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Electrodynamic Regolith Conveyor Sub-Orbital Flight Experiment**Aaron D.S. Olson^a**^a *Electrostatics & Surface Physics Laboratory, Swamp Works, NASA John F. Kennedy Space Center, Kennedy Space Center, Florida, 32899, United States of America, aaron.d.olson@nasa.gov***Abstract**

The Electrodynamic Regolith Conveyor (ERC) is a technology that is being developed for soil sampling, beneficiation, specialized conveying applications and dust mitigation. The ERC is an extension of the Electrodynamic Dust Shield (EDS). The EDS has been developed for lenses, solar panels, radiators, fabric, and other applications and is scheduled for a technology demonstration mission on the Moon in 2024. The objective of the ERC sub-orbital flight experiment is to perform testing to advance the TRL of the ERC technology by measuring the regolith transport flow rate, power consumption and range of particle trajectories at four different inclinations in a simulated lunar gravity environment. This testing supports discrete element modeling efforts by grounding the simulations with test data.

Keywords: Conveyor, Lunar, Electrodynamic, Regolith, EDS, Sub-Orbital**1. Introduction**

Researchers at the Electrostatics & Surface Physics Laboratory (ESPL) at the National Aeronautics & Space Administration's (NASA) Kennedy Space Center (KSC) are developing a comparatively low power lunar regolith transport technology to convey material without the need for rotating or vibratory mechanical actuation. This Electrodynamic Regolith Conveyor (ERC) technology uses a 4-phase traveling square wave approach to transport particles over a surface with interdigitated electrodes [1]. The ERC technology is being developed for multiple applications like the directional transport of dust away from dust sensitive surfaces. Other applications include sampling and conveying into analytical instruments and in-situ resource utilization reactors. The technology is also being developed for specialized particle size sorting and mineral beneficiation. An ERC sub-orbital flight experiment has been built as a technology demonstration in a simulated lunar gravity and vacuum environment as well as a method to anchor ongoing discrete element modeling with flight data. The ERC payload will measure regolith transport flow rate, power consumption and particle trajectories at different conveyor inclinations. Research on the motion of particles, acted on by dynamic electric fields, generated through alternating high voltage on conductive traces or electrodes dates to the late 1960s with Tatom [2] at NASA. This was followed in the 1970s by Masuda at the University of Tokyo [3,4]. Calle and others at the Electrostatics & Surface Physics Laboratory (ESPL) at Kennedy Space Center built on past studies to develop an active dust mitigation solution known as the Electrodynamic Dust Shield (EDS) [5–8]. Configurations of the EDS have been created to protect opaque, transparent, rigid, and flexible surfaces [9]. An

EDS technology demonstration mission on the lunar surface is currently scheduled for 2024. The payload, shown in Fig. 1, includes several iterations of the EDS, including for transparent and thermal radiator surfaces [10]. An example of an EDS for a transparent lens is shown in Fig. 2. In Academia, researchers have also developed lab scale versions of 4-phase traveling wave systems to directionally transport regolith particles [11].

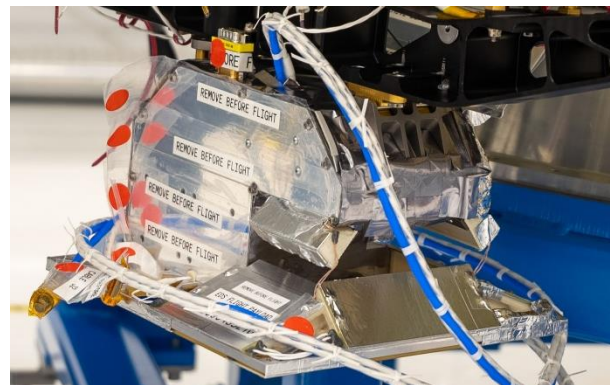


Fig. 1. EDS Technology Demonstration Payload integrated onto a lunar lander (Credit: NASA, Firefly Aerospace).

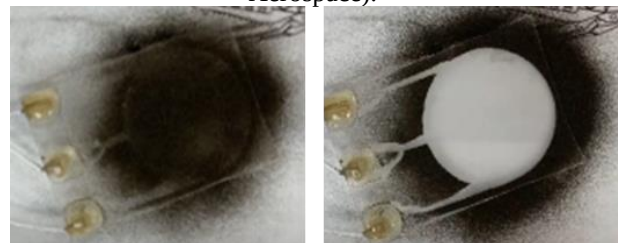


Fig. 2. A 3-phase EDS clearing lunar regolith simulant off a transparent surface (Credit: Calle [6])

2. Electrodynamic Particle Conveying Modeling

There are many forces acting on charged and neutral particles on an EDS or ERC surface. The equations of motion for these particles include coulomb, dielectrophoretic, adhesion, image, drag, friction, gravitational acceleration, and collisional interaction forces. These forces depend on environmental conditions (medium, gravity), particle properties (size, shape, charge, coefficient of restitution, etc...), and the electric field produced by the applied high voltage (amplitude, frequency, waveform, number of phases). Different modes of particle motion like the hopping, curtain, surfing, and vibrating modes can be present depending on system parameters [12,13]. A representative free body diagram of a particle moving on a 4-phase ERC is shown in Fig. 3. Bulk particle motion can be modeled with the Discrete Element Method (DEM). The equations of motion, using a hard sphere approximation, are shown in equations 1 and 2.

$$m_i \ddot{\mathbf{x}}_i = \mathbf{F}_{coulomb_i} + \mathbf{F}_{DEP_i} + \mathbf{F}_{image_i} + \mathbf{F}_{drag_i} + \mathbf{F}_{friction_i} + \mathbf{F}_{adhesion_i} + m_i \mathbf{g} \quad (1)$$

$$I_i \ddot{\boldsymbol{\theta}}_i = \mathbf{M}_{mechanical_i} + \mathbf{M}_{friction_i} \quad (2)$$

The coulomb force can be calculated as the product of the electric field, $\mathbf{E}$, and q , the particle charge, as shown in equation 3.

$$\mathbf{F}_{coulomb} = \mathbf{E}q \quad (3)$$

One approximation for the dielectrophoretic force is shown in equation 4.

$$\mathbf{F}_{DEP} = \frac{4\pi\epsilon_0(\epsilon-1)R^3\mathbf{E}_0\nabla E_0}{\epsilon+2} \quad (4)$$

The permittivity of free space is ϵ_0 , ϵ is the relative permittivity of a particle, R is the particle radius, and $\mathbf{E}_0$ is the electrostatic field (not accounting for moving charges). The image force can be described as shown in equation 5 where $\mathbf{d}$ is a vector representing the effective distance between a particle and an electrode.

$$\mathbf{F}_{image} = \frac{1}{4\pi\epsilon_0} \sum_{n=1}^N \left(\frac{q_i q_n}{2d} \right)^2 \left(\frac{\mathbf{d}}{|d|} \right) \quad (5)$$

A description of the drag force is shown in equation 6 where η is the viscosity of the medium through which a particle is traveling.

$$\mathbf{F}_{drag} = -6\pi\eta R \dot{\mathbf{x}} \quad (6)$$

The friction force, acting only between the conveyor electrode surface and particles directly on this surface,

can be described as in equation 7 where μ is a friction coefficient function (static and dynamic), $\mathbf{F}_n$ is the resultant normal force to the electrode surface, and $\mathbf{n}$ is a vector along the electrode surface in the direction of the particle sliding motion.

$$\mathbf{F}_{friction} = -\mu \mathbf{F}_n \mathbf{n} \quad (7)$$

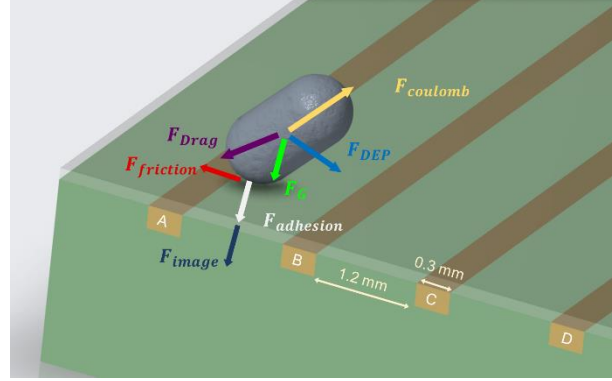


Fig. 3. Forces on a particle on an EDS surface

Further force descriptions and a comparison of EDS modeling approaches can be found in [11–14]. Past studies have shown qualitative agreement with some experimental results [6,11]. An EDS DEM model anchored with data from simulated lunar environmental conditions (gravity, vacuum) would allow for improved optimization of EDS and ERC systems for the Moon. This model would nominally consider the angularity of lunar regolith particles, particle size distributions, particle tribocharging, and appropriate particle-particle and particle-surface contact models.

3. Sub-Orbital Payload Requirements

The ERC payload was designed to operate within the limits of a single size payload locker of the Blue Origin New Shepard capsule. The available size, mass and power are shown in Table 1. The payload was also designed to meet the mounting interface, structural (flight quasistatic, random vibration, and shock loads), thermal, regolith containment, electromagnetic interference, and hazard requirements of the New Shepard vehicle.

Table 1. Blue Origin New Shepard Single Locker

Payload locker type	Single
Internal dimensions	52.3 x 41.4 x 24.1 cm
Payload mass	11.34 +0/-0.045 kg
Payload power	18 V, 8 A max

The New Shepard capsule, for simulated lunar gravity research flights, spins about its axis of symmetry at 11 RPM to achieve a centripetal acceleration of approximately 1.6 m/s² at a radius of 1.2 m. This occurs for approximately a 2-minute window after the capsule

achieves free fall during its sub-orbital trajectory. Images of the New Shepard rocket and capsule are shown in Fig. 4.



Fig. 4. Blue Origin New Shepard rocket and capsule

The payloads, mounted on racks around the perimeter of the capsule, as shown in Fig. 5, experience a radially dependent centripetal acceleration. The radius (1.2 m) corresponding to simulated lunar gravity passes approximately through the center of each payload locker.

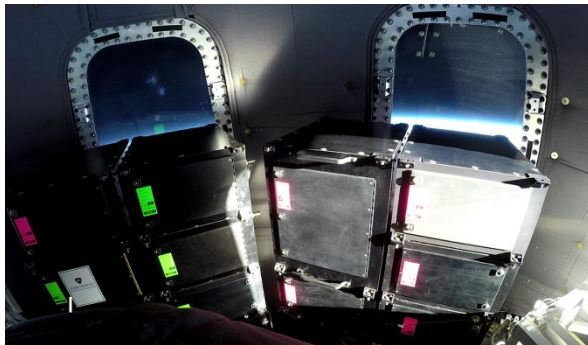


Fig. 5. Research payload lockers mounted around in the internal perimeter of the New Shepard capsule

4. Experiment Requirements

The experimental functional requirements of the ERC payload included environmental, regolith flow, conveyor operation, and instrumentation requirements. The major requirements are summarized in Table 2.

Table 2. High level ERC experimental requirements

#	High level requirements
Environmental	
1	<500 mTorr experiment pressure during operation
Regolith Flow	
2	Storage of 200 or more g of < 200-micron regolith simulant
3	Feed up to 1.2 g/s of regolith simulant onto and uniformly across the conveyor surface
Conveyor Operation	
4	+/- 4 kV 10 Hz 4-phase square waveform
5	Rotating conveyor plane >10 degrees from horizontal
6	Side and top view of regolith motion
Instrumentation	
7	240 fps video recording, profile and top views
8	Lighting for general observation and particle flow tracking
9	Regolith and experiment temperature measurement
10	Pressure measurement
11	Regolith flow rate measurement
12	Power measurement (voltage and current)

5. Subsystem Design

A rendering of the ERC payload, without its harnessing, can be seen in Fig. 6. The payload is placed in the locker from its top removable locker panel and is mounted on the bottom plate of the locker. The payload's aluminium vacuum chamber, allowing for < 500 mTorr experiment operating pressure, is the primary structure. A feedthrough and ball valve allow for the chamber to be pumped and held at vacuum before flight. The primary electronics assembly is mounted to the chamber and routes power and signal connections through a circular 61-pin feedthrough. The chamber, electronics and feedthroughs are shown in Fig. 7. The high voltage power supply and its feedthrough for the conveyor are mounted on the vacuum chamber face opposite the other feedthroughs.

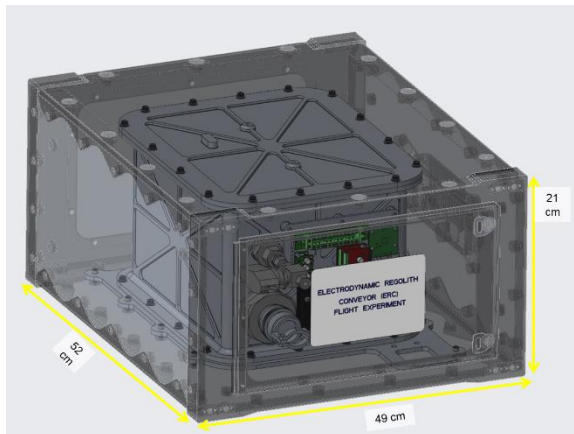


Fig. 6. ERC payload inside of its single payload locker. The locker is shown as transparent for clarity.

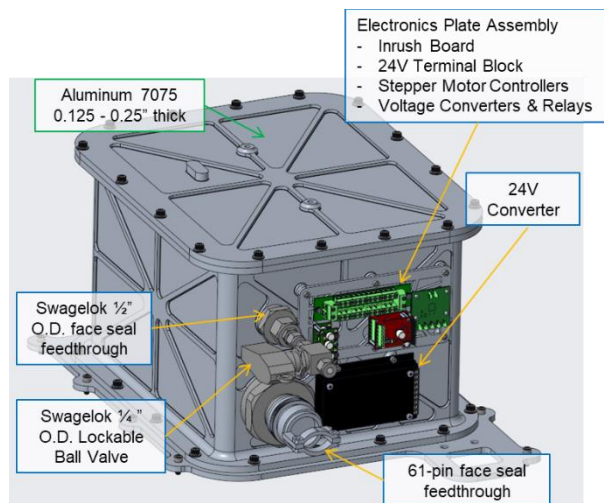


Fig. 7. The ERC vacuum chamber, electronics assembly, and vacuum feedthroughs

There are three primary subsystems inside of the vacuum chamber. The feeder subsystem, illustrated in Fig. 8, stores regolith simulant prior to the experiment starting and uniformly deposits up to 1.2 g/s of regolith simulant onto the conveying surface. This is done with a rotary valve and perforated slide gate shaker.

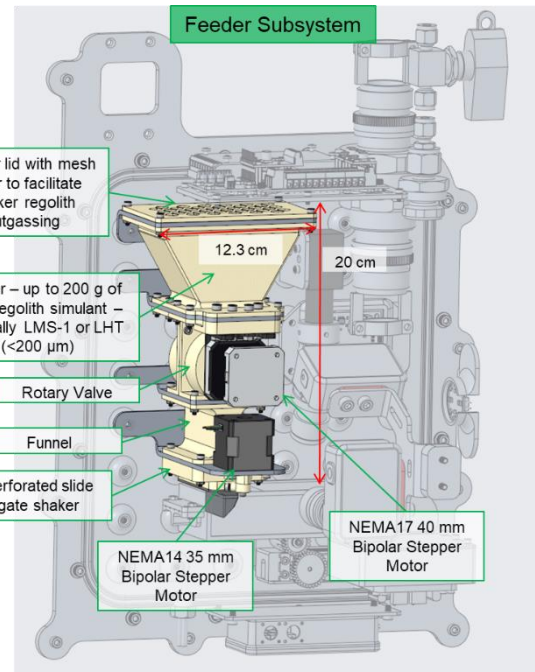


Fig. 8. ERC feeder subsystem components

Regolith is conveyed from the outlet of the feeder subsystem onto the second internal subsystem: the conveyor subsystem. This subsystem, shown in Fig. 9, consists of a 4-phase printed circuit board with a Paralene dielectric surface coating inside of an ULTEM and polycarbonate housing. The entire housing is mounted onto a servo motor driven pivot that can incline the conveying surface up to approximately 15 degrees. During the flight experiment, the conveyor is tilted 3 times to enable regolith conveying at 4 different inclinations. At the outlet of the conveyor housing is a load cell instrumented collection bin. The third internal subsystem is the instrumentation subsystem. The payload is instrumented with two GoPro cameras with c-mount lenses to observe regolith transport from profile and overhead views (through the conveyor housing's polycarbonate windows). The cameras are shown in Fig. 10. An LED light and a line laser alternate providing illumination for the two cameras during the simulated gravity window. The line laser, shown in Fig. 11, creates a line through the midplane of the conveyor surface and allows for particle tracking analysis. A resistance temperature detector (RTD) measures the vacuum chamber temperature. A 2nd RTD measures the rotary valve's stepper motor temperature. A miniature Pirani sensor measures the vacuum chamber pressure. An external integrated payload controller interfaces with the capsule to provide the payload power, triggering events for experimental timing, and storage for power draw and measurements from the RTDs, load cell, and Pirani sensor.

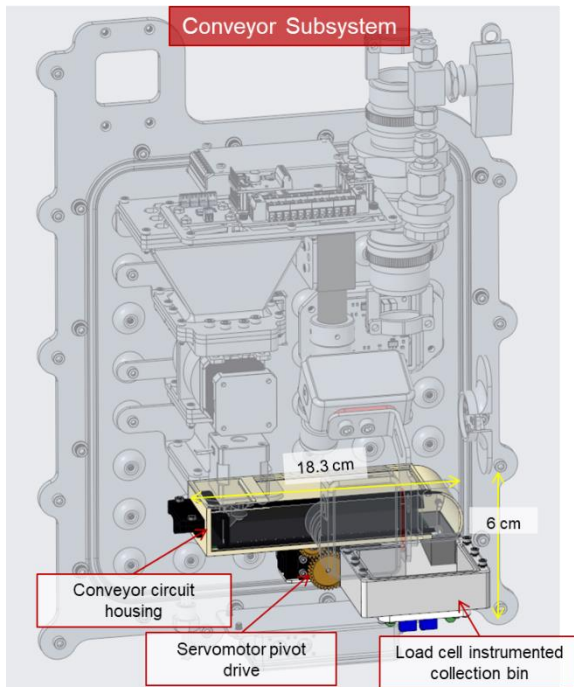


Fig. 9. The ERC conveyor subsystem components

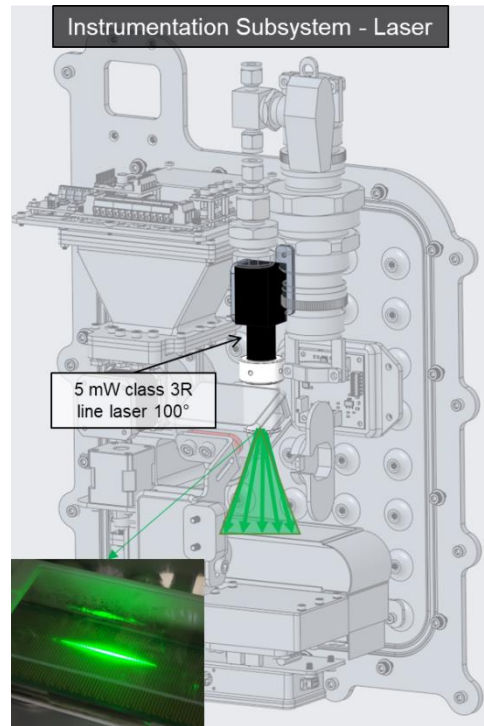


Fig. 11. The ERC line laser illuminating the conveyor surface for particle tracking analysis

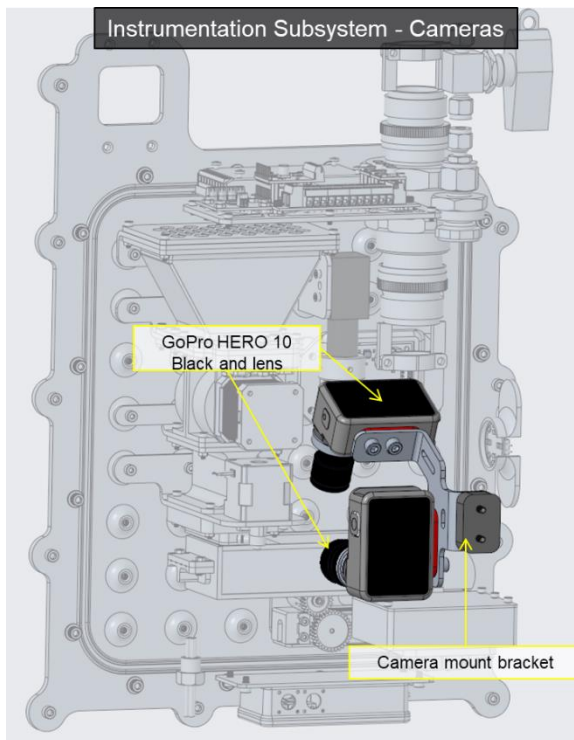


Fig. 10. The ERC GoPro Hero 10 cameras, their lenses and mounting bracket

An image of the exterior of the as-built payload is shown in Fig. 12. An image of the payload after a run for record at vacuum is shown in Fig. 13. An image of the internal as-built subsystems (without the cameras and full harnessing) is shown in Fig. 14. The 4-phase circuit for the payload is shown in Fig. 15 and the output waveforms from the ERC high voltage supply are shown in Fig. 16.

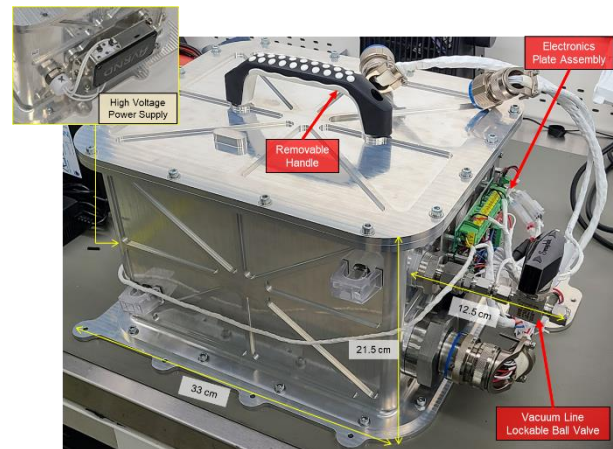


Fig. 12. The ERC payload prior to environmental testing

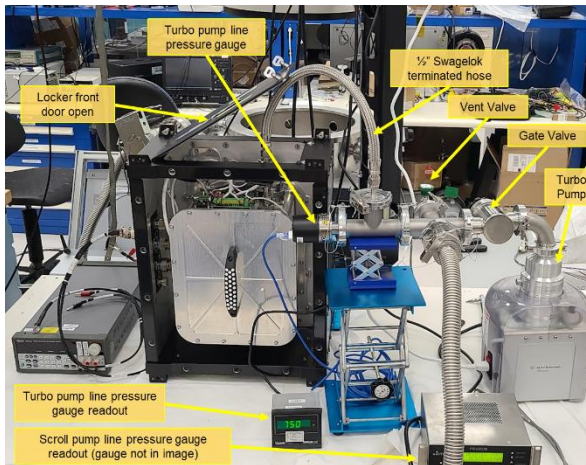


Fig. 13. The ERC payload after a run for record test

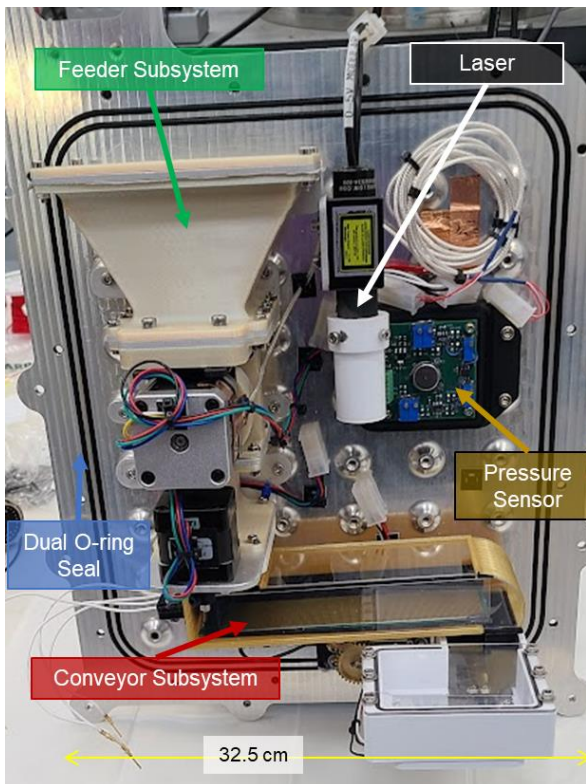


Fig. 14. ERC internal payload subsystems and components

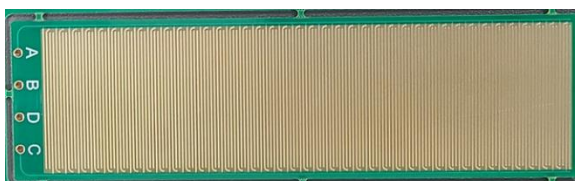


Fig. 15. ERC 0.3 mm trace width x 0.3 mm gap width 4-phase circuit.

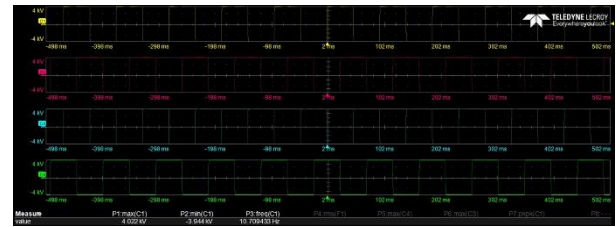


Fig. 16. ERC high voltage power supply 4-phase square waveforms

6. Future Work

Analysis of the lab operation data of the ERC payload in 1-g along with data from an upcoming lunar gravity sub-orbital flight will inform the establishment of DEM model parameters to accurately extend and optimize future EDS related technologies.

7. Conclusions

The Electrodynamic Regolith Conveyor payload was designed and built to measure regolith transport flow rate, power consumption and range of particle trajectories at four different inclinations in a simulated lunar vacuum and gravity environment onboard a sub-orbital vehicle. Data from the flight experiment will inform forthcoming DEM modeling efforts.

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References

- [1] Olson, A. D., "Design and Testing of a Prototype Electrodynamic Regolith Conveyor for Lunar ISRU," 2022.
- [2] Tatom, F. B., Adams, J. G., Cline, B. L., Contaxes, N. A., Johnson, R. D., Seaman, H., and Srepl, V., "Lunar Dust Degradation Effects and Removal/Prevention Concepts. Volume 1 - Summary Final Report," *NASA Technical Report*. Volume TR-792-7-207A, 1–3.
- [3] Masuda, S., Fujibayashi, K., Ishida, K., and Inaba, H., "Confinement and Transportation of Charged Aerosol Clouds via Electric Curtain," *Electrical Engineering in Japan*, Vol. 92, No. 1, 1972, pp. 43–52. <https://doi.org/10.1002/EEJ.4390920106>
- [4] Masuda, S., Matsumoto, Y., and Akutsu, K., "Characteristics of Standing-wave, Ring-type Electric Curtain. Experimental Study," *Electrical Engineering in Japan*, Vol. 93, No. 1, 1973, pp. 78–83. <https://doi.org/10.1002/EEJ.4390930111>

- [5] Immer, C., Starnes, J., Michalenko, M., Calle, C. I., Mazumder, M. K., Starnes, J., Michalenko, M., Calle, C. I., and Mazumder, M. K., "Electrostatic Screen for Transport of Martian and Lunar Regolith," 2006.
- [6] Calle, C. I., Buhler, C. R., McFall, J. L., Snyder, S. J., Buhler, C. R., McFall, J. L., and Snyder, S. J., "Particle Removal by Electrostatic and Dielectrophoretic Forces for Dust Control During Lunar Exploration Missions," 2009.
- [7] Calle, C. I., Linell, B., Chen, A., Meyer, J., Clements, S., Mazumder, M. K., Linell, B., Chen, A., Meyer, J., Clements, S., and Mazumder, M. K., "Numerical and Analytical Model of an Electrodynamic Dust Shield for Solar Panels on Mars," 2006.
- [8] Calle, C. I., Immer, C. D., Clements, J. S., Chen, A., Buhler, C. R., Lundeen, P., Mantovani, J. G., Starnes, J. W., Michalenko, M., Mazumder, M. K., Immer, C. D., Clements, J. S., Chen, A., Buhler, C. R., Lundeen, P., Mantovani, J. G., Starnes, J. W., Michalenko, M., and Mazumder, M. K., "Electrodynamic Dust Shield for Surface Exploration Activities on the Moon and Mars," 2006.
- [9] Manyapu, K. K., de Leon, P., Peltz, L., Tsentalovich, D., Gaier, J. R., Calle, C., Mackey, P., de Leon, P., Peltz, L., Tsentalovich, D., Gaier, J. R., Calle, C., and Mackey, P., "Investigating the Feasibility of Utilizing Carbon Nanotube Fibers for Spacesuit Dust Mitigation," 2016.
- [10] Buhler, C. R., "EDS to The Moon!," 2022.
- [11] Kawamoto, H., and Shirai, K., "Electrostatic Transport of Lunar Soil for In Situ Resource Utilization," *Proceedings of the 12th International Conference on Engineering, Science, Construction, and Operations in Challenging Environments - Earth and Space 2010*, 2010, pp. 57–65. [https://doi.org/10.1061/41096\(366\)8](https://doi.org/10.1061/41096(366)8)
- [12] Yu, Y., Cilliers, J., Hadler, K., Starr, S., and Wang, Y., "The Motion of Small Particles in Electrostatic Travelling Waves for Transport and Separation," *Powder Technology*, Vol. 425, 2023, p. 118587. <https://doi.org/10.1016/J.POWTEC.2023.118587>
- [13] Yu, Y., Cilliers, J., Hadler, K., Starr, S., and Wang, Y., "A Review of Particle Transport and Separation by Electrostatic Traveling Wave Methods," *Journal of Electrostatics*, Vol. 119, 2022, p. 103735. <https://doi.org/10.1016/J.ELSTAT.2022.103735>
- [14] Kawamoto, H., and Yoshida, N., "Electrostatic Sampling and Transport of Ice for In-Situ Resource Utilization," *Journal of Aerospace Engineering*, Vol. 31, No. 4, 2018. [https://doi.org/10.1061/\(ASCE\)AS.1943-5525.0000866](https://doi.org/10.1061/(ASCE)AS.1943-5525.0000866)