Heliophysics Environmental & Radiation Measurement Experiment Suite (HERMES): A Small External Payload for Gateway with Big Challenges

Joe Burt
NASA Goddard Space Flight Center
8800 Greenbelt Road
Greenbelt, MD 20771
Joe.Burt@nasa.gov

Mark Goans
NASA Goddard Space Flight Center
8800 Greenbelt Road
Greenbelt, MD 20771
Mark.D.Goans@nasa.gov

John Blackwood
NASA Goddard Space Flight Center
8800 Greenbelt Road
Greenbelt, MD 20771
John.R.Blackwood@nasa.gov

Kristen Brown
NASA Goddard Space Flight Center
8800 Greenbelt Road
Greenbelt, MD 20771
Kristen.M.Brown@nasa.gov

Abstract—**Currently scheduled for liftoff in 2024, Gateway will be an outpost orbiting the moon for astronauts headed to and from the lunar surface and will serve as a staging point for deep space exploration. In January 2020, NASA Headquarters contacted Goddard Space Flight Center (GSFC) with a request that they provide a Heliophysics instrumentation package for Gateway. This package would later become known as the Heliophysics Environmental & Radiation Measurement Experiment Suite (HERMES). HERMES consists of four high-heritage instruments – a Miniaturized Electron pRoton Telescope (MERIT), an Electron Electrostatic Analyzer (EEA), a Solar Probe Analyzer-Ions (SPAN-I), and Noise Eliminating Magnetometer Instrument in a Small Integrated System (NEMISIS), which consists of one fluxgate and two magneto-inductive magnetometers. Launching HERMES with Gateway would provide an opportunity to conduct early science experiments on Gateway, but the plan to develop HERMES concurrently with Gateway and launch with the co-manifested vehicle brought numerous technical challenges for the pathfinder payload. HERMES was intended to be a low-cost, tailored Class-D mission, and maintaining that programmatic position proved difficult as the technical challenges grew. The effects of Coronavirus Disease 2019 (COVID-19) were not factored in from the beginning and also created programmatic challenges. This paper will discuss what's being done to overcome the technical and programmatic challenges to put HERMES on track for a 2024 Launch Readiness Date (LRD).**

TABLE OF CONTENTS

1. INTRODUCTION 2
2. SCIENCE 2
3. CHALLENGES 4
4. CURRENT STATUS 9
5. SUMMARY 9
ACKNOWLEDGEMENTS 9
REFERENCES 10
BIOGRAPHIES 10

1. INTRODUCTION

The Artemis program was first introduced in 2017 and called for a United States-led international spaceflight program to land humans on the moon by 2024. NASA formally released the Artemis Plan in September of 2020, and in the plan NASA Administrator Jim Bridenstine said, "Pushing the boundaries of space exploration, science, and technology once again, America is on the verge of exploring more of the Moon than ever before. This new era of lunar exploration is called Artemis. Named after the twin sister of Apollo, she is the Goddess of the Moon, and we are the Artemis Generation." The plan establishes an Artemis base camp on the surface of the moon, which is supported by a lunar orbiting space station called Gateway. The goal was established to land on the moon in 2024, and as the report details, this date was set because it was, "the most ambitious date possible."

A great deal of work goes on behind the scenes before such a release, and as early as December of 2019 NASA Headquarters had already contacted GSFC requesting a Heliophysics instrumentation package to fly onboard Gateway. GSFC was a logical choice with its vast experience producing and managing Heliophysics instruments. However, this seemingly simple request would come with some sizable challenges as requirements became defined.

Gateway (Figure 1) initially planned to launch two separate modules that would be assembled into one module on orbit. These two modules were the Power and Propulsion Element (PPE) and the Habitation and Logistics Outpost (HALO). The contract for the Gateway PPE was awarded to Maxar in May of 2019 with a launch planned in late 2022. It was intended that the HERMES science package would fly with the PPE. This meant that the instrument delivery for integration into the PPE was scheduled for November of 2021, less than two years after the instrument package was requested. The abbreviated development schedule would turn out to be just one of many big challenges faced by the HERMES team.

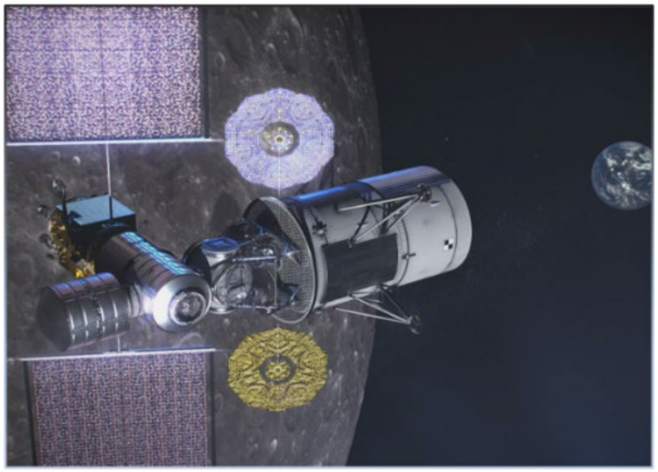


Figure 1. Artist rendition of Gateway

The first challenge was to respond to a request, which arrived five days before Christmas, for a complete instrumentation package proposal in less than four weeks. The proposal would include the instruments, an Instrument Control Electronics (ICE) box to be the single interface to Gateway, and all the required ground support and operations plans. Six different instrument types had been identified as possible candidates to comprise a science and space weather package for HERMES, but only four would be selected.

At that time of the proposal, there were many unknowns about the resources that would be available from Gateway to support a science package. Only the initial measurements were defined; a one half cubic meter volume and 25 kg mass were all that had been set aside for a science package. With this information and a short schedule for both the new proposal and actual delivery of flight instruments, a strawman architecture was created. The instruments would have to be small, lightweight, and very mature. Given this criteria, it didn't take long to narrow the selection of instrument candidates and settle on the four instruments for HERMES.

2. SCIENCE

The primary purpose of the instrument package flown on HERMES is understanding and predicting space weather events and their effects on humans and Gateway. The HERMES Science objectives are to: A) Determine mechanisms of solar wind mass and energy transport; B) Characterize energy, topology, and ion composition in the deep magnetotail; and C) Establish observational capabilities of an on-board pathfinder payload measuring local space weather to support deep-space and long-term human exploration. HERMES will concentrate on understanding the causes of space-weather variability as driven by the Sun and modulated by the magnetosphere. To support human exploration, Gateway will be in a highly eccentric polar lunar orbit with apoapsis of 70,000 km, or 11 Earth radii (RE), south of the Moon, and periapsis in the north at radial distance 3,000 km. Therefore, Gateway and HERMES will be in the solar wind for roughly three weeks out of four. The space weather instrument suite will gather data and enhance our ability to forecast events originating from the Sun that could affect our astronauts on and around the Moon as well as on future missions to Mars.

To accomplish these scientific goals, the HERMES instrument package consists of four instruments:

SPAN-I

The Solar Probe Analyzer-Ion instrument, or SPAN-I (Figure 2), is a direct copy of the instrument that is currently flying on Parker Solar Probe. It is an ion plasma sensor composed of an electrostatic analyzer (ESA) at its aperture followed by a Time-of-Flight (ToF) mass per charge (m/q) spectrometer. The sensor is capable of making ion measurements from two eV to 40 keV, with a delta E/E of seven percent and capable of distinguishing ions by mass per charge.

The SPAN-I sensor weighs ~3.2 kg, uses ~3.5 watts of power, and produces 145 kbps of continuous data. The SPAN-I sensor requires its own electronics box called the Solar Wind Electrons Alphas and Protons Electronics Module (SWEM). The SWEM weighs 1.5 kg, uses 4.5 watts of power and can transfer data at 250 kbps. The SWEM is also a direct copy of the electronics module that is currently flying on Parker Solar Probe.

Figure 2. SPAN-I

MERiT

The Miniaturized Electron pRoton Telescope (MERiT) designed for HERMES is based on the MERiT instrument flying on the Compact Radiation belt Explorer (CeREs) CubeSat that launched into low earth orbit in December 2018. The HERMES MERiT adds a second sensor head to allow measurements in both forward and aft directions simultaneously. The sensor is a stack of solid state detectors (SSDs) behind avalanche photo diodes (APDs). This APD-SSD combination allows electron measurements from 200 keV to three MeV and proton measurements from 10-200 MeV. MERiT science objectives include the study of Solar energetic particle source and acceleration mechanisms, Galactic Cosmic Ray (GCR) long-term variability, pristine tail reconnection studies, and Solar Particle Events (SPEs) event-based alerts and characterization.

The MERiT instrument (Figure 3) is ~10 x 10 x 30 cm, and weighs ~3.5 kg. It uses GSFC's Space Cube Mini-Z+ as its processor, draws ~5.5 watts of power, and produces ~20 kbps of continuous science data. Besides adding a second sensor head, the MERiT electronics were upgraded for the HERMES mission higher radiation environments.

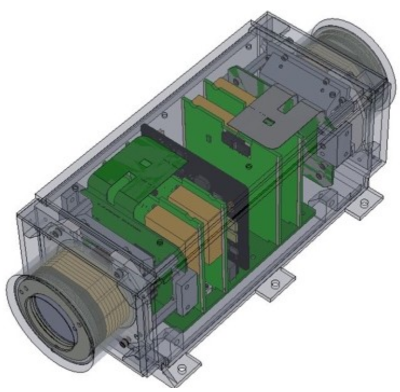


Figure 3. MERiT

EEA

The Electron Electrostatic Analyzer (EEA) gains its heritage from both the large Class C Magnetospheric Multiscale Mission (MMS) and the smaller Class D Dellingr CubeSat mission. EEA uses a microchannel plate detector to create a 360-degree top-hat electrostatic analyzer instrument. EEA measures electrons in the range from 5ev-10 KeV. The EEA Science objectives include determining mechanisms of solar wind mass and energy transport, characterizing energy, topology, and ion composition in the deep magnetotail, and establishing observational capabilities of an on-board pathfinder payload measuring local space weather to support deep-space and long-term human exploration.

EEA (Figure 4) uses ~two watts of power and weighs ~3.8 kg. It produces data at a rate of 150 kbps.

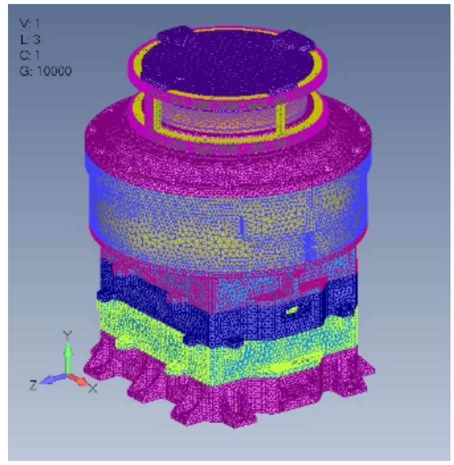


Figure 4. EEA structural analysis

NEMESIS

The Noise Eliminating Magnetometer Instrument in a Small Integrated System (NEMISIS) is a magnetometer package consisting of two magneto-inductive sensors (PNI RM3100), one fluxgate magnetometer and a NEMISIS electronics card. The accuracy, after processing out the noise, for the PNIs is ~1nT at a 10 Hz rate and the accuracy for the fluxgate is ~5 nT. The PNI sensor has heritage from Radio Aurora Explorer I and II and other commercial launches. The fluxgate sensor has heritage from Dellingr and other CubeSat missions. The magnetic measurements they provide will support all the particle measurements. The science of the magnetometer is to determine mechanisms of solar wind mass and energy transport as well as characterize the energy, topology, and ion composition in the deep magnetotail. The NEMISIS sensor package (Figure 5) uses < 1 watt of power and weighs less than 0.5 kg. It generates data at a rate of 2.23 kbits per second.

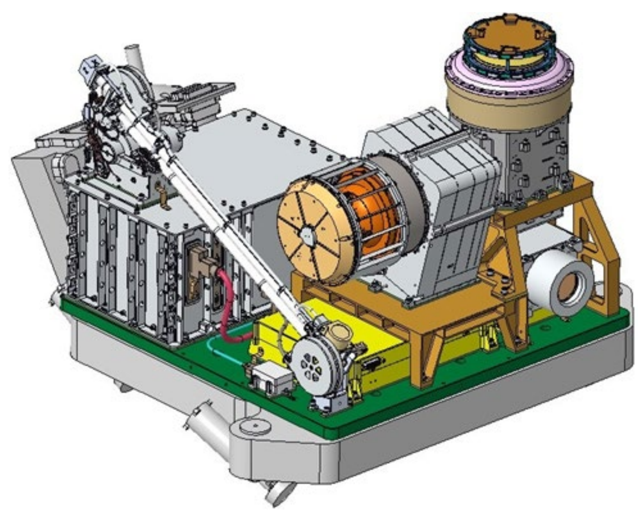


Figure 5. HERMES Platform with NEMISIS fluxgate magnetometer shown on stowed boom

3. CHALLENGES

From the beginning, the HERMES mission faced a number of challenges. It was constrained to fit in a small, half-meter cube envelope and was required to weigh no more than 25 kg. A new boom design for the magnetometer would be required, and for safety reasons it must be able to retract autonomously with power removed. Gateway was at the beginning of development, and the mechanical, thermal and electrical interfaces were not fully defined. To complicate matters the location of the primary interface for the HERMES platform to the Gateway elements, the SORI – Small ORU (Orbital Replacement Unit) Robotics Interface – was undetermined. Furthermore, the Canadian Space Agency was still designing the version of the SORI that would be flown on the Power and Propulsion Element (PPE) and Habitation and Logistics Outpost (HALO) elements, each of which are being developed by different contractors.

Additionally, we would later learn the International Space Station (ISS)-heritage SORI modules were not originally designed for launching on the Gateway elements with a payload directly attached. Instead, the payloads were intended to be brought up on a separate carrier from which the robotic arm on Gateway would be used to detach the payload and install it on the SORI adapters while on orbit. Launching the integrated Payload/SORI on the PPE and HALO elements complicates the stiffness requirements and coupled loads analysis. Adding to this are serious constraints on Field-Of-View (FOV) for solar viewing and severe radiation exposure considerations brought on by slowly raising the orbit through the Van Allen Belts.

Each of these challenges are discussed in more detail below.

Project Management Challenge

The challenges associated with HERMES have shifted significantly since its inception. Initially, one of the greatest challenges was the compressed schedule. As mentioned earlier, the project was originally expected to deliver an integrated payload in November 2021, twenty months after getting notification to proceed in March 2020. As soon as the HERMES project began in earnest, Gateway changed direction on their approach towards launching their initial two modules (HALO and PPE). Instead of two separate launches, with the modules being joined after arrival into lunar orbit, the decision was made to launch a co-manifested vehicle (CMV) on a single commercial Launch Vehicle (LV).

With this new launch approach the HERMES initial design would have to dramatically change to accommodate the slow (~12 month) transit of the CMV to the Near Rectilinear Halo Orbit (NRHO). The associated radiation environment of spending so much time in and out of the Van Allen belts would require a more robust avionics box than originally planned. There would also be new thermal challenges that did not exist with the previously planned rapid transit to NRHO. Also, and perhaps most importantly, with the CMV being a new concept, the PPE and HALO teams had to adapt to significant changes and challenges in their newly joined design. As a result, HERMES was instantly further along in the development process than our Gateway partners, which resulted in HERMES-to-PPE requirements being loosely defined, if at all.

As the location on the PPE matured, it was evident that the desired FOV of the sun and parker spiral were significantly obstructed by the PPE and HALO modules themselves. HERMES management discussed the scientific benefits with Gateway management, resulting in the decision to move HERMES from the PPE to the HALO module. This greatly improved the FOV, but also meant that the HERMES team would now be working with a new module provider. Fortunately, HERMES communications to Gateway personnel go through the Gateway Utilization Office (at Marshall Space Flight Center). This allowed some level of continuity as the switch to the HALO module occurred.

The initial Gateway concept had the PPE and HALO launching without external payloads, which would be added at some point in the future. However, a science gathering opportunity was clearly present, so there was a certain amount of catch up being played to accommodate external payloads. The interface between external payloads and the module (PPE or HALO) is through the SORI, which is supplied by the Canadian Space Agency. Likewise, the SORI was not designed to support payloads during a launch, but instead was meant to have payloads added while in orbit, as mentioned earlier. This resulted in more uncertainty in interface requirements, primarily in the mechanical arena.

In order to control costs, the decision was made to continue with the HERMES development in parallel with the Gateway development, with the understanding that as interface requirements matured there may be instances requiring HERMES to change hardware/software to accommodate Gateway. HERMES is now planned to complete the instrument builds, the Interface Control Electronics (ICE) Box and deployable boom (which supports a fluxgate magnetometer) as well as payload I&T in late 2022. The hardware will then go into storage, awaiting the completion of the SORI and CMV, in preparation for launch. While in storage the HERMES team will draw down to minimal numbers.

The biggest challenge from day one has been the mass allocated to HERMES, 25 kg. This represented a mass margin of less than five percent, and that number has steadily decreased over time as the design matures. HERMES has been assured by Gateway management that mass will be addressed and descoping of an instrument will not be incurred. While encouraging, the mass budget issue is still to be resolved.

Radiation Challenge

In order to maximize the Gateway mass launched to lunar orbit, the mission designers chose to do orbit raising via Solar Electric Propulsion (SEP). This is a popular approach for missions going to geosynchronous orbits. However, in the case of transit to a Near-Rectilinear Halo Orbit (NRHO) this method of orbit raising puts the vehicle in and out of the Van Allen belts continuously for a substantial part of a year. The estimated time to reach the final orbit is using SEP is around 365 days with a total of approximately 100 days in the Van Allen Belt. This provides a radiation dose well above the typical values seen on geosynchronous missions.

Unlike the Gateway electronics, which are somewhat protected inside the HALO and PPE modules, the HERMES electronics are external to the module and largely unprotected from radiation. As a result, very detailed radiation analysis was performed that included the circuit board geometries and relative shielding from one card to another in a worst case, part-by-part analysis. The total dose numbers for HERMES were calculated at >300 krad for exposed areas and <50 krad for areas that were under 100 mils of aluminum. This presented several challenges since the original designs of the instruments were not for such harsh radiation environments. In some cases, shielding was added by thickening the walls near certain parts, but that approach could not be used uniformly for the entire box because there was not enough mass margin to support that conservative approach.

The extended time in the Van Allen Belts also affected payload charging. Now there would not only be a surface charging requirement to be met but also a deep charging requirement. Electrons, ranging from 100 keV to a few MeV, are possible in that environment and would penetrate into boxes and harnesses. Any exposed areas greater than a few square centimeters that were not grounded would be subject to a buildup of charges that could lead to a discharge, arching, and failure. Harness terminations now needed to be addressed and all exposed cables would be required to have transient voltage suppressor (TVS) diodes, or transorbs, and bleed off resistors to control charge buildup.

Additionally, conformal coating of printed circuit boards would now have to be conductive. This is not the typical approach for spacecraft. Although Jet Propulsion Laboratory (JPL) has been experimenting with conductive coatings, generally missions going to harsher radiation environments would add mass for shielding. On the JUNO mission[2] this was done to the extent that a radiation protection vault is built into the spacecraft center. However, in the case of the mass constrained HERMES mission, additional shielding was not an option, and conductive coatings would need to be applied directly to the Printed Wiring Assemblies (PWAs).

Surface resistance measurements of hundreds of Megaohms/cm^2 are required to bleed off charge adequately while still providing enough isolation to prevent interfering with the intended functions of the circuits. The options for readily available static dissipative conformal coating were virtually non-existent, or so it was thought. A candidate material was identified but was risky since it was only in the infancy stage of testing. By pure chance, one of the review members in the instruments design review had knowledge of an industry Controlled Resistance Conformal Coating material. The HERMES project made contact with the industry technical expert and, eventually, was able to obtain sample kits for testing followed by kits to be used for flight application. It became apparent that this particular company had been using this material for many years in similar applications and had thoroughly tested the material via a qualification program. To date, this material has proven to be exactly what HERMES needed to protect the PWAs from the spacecraft charging that will be experienced during the transit into NRHO.

Thermal Challenge

The HERMES platform is mounted to the outside of the HALO module and the SORI design mandates that HERMES be thermally isolated from its attaching structure. This means HERMES cannot conduct heat back into the SORI or HALO. At launch, the SORI platform will be held firmly to the HALO module via four launch locks. However, the intention is to release these launch locks as soon as possible into the mission. While the exact time has not been defined it is expected that this value will be measured in hours not days. This means that HERMES must radiate all of its heat to cold space and consequently when not producing heat it will need significant survival heating to accommodate the areas that will continue to radiate to deep space. The maximum SORI-to-HERMES interface temperatures are not yet confirmed but they are assumed to be -10 to +30 deg C for operations and -20 to +40 deg C for survival.

Fortunately, power provided by Gateway is a less-restrictive resource. In fact, the allocation for a single SORI interface is 500 watts, much more than HERMES will ever need. There is a challenge, though. The heaters need to work on 120 VDC. Typically, spacecraft run at a standard 28 VDC which is fine for reasonably sized vehicles with low power needs. However, large vehicles like a space station need to increase the voltage to reduce transmission losses. This complicates matters in terms of available heaters for low-watt applications. Simple Kapton heaters are no longer readily available at 120 VDC so HERMES had to switch to larger, bulkier wire wound resistors and even then, had to double up to meet the required voltage deratings. The baseplate will have 20 of these larger resistors, the bridge platform will have another 10, and ICE box adds 12 more resistors to bring the total to 42.

Unlike a simple spacecraft, the Gateway station is a literal transformer of space vehicles. Plans for the outyears show close to a dozen different modules and vehicles attached to the station in many different configurations. All of these configurations affect the thermal environment of HERMES, if not by directly blocking its view to the sun then by blocking HERMES radiators view to cold space. The HERMES mission life of two years ends before many of these configurations are implemented, but the payload could encounter these environments in an extended mission life. As a result, additional thermal analysis is being performed to understand thermal impacts in later Gateway configurations.

The NRHO orbit chosen for maximum mass takes Gateway away from the moon to 70,000 km at Apolune by 3,366 km at Perilune. The average orbit period is ~6.56 days. Within this orbit an eclipse of up to ~73 minutes may occur. On the approximately one year spiral out to the moon, eclipse periods can vary from ~17 minutes to 1 hour. Unlike Earth orbits where planetary irradiance is a constant, Lunar IR varies from 5.2 W/m^2 on the dark side of the moon to 1314 W/m^2 (nominal) at the sub-solar point.

The HERMES project continues to work thermal challenges with Gateway. HERMES utilizes a Fine Sun Sensor (FSS), which is located at the elbow of the boom, to improve attitude knowledge near the fluxgate magnetometer. The FSS has very low mass and because it is located on the boom away from the payload mass, it becomes cold quickly. A heater was added to the FSS to address this issue. However, Gateway cannot commit to turning on the survival bus heater power after launch vehicle separation until launch vehicle separation plus five hours. This is much longer than any typical spacecraft launch and early orbit scenario, and it places the FSS outside of its allowable survival limit in as few as a couple of hours. Since no great solutions exist for heating without power, we are applying for a waiver to this requirement.

Mechanical Challenge

From the beginning, HERMES was given a mass requirement of 25 kg maximum. CSA was assigned through a partnership with Gateway the responsibility of providing the interchangeable interface for payloads on Gateway. The SORI concept is an evolution of the heritage ISS Mobile Servicing System's Wedge Mating Interface (WMI) used on multiple payloads. The SORI has a robotic interface for use with the end-effector on the Canadian-supplied robotic arm. After completing its science mission, HERMES will be removed from HALO via the robotic arm on Gateway and placed on a disposal vehicle for launch into a benign disposal orbit.

The SORI interface was designed to handle substantial payloads on orbit, up to 250 kg. However, it was not intended to launch with a payload attached and while mounted to the side of the HALO module. This is further complicated by the decision to launch the Gateway PPE and HALO modules together on a SpaceX Falcon Heavy with a newly designed, extra-large fairing. Since this variant of the SORI has never launched before in this manner, margin must be held back in the loads analysis. This is particularly relevant for acoustics, which remain unknown for this new fairing. As a result, Gateway is asking HERMES to meet the GSFC-STD-7000 Rev B – General Environmental Verification Standard which has loads as high as 14 Grms in every axis.

An additional complication of the SORI interface is that the baseplate is designed to be generic, and it was not possible to obtain a custom hole pattern for HERMES. This meant that an interface plate had to be created to accommodate the hole patterns of the HERMES components and adapt them to the locations of the holes on the SORI. While this might seem like a minor issue, like many things on HERMES, it became more challenging.

To meet the minimum frequency of > 90 Hz for the combined SORI and HERMES package, the HERMES interface plate would require 29 bolts to connect it solidly to the SORI baseplate and create the necessary stiffness. A large number of those bolts would need to be covered by HERMES boxes because of the compact packaging required on the payload half-meter-square baseplate. Even this would have been workable if the SORI baseplate would allow bolts to attach the Payload from the bottom. However, to maintain a standard plate with all future missions, CSA required the bolts to the SORI plate attach from the top. As a result, even with the custom interface plate, the HERMES experiment package must be disassembled down to the box level and reassembled on the SORI platform. This means that after all HERMES environmental testing is complete at the payload level, the tested configuration will be disassembled electrically and mechanically and then reassembled onto the SORI platform. This new assembly will not be environmentally retested at the SORI platform level due to the complication of the four hold-down latching mechanisms and lack of a HALO structural simulator.

The HERMES payload was already mass constrained at 25 kg. To accommodate this newly-required interface plate, the mass allowance was raised by 3 kg to 28 kg. However, HERMES was held accountable for the mass of the plate and fasteners, which put the mass needed at >3.2 kg and left HERMES with a net loss. This took the already taxed mass margin down to effectively zero. Any mass growth from this point forward would jeopardize the instrument complement. Currently, the only thing preventing this is a verbal agreement that additional Gateway mass will be released to HERMES at a future date and the understanding that Gateway intends to maintain full science capabilities. A waiver to the mass allowance has been requested.

The HERMES boom is intended to raise the fluxgate magnetometer as far above the Gateway interface as possible. Since the magnetic field decreases as a function of distance cubed, moving even small distances away from magnetic contamination sources helps. The intention is to get as far away from stray magnetic fields as possible. Therefore, the magnetometer boom is mounted with its baseplate on top of the ICE Box. This serves two functions. First, it allows the extended boom to be further away from HALO without taking the mass penalty that would be required if the boom provided its own stand. Second, by mounting the boom to the ICE Box and placing the elbow joint of the boom on the payload interface plate, it allows the boom masts to use the hypotenuse of the triangle within the confines of this ½ meter cubic volume to get a total boom mast length as long as possible for this minimum mass design.

The real challenge for the boom is to automatically retract upon removal of power. It is simple enough to store the energy for retraction in a spring. However, if the holding force comes from a powered device, it will continue to heat while it continues to hold, eventually risking thermal runaway. This is especially a concern in worst case hot conditions when the radiator is blocked, or the hold mechanism is in direct sun conditions for even short periods. To avoid this, the holding force was placed in a clever latching mechanism that requires no power to hold and instead requires power to unlatch. This means that when power is removed from the payload, power must also be applied to the latching mechanism so that the boom can retract. A second battery solution comes to mind, however, that brings with it complications like additional mass and chemical safety concerns as well as requiring a charger and monitoring. Instead, a simpler solution was sought by using capacitors. Originally thought to be needed, an investigation began into the use of super capacitors. Fortunately, a refined design combined with testing showed that these would not be required. Traditional capacitors could be used albeit more of them were needed. This required only a mild redesign to the ICE box packaging concept.

COVID Challenge

When the COVID-19 pandemic began in March 2020, work at NASA GSFC ground to a halt as the agency paused to assess and implement the necessary safety protocols to continue work on-site. This occurred at the same time that the HERMES project received authorization to proceed. Heritage instruments were chosen for HERMES to meet the rapid development timeline, but now the instrument teams were facing delays before they even began.

Obtaining access to GSFC was initially an arduous process and workforce capacity was limited. HERMES management and instrument teams worked with center management to implement the new safety policies that were established as a result of COVID, and after four to six months delay, the instrument teams were back on-site. Similar working restrictions and delays also hampered our university and industry partners.

COVID drove a new work-from-home culture. This was not an entirely negative development; in terms of integrating the software for HERMES, working remotely was a satisfactory approach. However, it was not without its challenges. First, each instrument needed to provide an emulator to the HERMES platform. This was primarily an electronic interface that matched the instrument electrical ICD with the ICE Box. However, before each instrument team could test their emulator, the ICE Box had to produce four ICE Box emulators and deliver them to the instrument teams to allow them to verify that their instrument emulators were working correctly. One additional ICE Box emulator needed to be built for HERMES software development. All five of these systems needed to be available concurrently in order to maintain schedule.

An emulator lab was set up with all the necessary local network and cloud access controls and firewalls to allow government, industry, and academia to collaborate. Additionally, it would need to be able to remotely power simulators on and off and remotely upload and download software. Just to make things a little more interesting the NEMISIS and boom electronics had to be moved into the ICE Box in order to save the mass of separate housings. This meant designing custom backplanes and other interconnects into the ICE Box housing.

Finally, returning to work at GSFC did not eliminate the challenges of the pandemic. The project still experienced inefficiencies as the center operated at 25 percent capacity and the required personnel and facilities were at times unavailable. Certain functions that needed hands-on-work in labs were eventually staffed, but even then, some of the engineering and oversight parts of the job remained in telework status making communication much slower.

As the challenges to return on-site at GSFC became evident, the HERMES management team made a strategic decision to move key activities to a nearby contractor facility. The Interface Control Electronics (ICE) Box and Flight Software development efforts were moved to a local support contractor facility just off-site of GSFC. The ICE Box was the most challenging aspect of the platform, and moving the work off-site enabled more rapid development.

The world-wide pandemic ignited a global supply chain issue and, as the pandemic continued past the one-year mark, the supply chain issue intensified. HERMES did not immediately feel the impact of supply chain delays since the hardware was in the early phase of development during the first year of the pandemic. However, as the instruments and platform progressed to ETU and flight designs and builds in the summer of 2021, the growing supply chain issue began to have a direct impact on deliveries.

Supply chain challenges surfaced in multiple ways. Fabrication times for instrument and payload parts, especially complex or tight tolerance parts, doubled as fewer machine shops were available and those that were still in business experienced COVID outbreaks. Shipping became unreliable and unsafe, and multiple packages containing critical ground support equipment were mishandled. The ICE Box emulator that was developed for testing with the UCB SPAN-I SWEM was so badly damaged that it needed to be shipped back from the west coast to Maryland for repair and regression testing, incurring a one-month schedule delay.

By far, the most significant impact was the disruption to flight EEE part deliveries. The global semiconductor shortage[3] became widely felt in the aerospace industry, and the challenge was exacerbated for HERMES since the mission's harsh radiation environment demanded high radiation tolerant parts. The instrument and ICE Box design engineers and HERMES parts engineers were in a continuous state of redesign as EEE part lead times grew and historically used parts were unavailable. The ICE Box team received news two weeks before expected delivery that the Command and Data Handling (C&DH) board bus switch controller would be delivered six months later than promised. The delay was untenable, and that circuit of the C&DH board had to be redesigned to design out the delayed part.

Astronaut Challenge

HERMES was originally assigned to be launched on the PPE but, as previously mentioned, was subsequently moved to the HALO module for an improved FOV. This brought with it new requirements. The HERMES module was now in a path near astronaut hand-holds. This meant that the boom must "do no harm" to the astronauts, who would be passing near the HERMES payload. The boom had been designed for retraction to move away from the path of the Canadian robotic arm, which would come up to the station a few years later. Now it would have to be designed not only to get out of the way of an astronaut instead of a robot, but also to survive a kick by that same astronaut.

The boom design team was supplied with generic astronaut boot geometries and representative kick load forces. While this might seem obvious and straight forward to teams that work with astronauts, it is not typical work for spacecraft boom design teams. Fortunately, the size of HERMES is small compared to the size of the boot. This prevents high concentrations of energy into smaller focused areas. Analysis showed that HERMES was able to able to sustain kick loads to all areas except the boom tubes. Since the boom would be retracted whenever the astronauts were near, the solution to ensure it would "do no harm" was to wrap the boom's composite tubes with tape to prevent sharp edges from being exposed in the unlikely event of a serious fracture. This combined with the power-off failsafe retraction of the boom was adequate to quell the initial fears of the safety review board.

Cyber Security Challenge

NASA-STD-1006 Space System Protection Standard is being implemented on HERMES. This new standard was in the process of being approved when HERMES was being conceptualized in late 2019; NASA-STD-1006 was released in October of 2019 with Change 1 released in November of 2020. This new standard is intended to protect space assets from targeted attacks and requires encryption of the command primary and backup links. It also requires reporting of any interference including with the Positioning, Navigation, and Timing (PNT) of the flight system.

Additionally, NASA-STD-1006 references National Institute of Standards and Technology (NIST) Special Publication 800-160, Systems Security Engineering and it is from this document that many questions can arise. Questions like: prove the integrity of the software used to program the ASIC chips in your system even when they were programmed years before and in facilities where you may not have had control over the programming. Prior to 2019 this level of protection was not typically undertaken or funded for most scientific space flight missions. Development of the HERMES Project Protection Plan (PPP) under these new guidelines quickly became a difficult and burdensome task. The HERMES project addressed this by hiring an outside consultant, Aerospace Corp, to assist in the PPP development.

ICE Box Challenge

The ICE box (Figure 6) was a completely new development for the HERMES mission. When HERMES was initially proposed, the Command and Data Handling (C&DH) system was intended to be a very low-cost CubeSat type system. In fact, the cost per copy was so low that the intention was to buy multiple flight copies of the hardware to deliver to the four instruments and Flight Software teams so they could develop and test their flight hardware at their own facilities. This had the added benefit that software development would not have to be separate for flight vs ground simulators.

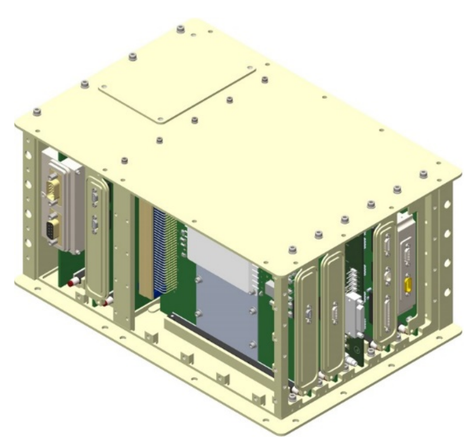


Figure 6. HERMES ICE Box

Unfortunately, this approach fell apart with the Gateway radiation requirements. The harsh radiation environment and the mass-mandated single string architecture of HERMES drove the ICE Box to search for a very radiation tolerant solution. That solution was a Cobham Gaisler GR712RC processor with a dual-core LEON3FT SPARC V8 processor that is latch-up immune and has a Total Ionizing Dose (TID) of up to 300 krad(Si). The ICE Box became a seven card C&DH system of an entirely new design – one of the most capable and radiation-tolerant systems GSFC has ever produced. In order to meet a 21 day outage requirement, the ICE Box has 0.7 TB of onboard radiation hardened memory. To meld between Gateway and the heritage instrument interfaces, the ICE Box has both SpaceWire and Ethernet interfaces as well as a plethora of other serial, parallel, analog and digital interfaces, all custom designed to meet the interfaces of previous spacecraft on which these instruments flew.

Designing a system with this much capability, in such a short time, with constantly changing interfaces was extremely challenging. Not only did the system have to work on the Gateway-provided 120 VDC but the power variability and spike tolerances exceeded anything previously seen on the ISS. The standard DC/DC converters designed by Interpoint for ISS would work, but the associated EMI filters would not. The ICE box team worked simultaneously with Interpoint and on their own custom design to develop a suitable EMI filter. In the end, there was not enough time to use the industry solution and the schedule mandated using the custom design the ICE box team had developed.

4. CURRENT STATUS

The HERMES Project successfully completed a Single Design Review in late October 2021. This review consisted of a PDR-level review for the ICE Box and platform. The instruments were reviewed at the CDR-level in November 2020. With design reviews complete, the instruments, ICE Box, boom and platform have moved into the build phase.

The SPAN-I, MERiT, EEA, and NEMISIS instruments are in the process of fabricating flight hardware and have completed building nearly all flight PWAs. Flight board interface testing and instrument assembly is ongoing, with instrument functional and environmental testing occurring in early spring 2022. Instrument deliveries are planned for late spring 2022.

The magnetometer boom Engineering Model (EM) assembly is complete and is currently going through qualification testing. The flight build and assembly will begin when boom EM qualification testing is complete. The ICE Box Engineering Test Unit (ETU) PWA builds are nearly finished following Engineering Development Unit (EDU) PWA testing. The HERMES payload mechanical and thermal designs are also nearing completion with some assumptions being made pertaining to Gateway and SORI interfaces that are not fully designed. These assumptions are closely coordinated with Gateway personnel so surprises down the road should be minimized.

The ground system development is also progressing well. A Gateway In A Box (GIAB) is not likely to be completed in time for HERMES use during environmental testing. GSFC-built Gateway first circuit hardware will be fabricated to allow verification testing to be performed until the GIAB is of sufficient maturity.

The HERMES team will begin payload integration and testing at GSFC in early summer 2022. The project is currently on track for a Pre-Environmental Review (PER) in August 2022 with a delivery to Gateway in January 2024 for a launch in November 2024.

5. SUMMARY

HERMES has been a challenge from the start. With an approximate 15-month development schedule in support of an originally-defined 2022 launch, a quick reaction, streamlined development process was required. The original challenge was for Artemis to go to the moon as quickly as possible along with needing a Gateway Lunar station as soon as possible. The next challenge was to get there with all of the required mass to the moon. This led to a lower energy NRHO at the moon and a slow SEP propulsion spiral out to the moon, which in turn led to some extreme radiation and thermal challenges. Next was the challenge of combining two large modules into a single new launch vehicle. This led to some difficult mass, vibration, and acoustic challenges. Additional challenges were provided by new cyber security standards being implemented, and by astronauts who apparently like to kick things. Throw in a worldwide pandemic, the inability to work onsite, plus supply chain interruptions and things start to get interesting.

Selection of instruments and components with proven spaceflight design and the availability of required parts were key in order to maintain the aggressive schedule. The HERMES team was able to divide and conquer a complex project development with a quick response by utilizing a diverse team of government, academia, and industry small contractors. Despite all these challenges, HERMES is currently on schedule for a November 2024 launch.

ACKNOWLEDGEMENTS

The authors would like to thank the HERMES Team who have remained dedicated and persistent in uncertain and dynamic times, and who have overcome great challenges during the HERMES payload development.

REFERENCES

[1] National Aeronautics and Space Administration, *Artemis Plan*, 2020 https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf

[2] Juno Mission, NASA Web site: https://www.nasa.gov/mission_pages/juno/spacecraft/index.html

[3] Vakil B, Linton T. 2021 Feb 26. Why We're in the Midst of a Global Semiconductor Shortage. Harvard Business Review. https://hbr.org/2021/02/why-were-in-the-midst-of-a-global-semiconductor-shortage

BIOGRAPHIES

Joe Burt *is the Deputy Program Manager Technical for the Explorers and Heliophysics Projects Division at NASA's Goddard Space Flight Center (GSFC). This includes oversight of several missions at various stages of development including, the Heliophysics Environmental & Radiation Measurement Experiment Suite (HERMES).*

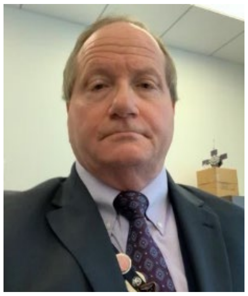
Previous missions include: Ionospheric Connection Explorer (ICON), Imaging X-Ray Polarimetry Explorer (IXPE), Galactic/Extragalactic Ultralong Duration Balloon (ULDB) Spectroscopic Terahertz Observatory (GUSTO), X-Ray Imaging and Spectroscopy Mission (XRISM), Interstellar Mapping and Acceleration Probe (IMAP), and Solar Orbiter Collaboration (SOC). Previous missions include Mars Atmosphere and Volatile EvolutioN (MAVEN), Sample Analysis at Mars (SAM), Origins, Spectral Interpretation, Resource Identification, Security-Regolith Explorer (OSIRIS-Rex), Lunar Atmosphere and Dust Environment Explorer (LADEE), Solar Dynamics Observatory (SDO), Magnetospheric Multiscale (MMS), Transiting Exoplanet Survey Satellite (TESS), Global-scale Observations of the Limb and Disk (GOLD), Neutron star Interior Composition ExploreR (NICER), and Parker Solar Probe (PSP). Prior to accepting this position, Joe was the chief engineer for the GSFC Lunar Program Office, which developed and managed the Lunar Reconnaissance Orbiter (LRO). Prior to that, he served for more than six years as the Chief Mission Systems Engineer for the JWST. Joe has been at GSFC for 37 years.

John Blackwood *is the Project Manager for the Heliophysics Environmental & Radiation Measurement Experiment Suite (HERMES), having joined the mission as the Deputy Project Manager.*

Previously John was the Chief Safety & Mission Assurance Officer (CSO) for the Plankton, Aerosol, Cloud ocean Ecosystem (PACE), Joint Polar Satellite System (JPSS), Magnetospheric Multiscale (MMS) Mission, and Radiation Belt Storm Probes (RBSP). Prior to working in the realm of Safety & Mission Assurance, John spent about 10 years within the Materials and Engineering branch where he developed a laser interferometer system used by JWST to measure ultra-low coefficient thermal expansion of composite structural layup samples down to less than 20 K. He also developed a Kelvin Probe force microscopy capability which was used to measure surface potential for the Laser Interferometer Space Application (LISA) project. John has been at NASA's Goddard Space Flight Center for 32 years.

Kristen Brown *is the Deputy Project Manager for Heliophysics Environmental & Radiation Measurement Experiment Suite (HERMES). Prior to HERMES, Kristen was the Deputy Project Manager for Hazard Detection Lidar, a new technology development at NASA's Goddard Space Flight Center (GSFC) that will enable safe and precise landing on the moon. Kristen served as the Deputy I&T Manager and Product Development Lead for the Laser Communication Relay Demonstration (LCRD) Mission.*

During her 20 year career at GSFC, Kristen has contributed to numerous in-house spacecraft developments in the areas of Attitude Control Systems, propulsion, and electronics packaging, resulting in the successful launch and operation of Magnetospheric Multiscale (MMS), Global Precipitation Measurement (GPM), Solar Dynamics Observatory (SDO), Lunar Reconnaissance Orbiter (LRO), and Space Technology-5 (ST-5).



***Mark Goans** has served as Deputy Program Manager within the Explorers and Heliophysics Projects Division of NASA's Flight Projects Directorate at Goddard Space Flight Center (GSFC) since 2010. There, he has provided programmatic guidance and institutional support to the Interstellar Mapping and Acceleration Probe (IMAP), Parker Solar Probe (PSP), and Van Allen Probes Projects, as implemented by the Johns Hopkins University Applied Physics Laboratory. He has also supported strategic projects including HERMES, which is managed by GSFC for flight on NASA's Lunar Gateway.*

Mark has served as the Standing Review Board Chair for the Aquarius and Soil Moisture Active- Passive (SMAP) projects, as implemented by the Jet Propulsion Laboratory. He currently serves as Standing Review Board Chair on the Climate Absolute Radiance and Refractivity Observatory (CLARREO) Pathfinder and NASA Jupiter Icy moons Explorer (JUICE) projects.

Mark holds a bachelor's degree in mechanical engineering from the West Virginia University and a master's degree in engineering administration from the George Washington University.