles cm^{-2} s^{-1} 20% continuous
FOV	54° (for size meas.) 135° (for flux meas.)

A trajectory is reconstructed from induced charges on 4 wire-electrode arrays in two DTS as a charged dust particle flies through the sensor.

- **Charge** is measured from the induced charges on all wire-electrodes in a DTS
- **Velocity** is determined from the time shift of the charge signals between the two wire-electrode arrays.
- **Mass (and size)** is derived from the trajectory deflection by DFE.

EDA – Engineering Model (TRL 6)

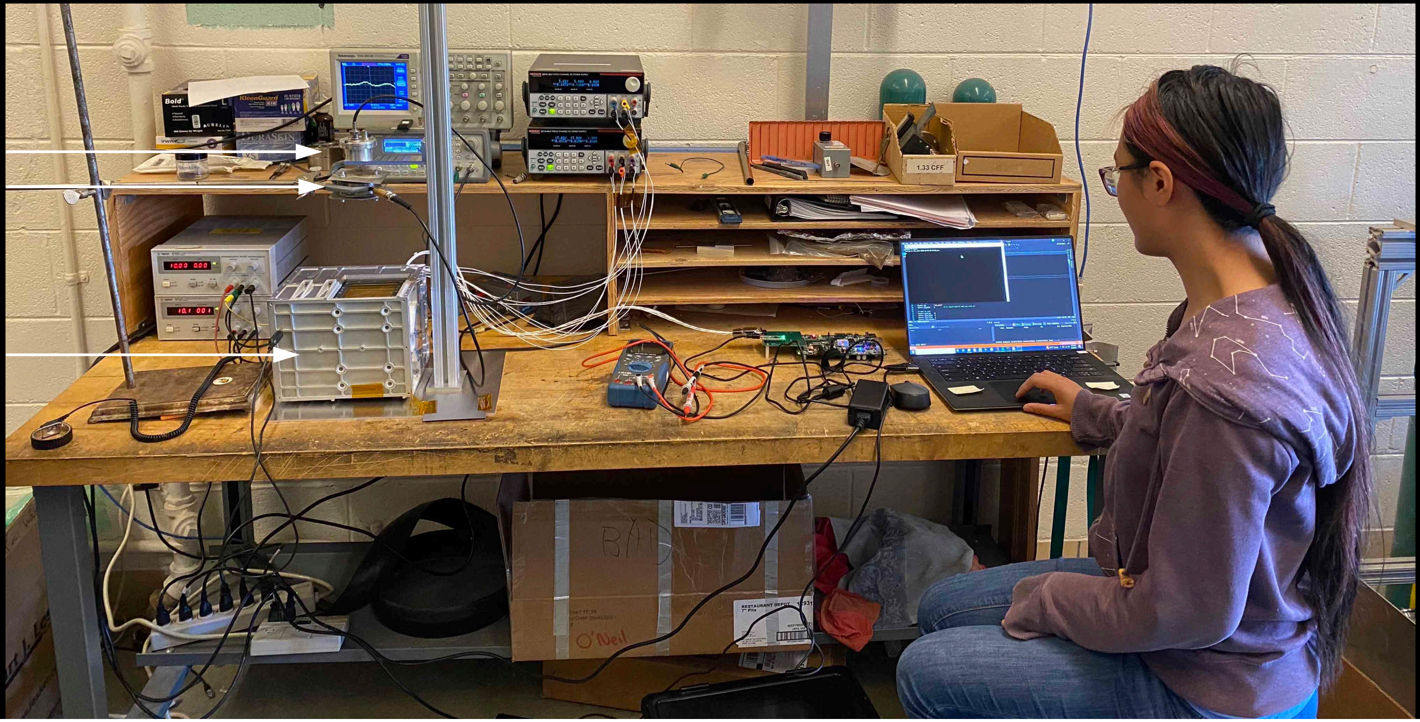


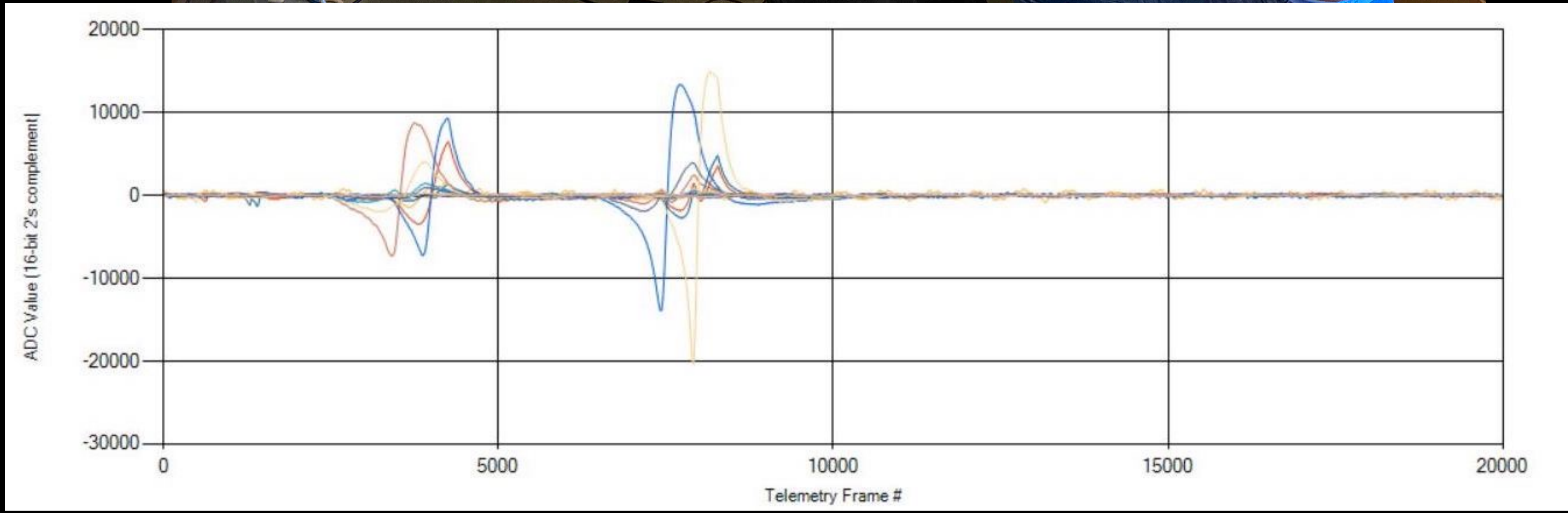


Sensor

First Dust Drop in Air

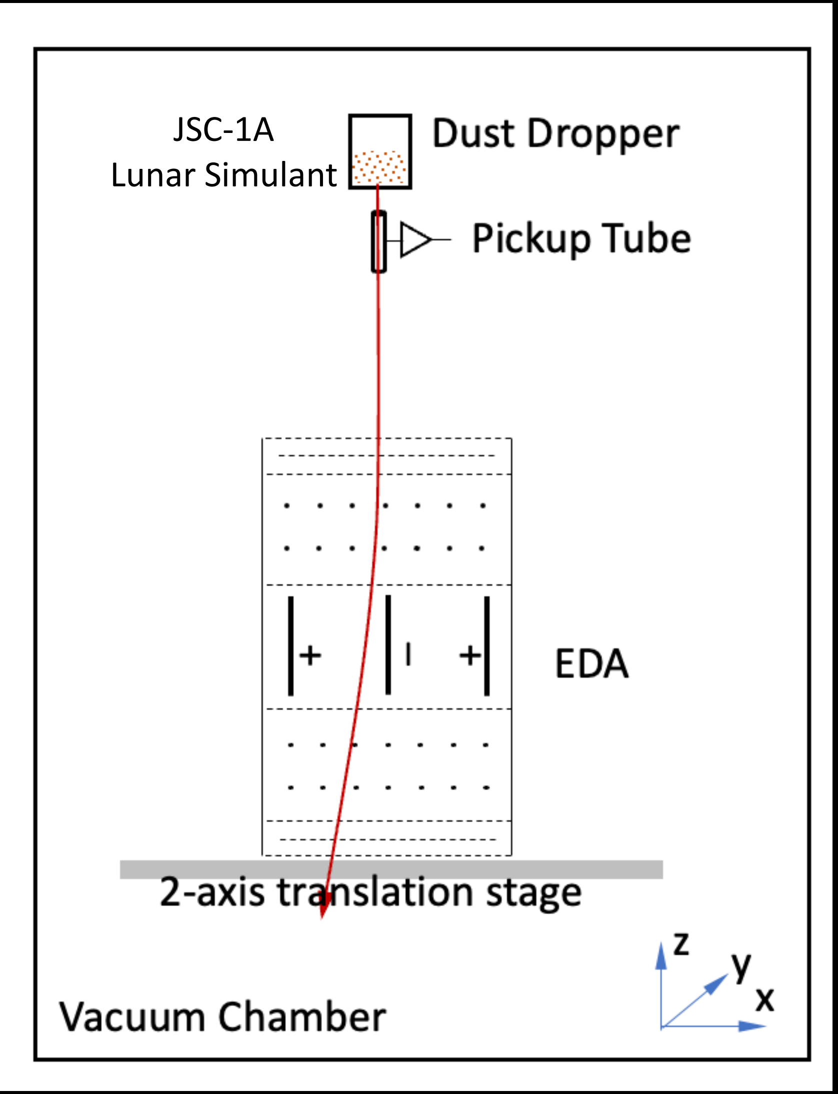
Dust Dropper
Pick-up Tube
EDA





First Signals

Dust Campaign in Vacuum Chamber

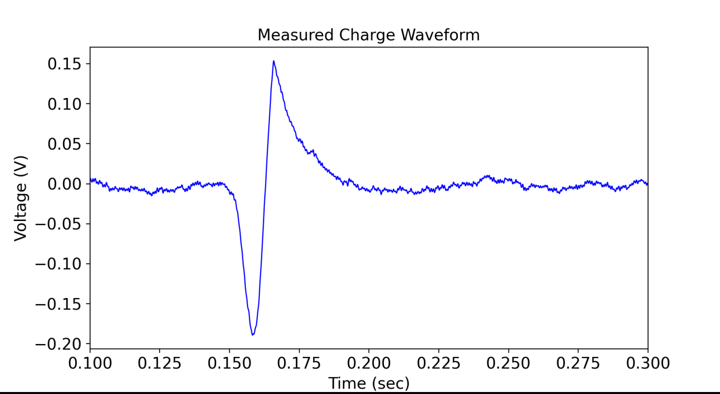


Data Analysis Flow Chart

ADC data

↓

Conversion to physical quantities



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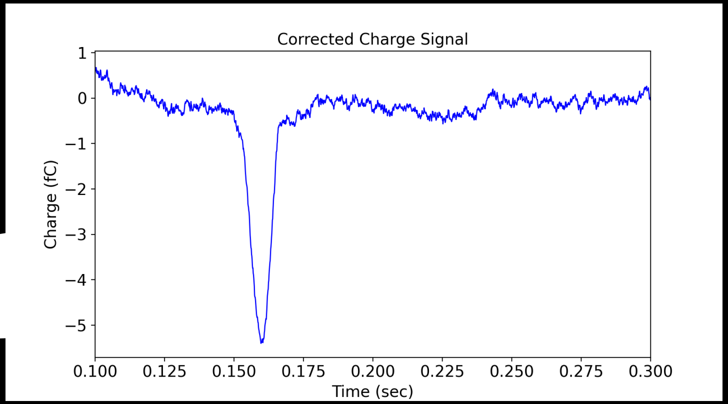
Convert and correct waveforms to charge signals using CSA impulse response



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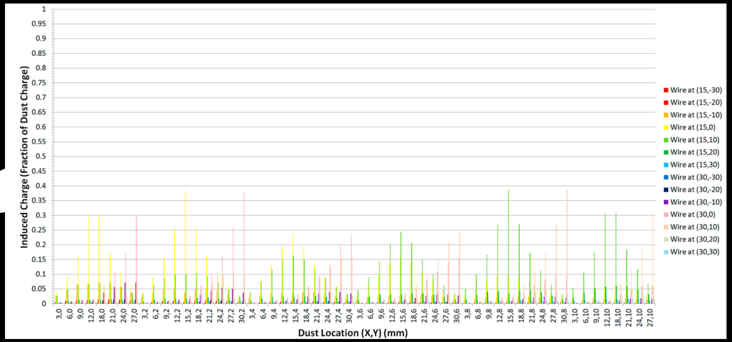
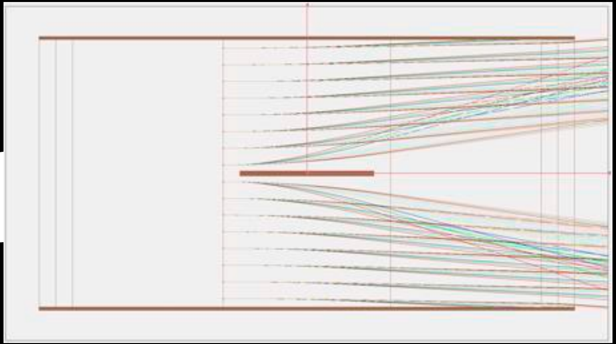
Correct charge w/ loss due to wall effect and determine particle locations using a modeled lookup table

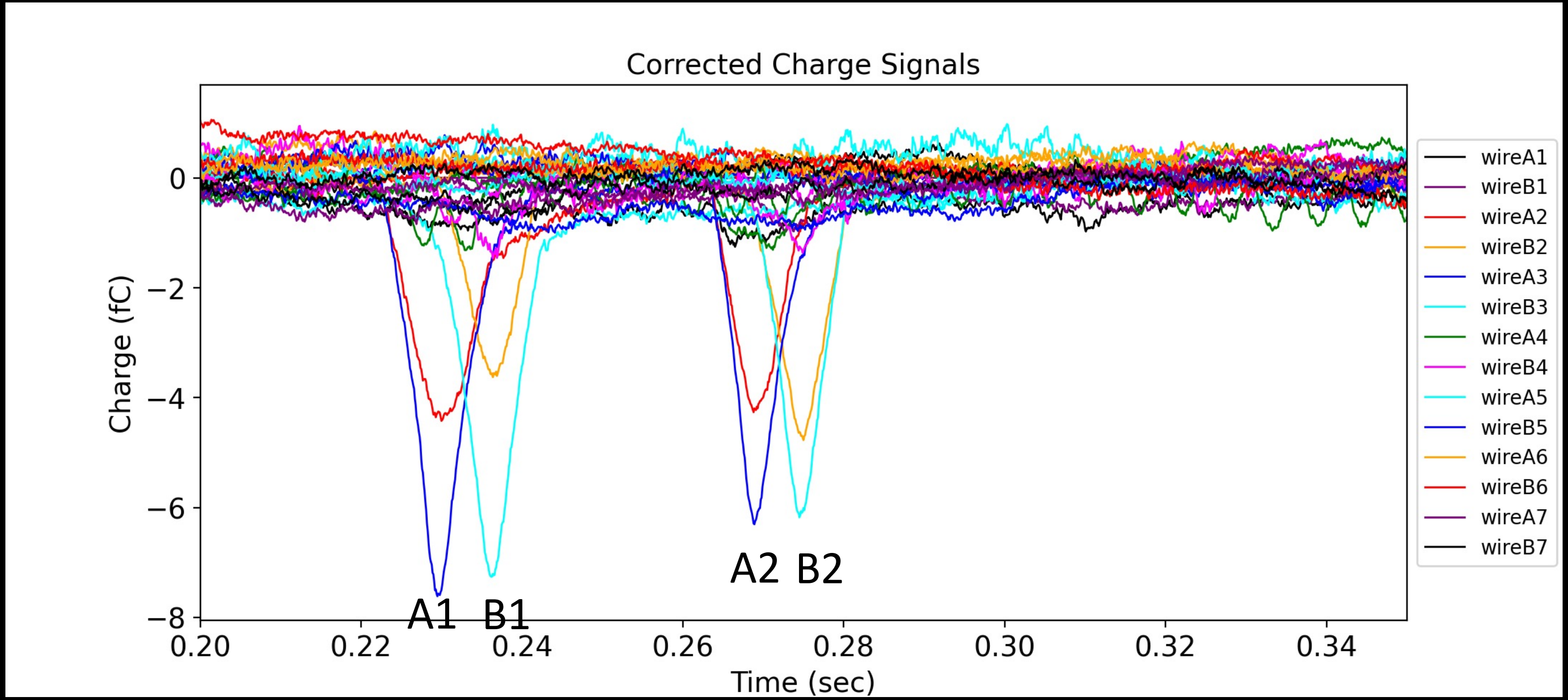


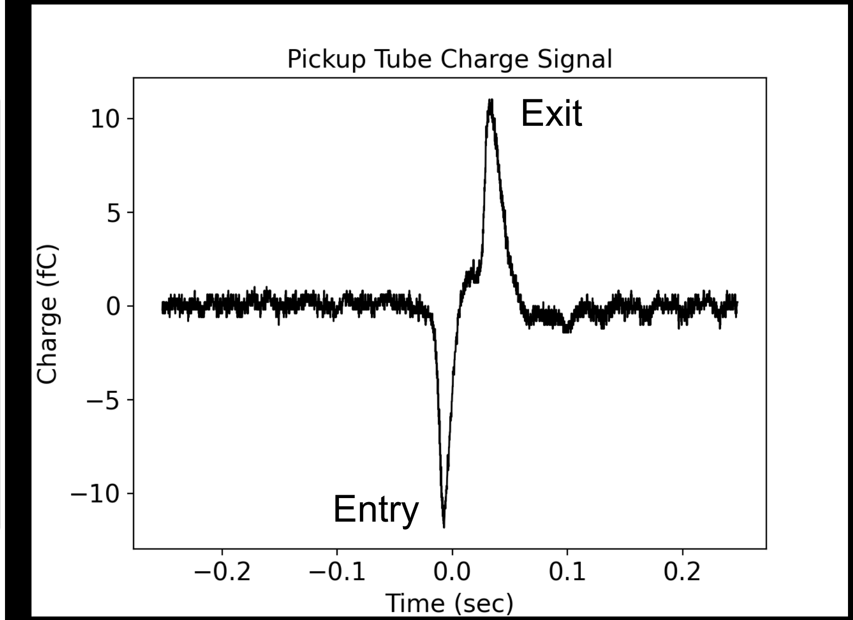
↓

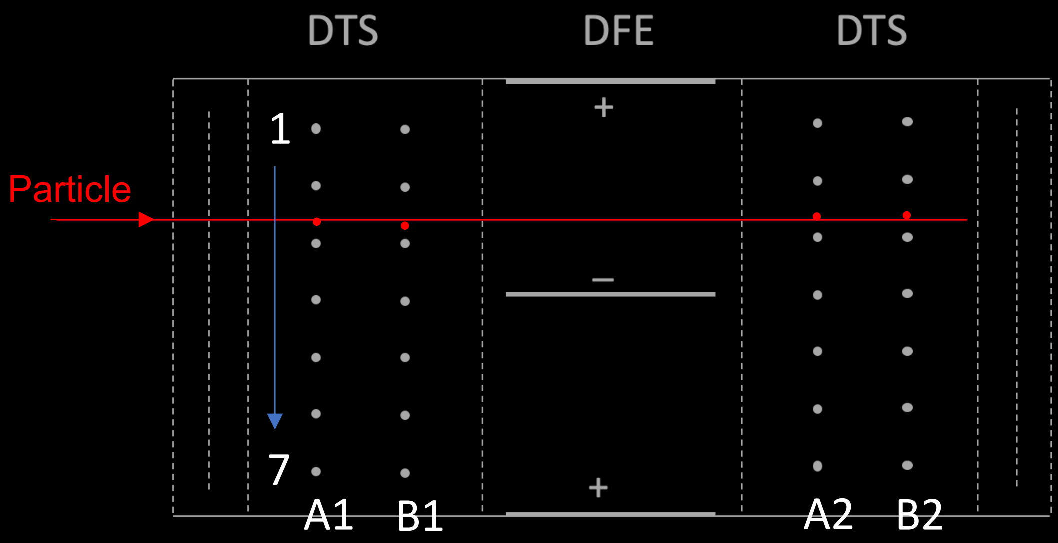
Fit trajectories with determined particle locations to derive mass (size)



Example Data (Large Charge w/o Deflection)



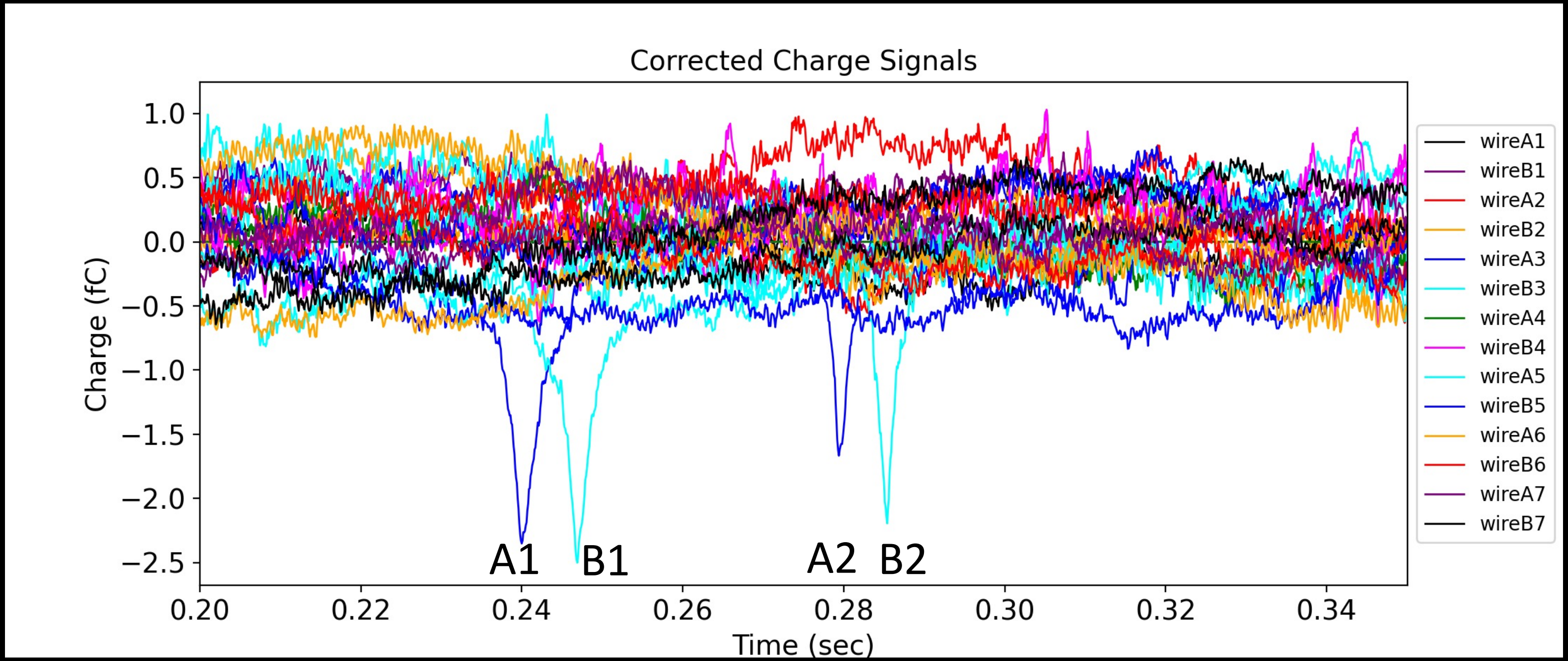


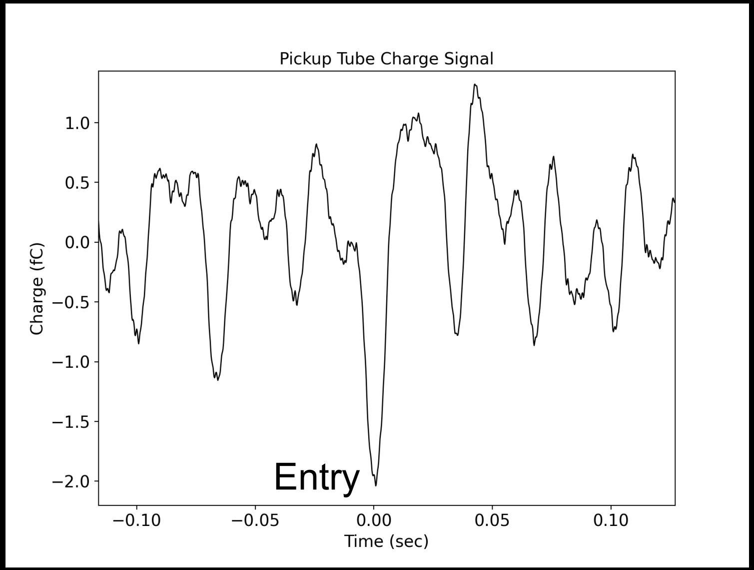


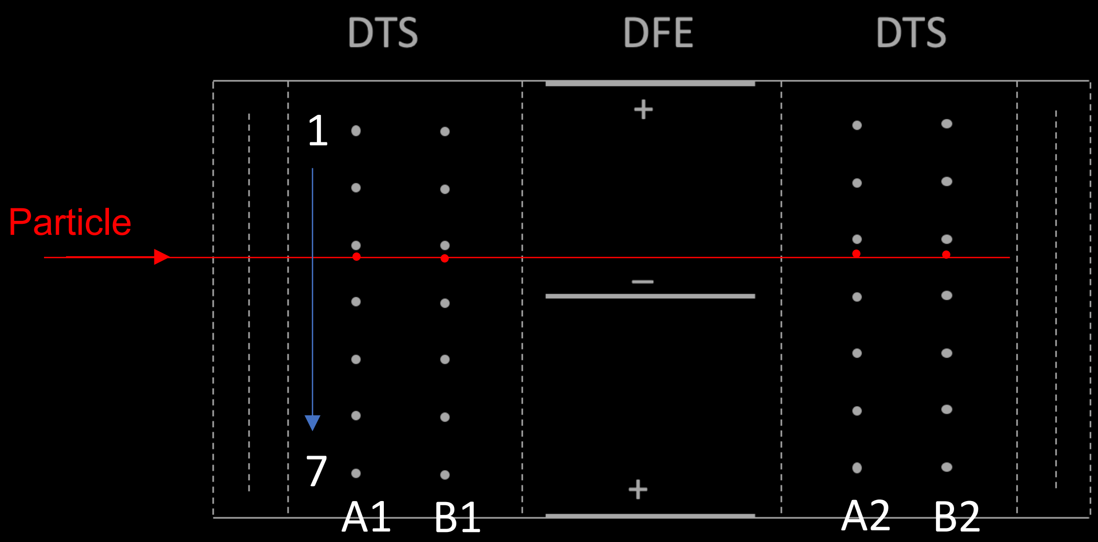
	EDA	Estimated
Dust Size	N/A	100 – 112 μm
Velocity (at two DTS locations)	2.2 & 2.6 m/s	2.17 & 2.5 m/s
Charge	24 ± 0.8 fC	11.5*2 = 23 fC

DatNum: 3-17--9-44

Example Data (Small Charge w/o Deflection)



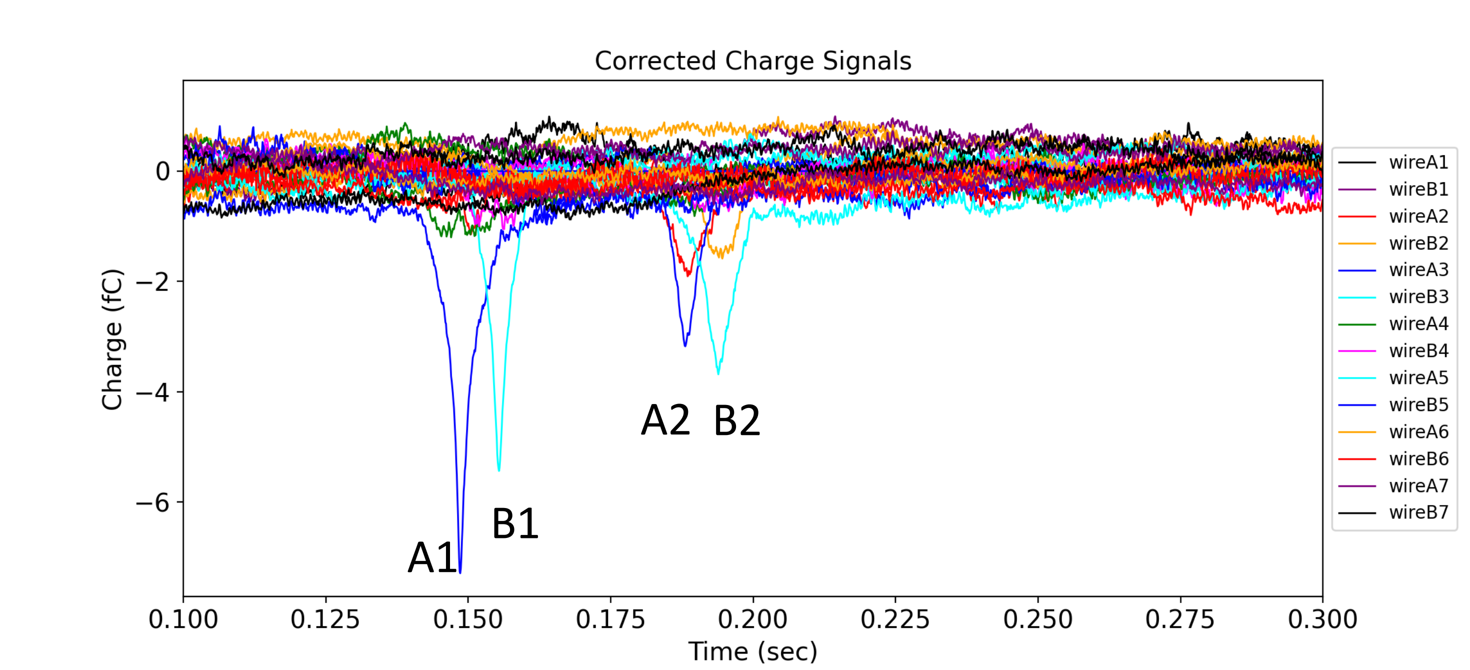


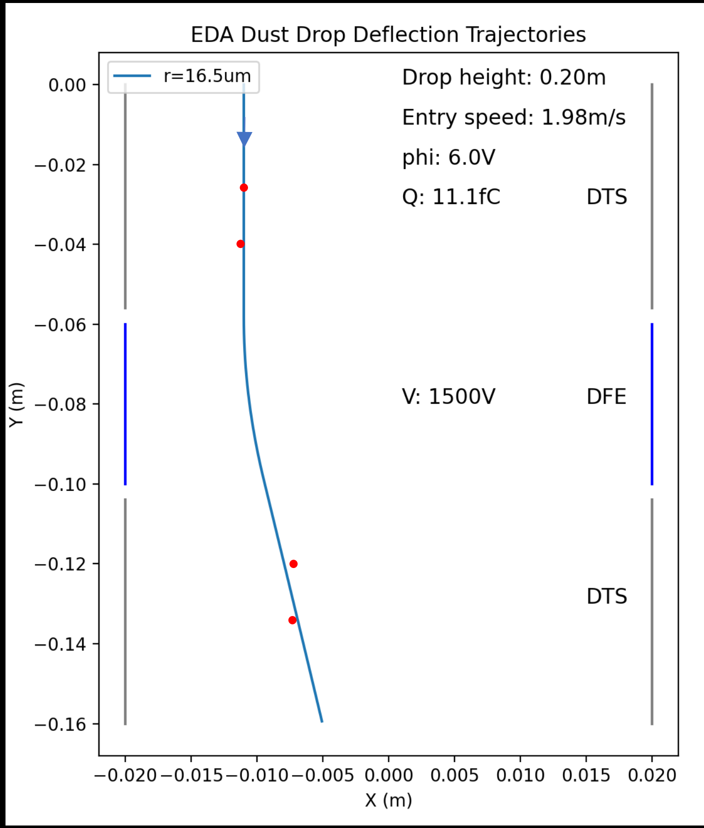


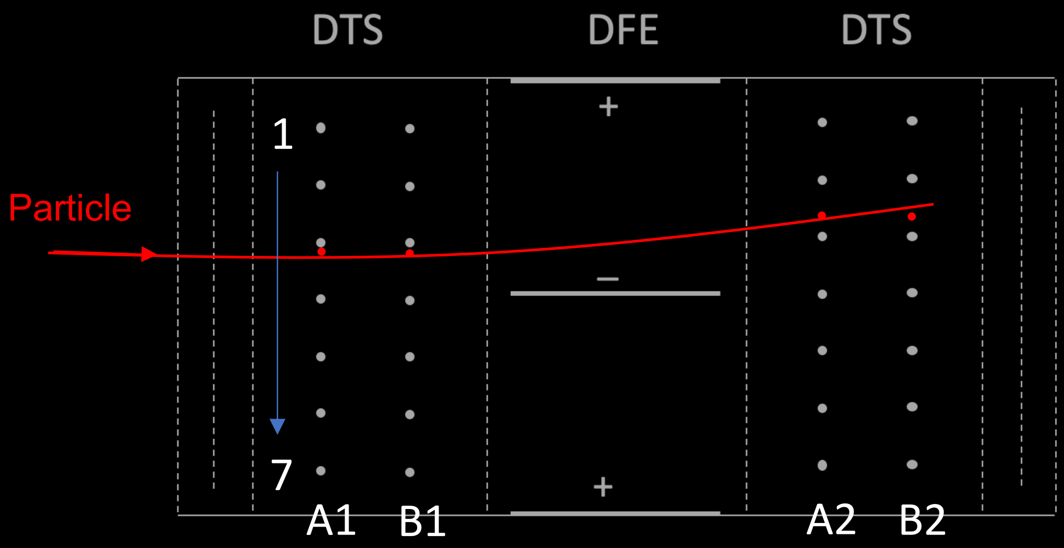
	EDA	Estimated
Dust Size	N/A	35 – 48 μm
Velocity (at two DTS locations)	2.1 & 2.5 m/s	2.17 & 2.5 m/s
Charge	4.6 ± 0.5 fC	2.0*2 = 4 fC

DatNum: 2-8-23--14-34

Example Data (Deflection)







	EDA	Estimated
Dust Size	33 µm	35 – 48 µm
Velocity (at two DTS locations)	2.2 & 2.5 m/s	2.17 & 2.5 m/s
Charge	11 ± 0.8 fC	3.6*2 = 7.2 fC

DatNum: 3-29-23--15-09

Concluding Remarks

- Charging and lofting of dust particles on the lunar surface is a long-standing problem, which has important implications for planetary science and human exploration.

- Recent laboratory breakthroughs have improved our understanding of the underlying physics, paving a road for in-situ measurements on the Moon.

- EDA developed under the NASA-DALI program will provide direct measurements of electrostatically lofted dust on the lunar surface to ultimately solve this five-decade-old problem.