WHITE PAPER

Leveraging commercial technology to
enable on-orbit sensor fusion

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Space and Beyond: Commercial Technology and the Space-Based Data Chain

Space-based electronics are critical components of the satellites that help us maintain our national defense advantage, and the rise of sensor technology that can gather extreme amounts of data is creating an opportunity to secure this advantage long term. Accomplishing this goal will require space microelectronics that can properly collect, store, process, interpret, and transmit a large amount of information—all while overcoming environmental conditions such as intense electromagnetic radiation and size, weight, and power (SWaP) limitations. This white paper discusses these challenges and explores how commercial technology companies and the aerospace and defense industry are merging their expertise and innovations to help the government organizations meet this moment.

MICROELECTRONICS AND THE FUTURE OF SPACE

The evolving space technology landscape

When the Soviet Union launched Sputnik 1 in October 1957, space suddenly became a very real domain for U.S. national defense, as shown by the creation of both DARPA and NASA the following year. Sputnik sent radio signals back to Earth for 22 days on its three silver zinc batteries before burning up in the atmosphere exactly three months after its launch. Satellites and other space vehicles have come a long way since the beach-ball-size first artificial satellite.

Today's satellites have an average life span of 5 to 15 years and can do far more than send and receive radio signals. They are now used for broadband internet, TV, observation, weather, intelligence, communications, security, defense, environmental health, and more. The electronic components used in these satellites and their on-orbit sensor processing subsystems have traditionally come with a high financial cost and long development timeline. This is due to their roots in government programs, the need for them to meet complex performance and testing requirements, and the large amount of testing required for every customized, mission-specific component.

However, this technology landscape is evolving because the availability of commercial off-the-shelf (COTS) microelectronics is quickly removing this roadblock to space. By applying advanced, secure packaging and upscreening techniques to COTS parts, space-ready components that meet extreme environmental requirements can now be developed and deployed at much lower costs and in much shorter time frames. This lowered entry barrier is enabling a satellite- and space-based data boom, opening the door to new missions and applications. For example, it has been especially helpful for the creation of satellite constellations such as SpaceX Starlink, which uses numerous connected and similar satellites and components to create one internet network.

Modern space vehicles and the technology data chain

Modern space vehicles are relatively small for their powerful capabilities. For example, LEO satellites, which live at a low orbit height of 180 km to 2,000 km, typically range in size from a washing machine to a compact car, and defensive weapons such as hypersonics are scores smaller than the multistory-tall ICBMs of the past.

The advanced components on these modern vehicles include sensors capable of detecting radio frequency and microwave signals; visible, ultraviolet, and infrared light; gas emissions; and more. The big data collected by these sensors present an enormous opportunity to increase and strengthen our intelligence and technological capabilities. For example, continual access to this data can help provide greater situational awareness and decision-making abilities, whether the mission is hypersonic weapon threat mitigation, improved scientific data collection to address challenges like climate change, or on-orbit AI to improve image accuracy.

Capturing, storing, processing, and transmitting this information through a secure data chain connecting satellites, ships, planes, ground control, and more requires a complex system of onboard microelectronics and processing technology. This includes IR and microwave sensors, storage data recorders, RF to digital conversion, digital to RF reconversion, low-latency processors and memory, all of which must be durable and reliable under the toughest of conditions: space.

JADC2/EDGE STORAGE AND PROCESSING

The Department of Defense Joint All-Domain Command and Control (JADC2) concept is meant to provide our armed services and allied partners with a vastly improved ability to capture, collect, make sense of, and act on information across all domains. As such, microelectronic technology like processors, rugged storage, and system-on-a-chip (SoC) devices are getting a lot of attention for bringing new capabilities like artificial intelligence and machine learning to the edge.

From a technological perspective, the satellite microelectronics the space data chain relies on are some of the most vital pieces of this vision. This is the catalyst behind DARPA's Blackjack program, which is creating its own LEO constellation—similar to SpaceX Starlink —to connect technology across all domains and keep it connected via a reliable long-term network. Accomplishing this will require replacing the current approach of using satellites as repeaters with an entirely new one: a data chain of connected satellites with space-based microelectronics that can perform onboard capture, digitization, processing, storage, and transmission of data. Additionally, the availability of commercial technology means Blackjack can integrate different bus types within these satellite designs so they can be reused for purposes beyond the network.

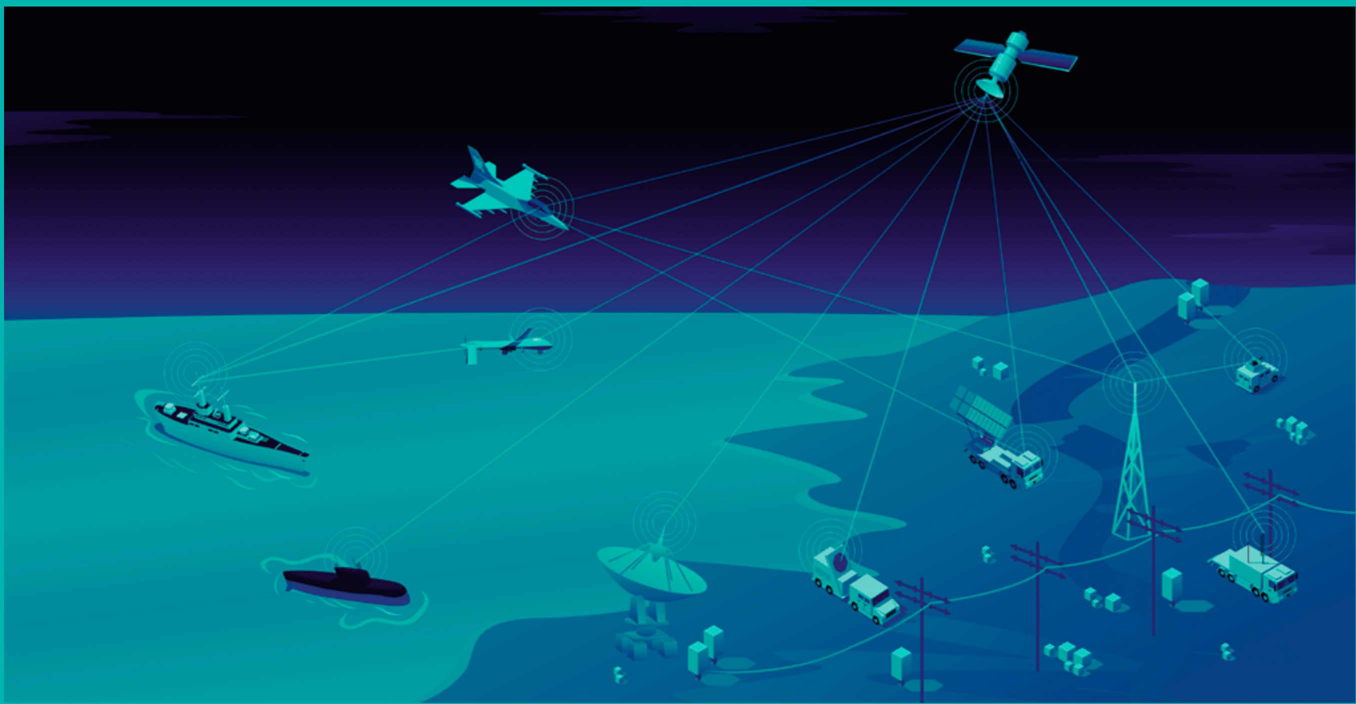


Figure 1

JADC2 is a concept directive from the Pentagon to create a wholly connected military in which information flows quickly, securely, and accurately across sea, land, air, cyberspace, and space

ELECTROMAGNETIC RADIATION AND OTHER ENVIRONMENTAL COMPLEXITIES

The space domain's benefits are clear and unmatched, but it comes with environmental factors and obstacles that developers of earthbound technology do not face. This, combined with the same ever-evolving requirements and user demands seen in the commercial and defense worlds, has created the need for technology that is fast, small, low power, reliable, cost-efficient, and durable. The following sections discuss and examine these environmental difficulties.

- **Solar flares and electromagnetic radiation**
Space vehicles and their electronics are continuously subject to radiation in the form of waves or small subatomic particles, the latter of which is of a particular concern to spacecraft. Subatomic particle radiation, which includes protons and electrons, and other radiation can cause issues with space-based systems in several ways:

  – **Single-event upset**
  A single-event upset, or SEU, is caused by a single ionizing particle—such as ions, electrons, or photons—that strikes sensitive areas of a microelectronic device. This free charge creates a state change and can directly change data; for example, it can change a one to a zero or vice versa in computer code, which is also called a bit flip. Although this soft error does not cause permanent damage to electronics, radiation environment electronics must include advanced error correction code algorithms to counteract the issue.

  – **Single-event effects**
  Other single-event effects (SEEs) include single-event latch-ups (SELs), a short circuit that can occur in a silicon chip that requires a power cycle to correct; a single-event gate rupture (SEGR), where a single particle strike results in a breakdown and subsequent conducting path to the gate oxide of a metal oxide semiconductor field effect transistor (MOSFET); and a single-event burnout (SEB), where a particle strike induces a high current state, resulting in catastrophic failure. There are also instances where particles will erode a component over time, leading to its eventual failure.

  – **Geomagnetic storms**
  Large geomagnetic storms caused by the sun have the potential to heavily damage not only space vehicle electronics but also those across the globe. Take, for example, the Carrington Event of 1859, the most intense geomagnetic storm in recorded history. Auroras were seen around the world, including at the equator, and telegraph equipment sparked, caught on fire, or maintained an electrical charge even after being disconnected from the grid. It is estimated that a storm of this magnitude today would cause worldwide blackouts or widespread electrical disruptions as well as global infrastructure and personal property damage.

- **Signal saturation and the space-link-ground triad**
Satellites are not always in constant communication with their network or ground stations. For example, signal saturation, or the overuse of certain available frequency bands, can result in desired bandwidths and the ability to downlink being available only at certain times. The space-link-ground triad of communication can also cause the same issue because transmitters and receivers are not always within range of each other. To counteract this inability to transmit data—whatever the cause—extraordinarily reliable and radiation-tolerant data storage hardware is required to keep the data secure and accurate until the transmission is possible.

- **Non-feasibility of fixing or upgrading existing satellites**
Open architecture and modular hardware designs allow for the use of COTS parts and reduce the time and cost it takes to develop systems for all domains. Another advantage they typically bring is the ability to physically replace electronics and other subsystems with newer and more advanced plug-and-play parts. However, upgrading or fixing existing satellites in this manner is not feasible. That is because performing such a procedure in the space domain on a vehicle like a satellite—for example, the five spacewalks undertaken to fix the Hubble Space Telescope—is an extremely complicated and expensive task reserved for the most important and expensive missions. Therefore, the space components must work the first time and every time throughout the satellite's operational life.

- **Dangers of space junk and other material**
Electromagnetic radiation and other light and energy sources are not the only environmental threat. LEO space junk comprising material from previously functioning vehicles like satellites and from naturally occurring objects such as micrometeoroids and orbital debris (MMOD) can stay in low Earth orbit from 5 to 400 years. They can also range in size from a school bus to a grain of sand, collide with each other to create more debris, and result in extreme damage when making contact with an object while traveling at hypervelocity speeds as high as 7.7 km/s. This means shielding on space vehicles and even astronaut suits are not limited to just antiradiation requirements; it must also protect against extreme physical impacts.

EARTH SURFACE MINERAL DUST SOURCE INVESTIGATION (EMIT)

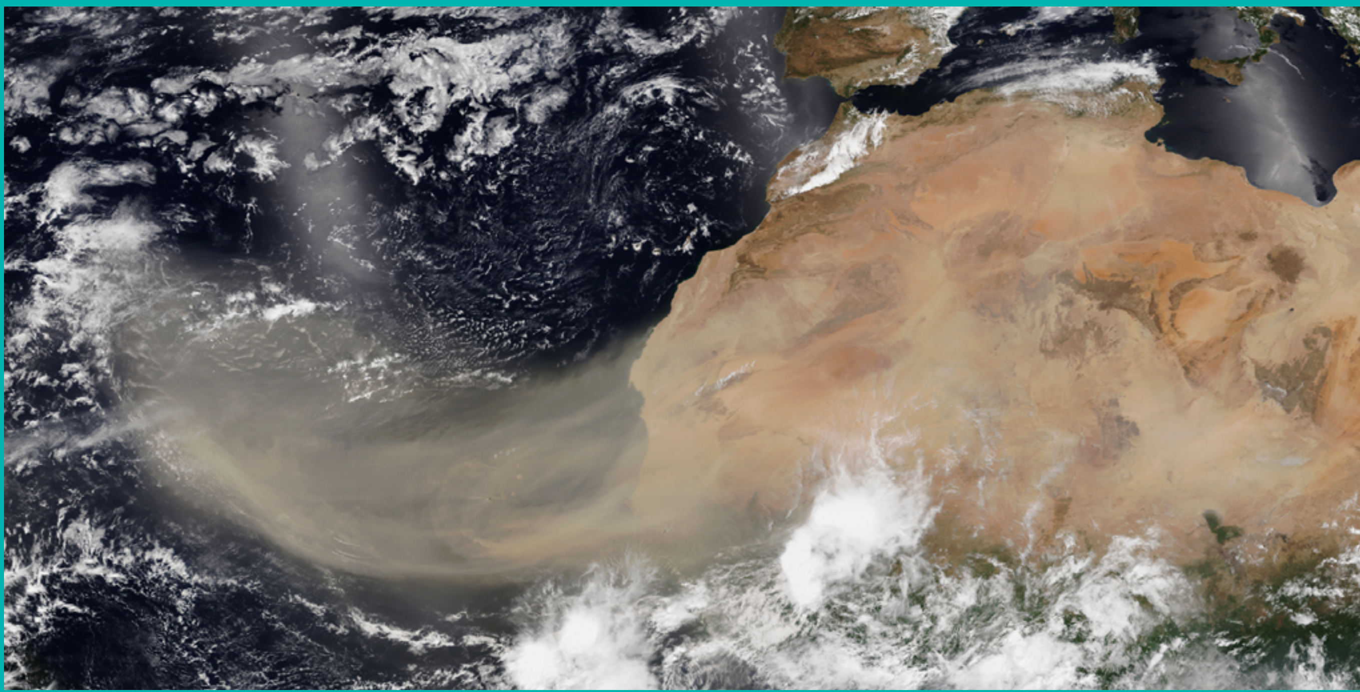


Photo courtesy by NASA/JPL-Caltech

Numerous intangibles can affect the Earth's weather. To better understand the effects of one in particular—mineral dust—NASA kicked off the Earth Surface Mineral Dust Source Investigation (EMIT) mission in 2022 by sending an Earth-imaging spectrometer to the International Space Station.

The EMIT mission maps the surface mineralogy of dust source regions on Earth. The data will improve forecasts by helping us better understand the role of mineral dust in the warming or cooling of Earth's atmosphere. For example, strong winds can move air particles, such as mineral rock dust, all over the world, even from one continent to another. By accurately mapping the composition of areas that produce this mineral dust, the mission will also ultimately help advance the understanding of dust effects as well as patterns on Earth and in human populations, now and in the future.

EMIT is the first instrument to use this new NASA-invented imaging spectroscopy technology. To capture, store, and process the large amounts of high-quality data collected by the spectrometer, NASA JPL chose radiation-tolerant solid-state data recorders (SSDRs) from Mercury Systems. The high-performance RH3440 SSDRs used in the EMIT spectrometer, each with a large storage capacity of 480 GB, enable reliable on-orbit sensor data processing and precise long-term operation in harsh environments like the Earth's atmosphere.

Its architecture and design also allow the mission to transfer significantly more data in less time, making the overall mission more efficient. For example, the program delivered more than 5,000 data sets in its first seven months, each with a spectral fingerprint containing more than 1.4 million spectra.

METHANESAT: USING TECHNOLOGY TO ENABLE A SUSTAINABLE FUTURE

Photo courtesy by Ball Aerospace

Humankind produces 80 million tons of oil and gas methane emissions every year, most of which are a direct byproduct of natural gas production. While C02 has the largest net negative effect on climate change due to the massive amount we produce, the threat posed by methane emissions is just as real: it is 80 times more powerful at warming the Earth than C02 over a 20-year timeframe. As the world looks to move to greener technology and a more sustainable future, it is increasingly important to better understand the impact and source of these harmful emissions. To help with this effort, the Environmental Defense Fund is launching the MethanSAT mission.

MethaneSAT, at the cost of $90 million, is the world's most advanced methane tracking satellite and is capable of measuring methane emissions anywhere on Earth. The satellite will find emissions and regularly monitor emission sources, particularly within the regions that account for at least 80% of global oil and gas production. This will increase accountability for natural gas production sites, and limit or stop the ability of some sites to emit methane directly into the atmosphere by illegally bypassing methane byproduct burn-off. The mission's analytics will also shorten the time it takes to receive actionable methane emissions data from weeks or months to a matter of days.

Because MethaneSAT's state-of-the-art spectrometer processes data at a rate higher than can be telemetered in real time, the spectrometer's primary developer chose Mercury Systems to provide SSDR solutions. The Mercury SSDR in the satellite—the RH3480—has a store-and-forward feature that maintains data integrity while also delaying the transmission of data to ground stations when dedicated links are unavailable. Each SSDR also features 480 GB of industrial-grade flash memory and is designed for long-term reliability in the harshest of radiation-intense environments.

With the ability to store, process, and transmit this large amount of data, MethaneSAT will support publishing publicly available data that can help reduce methane emissions, illuminate ecological change, and protect natural resources.

NEW SSDRs ARE ADVANCING THE SPACE DATA CHAIN

Modern space data systems rely on what are known as solid-state data recorders. SSDRs are designed to withstand harsh, radiation-intense, SWaP-constrained environments and include advanced integrated error correction algorithms to minimize the effects of radiation without depending on heavy physical shielding. These data recorders are the heart of the space data chain—the overall procedure of capturing, digitizing, processing, and transmitting data requires secure and reliable data storage. Thanks to the integration of COTS-based parts, this crucial piece of the data chain is now seeing significant improvement.

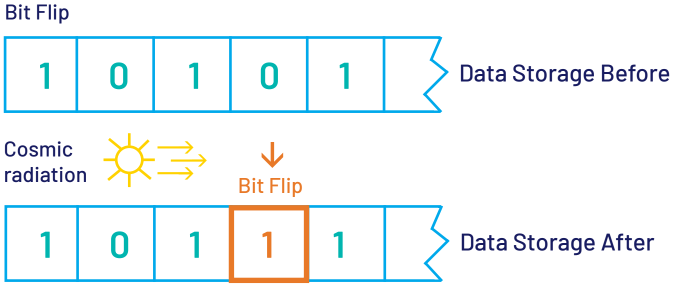
Large storage capacity in a small form factor

Next-generation data recorders use little power and are small, lightweight, and high performing. They can store and provide data that is captured, processed, and transmitted by other data chain components such as sensors and processors. For example, the space data recorders produced by Mercury Systems are in a 3U VPX form factor, which is roughly the size of 100-page book or the width of two cell phones. Compatible with existing architecture, the recorders use NAND flash, have storage capabilities ranging from 440 GB to 4.5 TB, and are performance equivalent to today's fastest gaming SSDs. They are also designed to operate under the most extreme circumstances to ensure data is accurate and reliable.

Harsh environment protection and error correction

Space is a demanding environment for microelectronics. Modern SSDRs use radiation- and temperature-tolerant components and materials. They are shielded with material such as aluminum, which is effective against small amounts of radiation but adds weight. Error checking and correction (ECC) software is also used, specifically for memory and data storage components. ECC software detects and corrects bit flips, or the changing of zeros to ones (and vice versa) that can occur when a device is struck by a single ionizing particle. Depending on the space data recorder and the software's level of sophistication, ECC can correct either single-bit errors or multiple errors across storage blocks.

Bit Flip

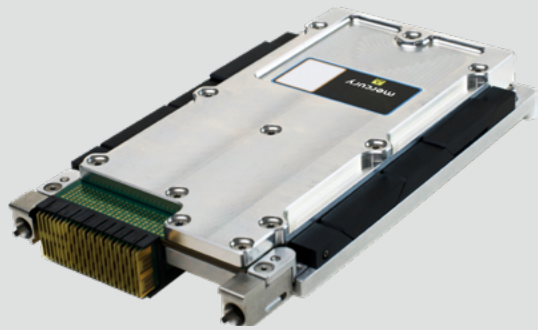


NAND chips and built-in redundancies

SSDRs and almost every other space microelectronic now use NAND flash for storage and memory. As opposed to dynamic random-access memory (DRAM) chips, which require constant power to retain data, NAND chips do not require constant power and their power can be turned off during any downtime between data collection and data transmission with no ill effects. However, NAND chips also naturally produce several errors. For example, when data is written and then read back, there are small errors; but there are mechanisms to fix these errors such as complex math algorithms. Although NAND flash was also not initially made for use in space, it has undergone thorough testing, is proven to work, and its benefits, issues, and limitations are well-understood.

To manage the errors and ensure proper capacity throughout the lifecycle, Mercury Systems includes large amounts of NAND chips in its SSDRs—more than required—and screens them first to ensure they are functioning properly. These extra NAND chips are used to provide redundancy in the case of the failure of other NAND chips and to aid in ECC. These devices also undergo power cycles when possible, which itself can fix issues with any NAND chips suffering errors. These techniques, in collaboration with ECC, provide SSDRs with highly reliable defect mitigation.

MERCURY SYSTEMS DATA RECORDER SOLUTIONS



Space storage solutions must be low latency, capable of capturing large amounts of data and resilient against harsh environmental factors such as radiation and vibration. Mercury Systems provides such solutions for a range of missions—LEO satellite launch vehicles, scientific payloads, and terrestrial environments with the potential for radiation exposure.

The following Mercury data recorder solutions all have microprocessor-free and code-free designs, built-in radiation tolerance, triple-redundant RTG4 controllers, drive erase times under 30 seconds, and horizontal Reed-Solomon ECC for data error correction. This line of data recorders is also capable of withstanding extreme vibrations and temperatures (rail temps of -40°C to +72°C and storage temps of -55°C to +105°C) and includes the option of two different fast VPX connectors: Smith's KVPX or TE Multigig RT-2.

RH3440 3U VPX

Storage: 440 GB

Form Factor: 3U VITA 48.2 VPX

Interface:
- SRIO, 4 lane or 1 lane at 3.125 Gbps

Performance:
- 1,160 MB/s (9.28 Gbps), 4 lanes
- 250 MB/s (2 Gbps), 1 lane
- Fill time of 6.3 minutes (4 lanes)
- Single-pass error correction

Operating modes:
- Data recorder: sequential writes/random reads
- HA mode: random reads/ writes using UltraBlocks

Weight: < 620 grams

Power (2 voltages required):
- 12 V (10.8 V to 12.3 V) / 3.3 V (3.25 to 4 V)
- 6 W idle, 12–14 W write

RH3480 3U Twin Port VPX

Storage: 480 GB

Form Factor: 3U VITA 48.2 VPX
- For other form factors, contact sales

Interface: Twin SRIO ports in 3U form factor
- Dual port (8 lanes, 1 host) at 2,300 Mbps
- Dual host (4 lanes, 2 hosts) at 1,160 Mbps

Performance:
- 2,300 Mbps SRIO (18,400 Mbps)
- 1,160 Mbps dual-host mode
- Fill time of 3.5 minutes (1 host mode)
- Single-pass error correction

Operating modes:
- Data recorder: sequential writes/random reads
- HA mode: random reads
- MRAM for host: 512k words

Weight: < 650 grams

Power:
- Single 5 V supply (4.5 to 5.5 V)
- 8 W idle, 24 W write at full speed

RH304TNM6S 3U 4.5 TB

Storage: 4.5 TB

Form Factor: VITA 78 3U VPX
- For other VPX form factors, contact sales

Interface: Twin SRIO ports in 3U form factor
- Dual port (8 lanes, 1 host) at 2,000 MB/s
- Dual host (4 lanes, 2 hosts) at 1,160 MB/s

Performance:
- SRIO at 3.125 Gbps
- 2,000 Mbps SRIO (16,000 Mbps)
- 1,160 Mbps dual-host mode
- Fill time of 37.5 minutes (dual-port mode)
- Dual-pass error correction

Operating modes:
- Data recorder: sequential writes/random reads
- HA mode: random reads/writes
- MRAM for host: 512k words

Weight: < 650 grams

Power:
- Single 5 V supply (4.5 to 5.5 V)
- 8 W idle, 24 W write at full speed

SUMMARY

The evolution of microelectronics in the space data chain is driven by advancements in system packaging and the availability of high-performing COTS hardware. This has shortened the development-to-deployment timeframe and has lowered costs as compared to traditional systems, which is particularly beneficial for developers and manufacturers of LEO systems because they have a shorter operational life span and their networks may require numerous satellites. It is also driving the transition to space data chain technology that is smaller, faster, and more powerful—from data recorders to RF microwave amplifiers to frequency converters to power supply cards, direct RF converters, flash memory, custom multichip modules, processing cards, and more.

The replacement of traditional space technology with these new microelectronic solutions will greatly benefit government and industry assets such as LEO satellites, radiation-hardened weapons, aircraft, ground-based command and control, launch vehicles, and space exploration missions. However, it is of utmost importance that this technology is reliable and designed to overcome SWaP restraints, cosmic radiation, extreme temperatures, and other space-based factors.

Mercury Systems has more than 40 years of history providing quality space-based products—including an RF microwave product line that has flown, without failure, on every Mars rover mission and a data recorder currently on board the International Space Station. In 2022, Mercury opened a new 150,000-square-foot facility in Phoenix, Arizona, dedicated to state-of-the-art custom microelectronics packaging. This facility is accredited by the DMEA and will provide secure packaging for the Department of Defense's State-of-the-Art Heterogenous Integrated Packaging (SHIP) program. Our facilities and history of innovation—combined with key partnerships with commercial leaders such as Intel, AMD, Micron, and Nvidia—allow Mercury to offer space-level solutions based on commercially developed technology with shorter deployment times and reduced costs.

Read more about space-based data recorders or other microelectronics from Mercury Systems, or contact us at space.qualified@mrcy.com.

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