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Ground-Based Capabilities for Lunar Infrastructure Testing

Aaron Weaver[a]*, Jacquelynne Houts[a], Lee Mason[a], Jeffrey Csank[a], James Nessel[a], Michael Zemba[a], Bryan Schoenholz[a]

[a] *National Aeronautics and Space Administration, John H. Glenn Research Center, 21000 Brookpark Rd., Cleveland, OH, USA 44135*
* Corresponding Author

Abstract

A focus of NASA's Moon-to-Mars objectives is the development of the infrastructure on the lunar surface that will be needed to support broader lunar surface operations. This infrastructure is intended to support both United States and international partners to expand human presence on the lunar surface. As this lunar infrastructure is designed and established, it will be critical to ensure that the various hardware elements work together to both enable the capabilities and to avoid unintended actions.

NASA's Glenn Research Center (GRC) is establishing ground-based testing and emulation facilities to mimic the lunar environment that the surface power and communications infrastructure will operate in. These facilities are intended to represent power and communications providers, users, and interfaces to ensure that systems operate as intended to support the lunar economy. They will empower industry to rapidly evaluate new technologies under realistic conditions.

In 2023 GRC is opening a new, state-of-the-art, Aerospace Communications Facility featuring hardware-in-the-loop and ground-to-orbit testbeds. The Multiple Asset Testbed for Research in Innovative Communications Systems (MATRICS) capability will emulate the lunar communications environment, enabling validation of mission concepts and technologies to reduce risk through performance and operations testing, training, and uncover potential issues in compatibility among communication systems providers and users.

In addition to the communications testbed, GRC is also developing a full-scale power grid to reduce lunar mission risk. The Adaptable Surface Power Integration and Research (ASPIRE) project aims to reduce mission and hardware risk via high-fidelity integrated testing and pave the way for commercially supplied utility power on the lunar surface. The facility will be scalable and highly adaptable and will be available to NASA, Industry, Academia, and International Partners. ASPIRE will allow developers to integrate and demonstrate their power solutions in a relevant environment, and it will be able to characterize the lunar power performance in representative mission contexts.

Keywords: ground-based testing, Moon-to-Mars, power, communications, infrastructure, lunar environment

Acronyms/Abbreviations

Aerospace Communications Facility (ACF)
Adaptable Surface Power Integration and Research (ASPIRE)
controller hardware-in-the-loop (C-HIL)
Glenn Research Center (GRC)
hardware-in-the-loop (HIL)
intermediate frequencies (IF)
Multiple Asset Testbed for Research in Innovative Communications Systems (MATRICS)
National Aeronautics and Space Administration (NASA)
power hardware-in-the-loop (P-HIL)
radio frequency (RF)
Technology Readiness Level (TRL)
Universal Modular Interface Converter (UMIC)

1. Introduction

The National Aeronautics and Space Administration (NASA) is establishing a Moon-to-Mars architecture aiming to expand the reach of humanity to the moon and forward to Mars. Key driving objectives guiding the development of this approach were published by NASA in September 2022 [1]. These objectives address what NASA plans to achieve in deep space exploration and why it is important. They include science, infrastructure, habitation, and transportation objectives as well as recurring themes across all the objectives.

The development of the lunar infrastructure is critical to the success of expanding and sustaining human and robotic exploration of the lunar surface. Power infrastructure is needed to enable elements to operate and survive periods of extended darkness. Communications infrastructure is needed to enable reliable communication for the safety of the crew, to transmit large quantities of science data from the lunar surface to Earth, and to ensure that the network of elements on the surface and in lunar orbit can effectively operate together.

When developing space flight systems, testing in a relevant environment is critical to understanding system behavior and to ensure reliability for the mission application. Testing in the relevant environment can be challenging for single pieces of hardware. This challenge increases when the system to be tested encompasses multiple assets, potentially developed by numerous suppliers, networked in a harsh environment.

NASA's plans to explore the lunar south pole adds to the challenges and emphasises the importance of establishing testing capability. The Apollo program visited equatorial regions for short duration missions. With Artemis, NASA is planning south pole missions for longer durations. The south pole contains many sites of interest to the science community for exploration, and it has some technical advantages. It also presents challenges like low elevation angles and varying sun/shadow environments. These unique challenges will require testing capability to determine system performance in the environment.

To help meet the challenges of developing the lunar infrastructure NASA's Glenn Research Center (GRC) is aiming to establish testing capability to support both the emerging lunar communications and power infrastructure. GRC is working to establish facilities to emulate the signals, interferences, loads, and sources that lunar infrastructure hardware can expect to see. These facilities will allow hardware developers the ability to test the functionality of new equipment, providing confidence in the operation on the moon. The testing capability will also allow system designers and integrators tools to ensure that the complete system is robust to accommodate new elements of the infrastructure as they are developed, delivered, and integrated on the lunar surface.

To address the needs for both communications and power infrastructure development, GRC is establishing the Multiple Asset Testbed for Research in Innovative Communications Systems (MATRICS) and Adaptable Surface Power Integration and Research (ASPIRE). The concepts, progress, and planned capabilities of these facilities are described below.

2. Lunar Surface Communications Testing

A robust lunar communications and navigation infrastructure will be required to establish both a human and robotic presence on the moon. The lunar terrain provides a difficult radio frequency (RF) environment for communications, especially at the low elevation angles for communications to the lunar south pole. Additionally, as more hardware is delivered to the south pole and operations increase, the demand for communication, both surface-to-surface and moon-to-Earth, will create more complex RF environments.

The Multiple Asset Testbed for Research in Innovative Communications Systems (MATRICS) is a proving ground designed to operate a communications system, or its digital twin, in an accurately recreated, complex, and dynamic environment. By integrating cutting-edge hardware, advanced modelling and simulation capability, and a wealth of historical mission data, the MATRICS can drastically reduce risk and improve understanding of system performance for both space and aeronautical applications.

2.1 Facility Overview

The MATRICS employs dynamic hardware-in-the-loop testing techniques to enable the evaluation of real antennas, receivers, and radios which can be embedded within their actual flight vehicle structures. Advanced channel emulation capabilities apply adverse weather effects, terrain-induced multipath fading, delay spread, interference, jamming, as well as the ability to play back previously measured link performance. Altogether, the unification of these high-fidelity emulation capabilities results in highly realistic environments and test scenarios. As a result, MATRICS can provide cost-effective risk reduction by efficiently performing hundreds of virtual flight tests in a controlled and automated setting.

The Aerospace Communications Facility (ACF), pictured in Fig. 1, opened in August 2023, and houses the MATRICS alongside a variety of state-of-the-art communications facilities including a 10m class Planar Near-field Range, a Spherical Near-Field Range, a Compact Antenna Test Range, and a fast-tracking 3.7 m S/Ka-band ground station. In many ways, the MATRICS capability is the unification of these constituent parts. The proximity and close integration between these facilities allows for hybrid emulations that take advantage of capabilities needed for a given study: for example, an emulated link may be set up with antennas and radios installed on a full-scale rover in the 10-meter range, or an emulated Lunar surface user may simulate Lunar surface propagation effects but communicate with a link to a live space asset through the 3.7-meter ground station.

The MATRICS also enables robust pre-flight and post-flight analytics. Pre-flight, engineers can prepare for flight tests by conducting dry runs in the laboratory, and post-flight, they can diagnose anomalies observed in flight data by precisely altering or disabling channel variables such as multipath, interference, or weather effects. This results in more efficient use of flight-testing resources, while also enabling the extraction of more valuable information from flight data.

Fig. 1. The Aerospace Communications Facility at NASA Glenn Research Center, which opened in August 2023

2.2 Key Features

Dynamic Hardware-in-the-Loop: A set of UR10e robotic arm positioning systems give the MATRICS the ability to orient real antennas, mounted in real flight-vehicle structures, to utilize gain patterns as they would be realized during actual operations. This dynamic hardware-in-the-loop (HIL) testing can be used to simulate vehicle motion effects such as the roll, pitch, and yaw of a vehicle in flight or traversing across the uneven Lunar surface.

Channel Emulation: A Keysight Propsim F64 channel emulator is the heart of the emulation environment, used to translate physical channel models for hardware emulation. The Propsim can be used to impart multipath effects, line-of-sight shadowing, and adverse weather effects into the propagated radio RF channel. Significant research into the Lunar propagation environment has advanced the state-of-the-art for Lunar surface propagation modelling. Real RF environments are chaotic and constantly changing. Channel emulation enables MATRICS to recreate highly realistic test scenarios so engineers can evaluate system performance across a wide range of use cases. The use of high-resolution geospatial landscapes to dynamically simulate the propagation channel allows test vehicles to accurately "fly" through a city or traverse the surface of the moon without leaving the laboratory.

Software Defined Radios: Software defined radios also allow for quick reconfiguration of RF channel parameters, based on real-time link performance. Communication networks of the future require adaptive and cognitive abilities to deal with crowded spectrum and interference.

Overall Specifications: Presently, the MATRICS supports intermediate frequencies (IF) up to 6 GHz and RF up to 110 GHz. Up to 64 physical RF channels are possible, with a dynamic range of 100 dB per channel and a channel bandwidth of 600 MHz. The maximum doppler shift is ±1.5 MHz. For hardware in motion, a load capacity of 10 kg can be positioned 360° with ±0.05 mm accuracy.

2.3 Benefits

Some of the benefits of a robust communications proving ground include:

- End-to-End Link Analysis - Assess performance of the many interconnecting communications and navigation assets from end-to-end, including multiple hops through relays (Fig. 2).
- Hardware Test, Evaluation, Verification, and Validation - Place hardware in an accurately simulated/emulated environment for test and evaluation, as well as verification and validation. Ensure interoperability between many different users and service providers.
- Model Refinement - Compare RF propagation models against in situ performance data to refine existing models and develop new models representative of unique lunar surface propagation phenomena.
- Anomaly Investigation - Provide a realistic sandbox for tracking down the source of unknown anomalies.
- Mission Planning - High fidelity assessment of performance pre-flight offers opportunity to plan missions around connectivity, e.g., define optimized rover paths that maintain connectivity, or identify permanently shadowed regions with RF coverage despite lack of line-of-sight.

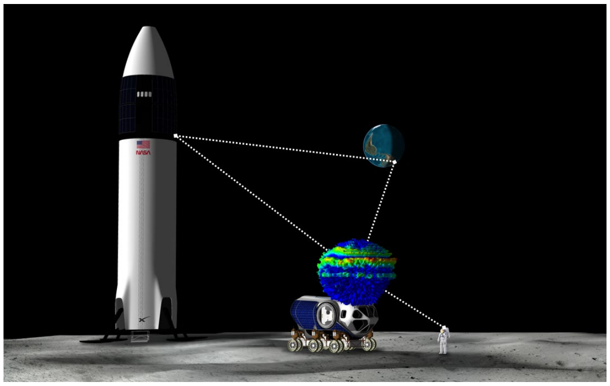

Fig. 2. Illustration of emulated lunar surface communications links using MATRICS.

3. Lunar Surface Power Testing

Establishing a permanent presence on the lunar surface requires access to highly reliable and available electric power. High elevation locations at the lunar south pole, such as Shackleton Crater Rim, De Gerlache Crater Rim, etc., can access sunlight for more than 80% of the lunar year making solar power a viable option. However, there exist periods of up to 150 continuous hours of darkness where power is needed to keep systems alive and extend operations into the lunar night. Nuclear power sources offer the ability to produce power regardless of the solar illumination condition, but current concepts are limited to around 40 kW total power and a limited number of total sources. Batteries offer the ability to store energy produced during the lunar day that can be used during the lunar night, but the extremely cold temperatures at the lunar south pole or in permanently shadowed regions (<110K) [2] are not compatible with current battery technologies. Regenerative fuel cells offer improved power density as compared to batteries and the ability to operate at lower temperatures, but they also require technology advancements before flight.

There is no current technology that can produce, on its own, the highly reliable and available electric power on the lunar surface needed to establish a sustained permanent presence. Therefore, lunar surface operations will require integrating and utilizing dissimilar power sources and a highly intelligent power controller to fully take advantage of each technology to meet the anticipated power demand (Fig. 3). Integrating dissimilar power sources in a highly distributed architecture is challenging and requires technology advancement.

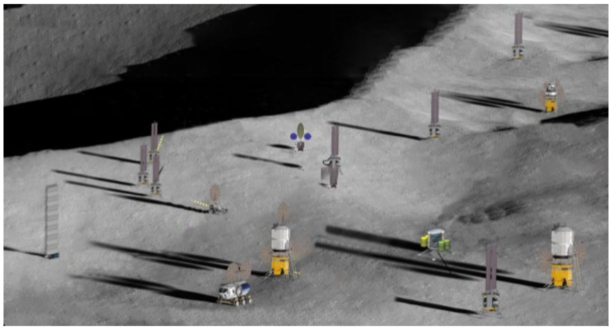

Fig. 3. Concept of distributed power sources with associated loads during lunar south pole operations

This is further complicated by the potential distances required for a Lunar or Martian power system, lack of power interoperability standards and specifications, and the desire to remove human operators from regulating the power system. To help address integration issues, interoperability, stability, and standards, a ground-based surface power development capability known as Adaptable Surface Power Integration and Research (ASPIRE) is being developed. The ASPIRE concept aims to advance critical technologies from early development and demonstrations and help mature them to in-flight demonstrations. The ability to integrate lower Technology Readiness Level (TRL) components and obtain system level performance offers advantages such as simplifying the design change process (design changes become more complex as TRL increases), providing data that can help build advocacy for funding, and identify other critical areas of technology development. Obtaining system data requires building an entire system with low TRL components, which is expensive in both cost and schedule, or a rapid prototype system that can combine hardware and accurate real-time models known as Hardware-in-the-Loop (HIL) systems.

3.1 Hardware-in-the-Loop Testing

Hardware-in-the-Loop systems combine hardware components with accurate real-time models and can come in several different forms. Controller HIL (C-HIL) systems combine control systems with real-time system models that test complex control and protection systems. Power HIL (P-HIL) systems combine partial power hardware with larger system models that test the specific power hardware. The advantage of these HIL systems is that a complete hardware system is not needed to capture how these components will perform within the larger system. The ASPIRE capability serves as both a C-HIL and P-HIL solution for lunar surface power technologies for internal projects, such as the Autonomous Power Controller, the Universal Modular Interface Converter (UMIC), Fission Surface Power, and external projects under Grants including Small Business Innovative Research Grants.

3.2 Power System Technology Development

The goal of ASPIRE is to offer these technologies a larger system environment to integrate and test their lower TRL technologies. Once the technologies have been integrated and demonstrated within the larger system environment, the technology can be further advanced. NASA GRC offers expertise in power system technology development and maturation. In addition, the facilities at GRC include many different thermal vacuum chambers to allowing these technologies to be tested to achieve TRL 5/6.

3.3 ASPIRE Status

The overall ASPIRE capability is in its early development phase with the establishment of the initial facility in progress. As of now, the initial HIL system is being assembled and is planned to test the Space Technology Mission Directorate, Game Changing Development program’s UMIC, which enables long-distance (1-10km) power transmission on the lunar surface. Once the UMIC testing is complete, two additional HIL system will be established and connected with underground power cables. Each HIL location will have the ability to integrate different power hardware and test independently. These three locations can also be connected to form a distributed energy system. Each location can manage its own power and share power via the long-distance cables or grid network. This system aims to mimic a lunar power grid where several lunar locations are connected with a larger grid network. This type of system will be very useful in evaluating individual power hardware components and to develop an overall lunar power management system.

4. Synergies and Partnerships

The MATRICS is intended as a testbed for considerable collaboration between NASA and its partners in industry, academia, and other government agencies. Remote connection of digital twins, as well as remote connection of RF hardware, are envisioned as a long-term capability of the facility. As humanity returns to the moon as a broad coalition under the Artemis Accords, researchers and engineers from a variety of organizations can utilize the capabilities of MATRICS to refine their lunar communications systems and accelerate technology readiness levels.

ASIPRE will allow developers an environment to test power loads and sources in a realistic lunar infrastructure environment. This will provide opportunities for integration of lunar surface power technologies for internal NASA projects, such as the Autonomous Power Controller, the Universal Modular Interface Converter (UMIC), and Fission Surface Power, and external projects such as grants, Small Business Innovative Research projects, and other external partnerships.

In addition, it is envisioned that the MATRICS and ASPIRE facilities can be integrated to test both the communications and power infrastructure in a fully representative environment. This integrated capability would accelerate the development of technologies involved in multiple functions in the lunar surface infrastructure. Hardware providers could leverage their systems to address multiple infrastructure needs, and the facilities at GRC are aiming to provide the capability to test those systems in the most realistic, integrated environment possible.

5. Conclusions

As NASA, its partners, and commercial entities develop integrated systems to enable a sustainable presence on the lunar surface, new ways to test these systems prior to operation will be needed. To ensure the compatibility, interoperability, and reliability of the infrastructure, realistic testing replicating the lunar environment and system-of-systems will be required.

The MATRICS and ASPIRE are two facilities that the Glenn Research Center is establishing to meet these needs. These unique capabilities will allow for integrated hardware testing in environments simulating that of the lunar surface. This will allow for the advancement of TRL for these systems as well as the ability to test hardware as the lunar infrastructure expands and evolves.

References

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