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# **COSMIC**

## **CONSORTIUM FOR SPACE MOBILITY AND ISAM CAPABILITIES**

### **UNITED STATES ISAM INTERFACE ECOSYSTEM 2025 REPORT**

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## 1. Enabling the Future of Space Sustainability: A Review of Modern Servicing Interfaces

The U.S. commercial in-space, servicing, assembly, and manufacturing (ISAM) interface ecosystem has transformed from concept to operational reality over the past five years. From 300+ DogTag interfaces deployed in orbit, to Orbit Fab’s 2024 achievement of the first commercially flight-qualified refueling interface, the technical foundation exists for a servicing economy. However, this progress reveals a critical challenge: while individual technologies reach flight readiness, the absence of a comprehensive standardization framework threatens to fragment the very marketplace these innovations aim to serve. The transition from demonstration to commercial viability is accelerating.

U.S. Space Force (USSF) procurement of refuellable architectures, NASA’s Artemis infrastructure development, and commercial operators seeking mission extension capabilities signal that the serviceable satellite market is moving toward revenue generation. As the ecosystem matures, achieving interoperability across these solutions will be essential for long-term economic sustainability. The industry faces a narrow window to establish consensus standards before market fragmentation becomes entrenched. Success stories demonstrate what becomes possible through collaborative development. Communications technologies show that open standards accelerate market growth: Core Flight System supports over 40 missions<sup>i</sup>, while TESAT’s optical terminals maintain leadership through standardization participation.<sup>ii</sup>

Electrical interfaces benefit from eight major U.S. manufacturers who successfully transitioned from NASA-centric production to commercial markets, demonstrating American competitiveness in radiation-hardened components and optical transceivers. Structural interfaces show rapid innovation with multiple companies achieving flight testing within compressed timelines. However, the proliferation of proprietary interfaces creates a standardization crisis with profound implications. A servicer equipped with one docking standard cannot easily service satellites designed for another, fundamentally limiting market addressability. USSF’s August 2024 decision<sup>iii</sup> to place two refueling port designs under interface standards—establishing configuration control rather than selecting a single standard interface—reflects the practical challenge of managing convergence while enabling near-term adoption.

Dual standards may enable near-term procurement but risk creating incompatible ecosystems. Unlike communications protocols, which are updatable through software, mechanical interface decisions lock in decades of architectural constraints. The standardization challenge extends beyond technical specifications to safety frameworks and operational protocols. Current regulations developed for traditional operations do not adequately address ISAM scenarios involving physical spacecraft contact, propellant transfer, and potential debris generation. The Space Safety Coalition’s Best Practices<sup>iv</sup> and ISO 24330<sup>v</sup> represent important steps, but comprehensive frameworks governing multi-party interfaces and repeated servicing operations remain under development.

Without clear standards, insurance underwriters struggle to assess risk, operators hesitate to design servicing-compatible spacecraft, and investors question market scalability. The absence of standardization creates a coordination problem where each stakeholder’s rational decision to wait for others collectively prevents market formation. Technical gaps compound the standardization challenge. The industry lacks standardized blind-mate electrical connectors with flight heritage, comprehensive characterization of repeated mate/demate cycles under space conditions, and defined robotic manipulation compatibility



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parameters. These gaps translate directly to programmatic risk for servicing missions and represent areas where coordinated development could unlock currently uncertain capabilities.

The path forward requires three parallel efforts within a critical timeframe. First, accelerate consensus standardization through CONFERS, AIAA, and Space Safety Coalition working groups to establish baseline interoperability frameworks. Standards developed within three years can influence USSF procurement and Artemis implementation; standards beyond this window risk becoming academic exercises. At the same time, standardization efforts must be informed by flight heritage and premature convergence on unproven designs carries its own risks. Accelerating flight demonstrations is therefore as critical as the standards process itself. Second, coordinate demonstration missions that validate critical capabilities while building flight heritage that reduces perceived risk. Third, foster supply chain resilience through manufacturing automation that compresses current 16- to 24-week lead-times for space-grade components. Investment dynamics and government program stability significantly influence standardization pace.

Recent program cancellations eliminated substantial development funding, increasing the importance of industry-led standardization that persists across government transitions. U.S. companies hold technical advantages in radiation-hardened optics, established manufacturing infrastructure, and government relationships. However, these advantages face temporal limits as international competitors advance their capabilities. The competitive window for establishing U.S.-led interface standards extends approximately three to five years before international alternatives mature and potentially establish competing standards for lunar operations.

This white paper documents which technologies have achieved commercial viability, which gaps require coordinated attention, and where collaboration yields greatest impact. The emerging ISAM marketplace depends not just on individual technologies achieving flight qualification but on a coordinated ecosystem where interfaces enable rather than constrain mission possibilities. The United States possesses the technical foundation to lead global ISAM interface standardization. Success depends on recognizing that interface standardization is not merely a technical problem requiring engineering solutions but a coordination challenge requiring collaborative leadership and recognition that individual success depends on collective ecosystem viability.

The current moment represents the opportunity to establish standards governing space operations for decades and also the risk that fragmentation could prevent the ISAM marketplace from achieving its economic potential.



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## 2. State of Interfaces: Fluid Transfer

Maturity of in-space fluid transfer technologies is nearly polar, with large manned systems like the International Space Station (ISS) having years of history of successful refueling operations, while uncrewed and small satellites have had just a handful of successful fuel transfer demonstration missions. This section focuses on the emerging technologies for unmanned and small satellites. With recent increased interest and investment in ISAM, several promising on-orbit refueling (OOR) solutions are being developed; however, few have achieved full maturity as integrated systems. VACCO developed the Orbital Express refueling coupler (TRL 9) which was successfully demonstrated in space in 2007.

Orbit Fab's Rapidly Attachable Fluid Transfer Interface (RAFTI) Service Valve was first demonstrated on Orbit Fab's Tanker-001 Tenzing Fuel Depot, which launched to low Earth orbit (LEO) in June 2021. The interface achieved TRL 8 status based on flight qualification of the hardware in 2024, representing the first commercially available refueling interface to reach this milestone; however, no fluid was transferred on orbit during the Tanker-001 mission. Moog is developing the Fluid Transfer Coupling (FTC) through Northrop Grumman for the HALO module originally intended for the Gateway program. The Goddard Space Flight Center (GSFC) FTC was a separate concept (PDR-level prototype only). OSAM-1 developed the Cooperative Servicing Valve (CSV), flight-qualified for hydrazine, which was slated to demonstrate a number of ISAM technologies before it was canceled in early 2024.

### 2.1 Industry Gap Analysis

For storable propellants (e.g., hydrazine, MON-3, etc.), the sub-systems essential to perform OOR are mostly well-developed and mature, with the exception of leak detection, high pressure compressors, accurate quantity gauging and flow measurement, and liquid-free propellant tank venting. Cryogenic fluid transfer represents a fundamentally less mature domain. Key gaps include cryogenic fluid management for long-duration storage and infrastructure development such as fuel depots and established logistical chains. However, while some OOR technologies have been successfully demonstrated in space, many critical systems still lack flight heritage which increases risk for missions wanting to utilize the technology.

### 2.2 Market Context and Adoption Trends

The market for fluid transfer interfaces mostly revolves around on-orbit refueling for mission extension and dynamic space operations. With space becoming a more crowded and contested environment, the ability to maneuver satellites without reducing their mission life is increasingly more useful and necessary for many missions. There may also be business cases for refuelable space tugs operating LEO and geostationary Earth orbit (GEO), and between LEO and lunar orbits. Another important market for OOR is launch vehicle and transfer vehicle refueling for mid-trip range extension.

The ability to refuel after reaching orbit around the Earth and before heading farther afield in the solar system is a key enabler for lunar and Martian missions, especially those carrying high-mass payloads. While there is little heritage of OOR for uncrewed satellites, the space industry and various governments are actively developing OOR capabilities, and several upcoming missions are slated to further advance the state of practice. SpaceX is planning to demonstrate OOR of their Starship rocket, transferring cryogenic fuels between two Starships in orbit around the Earth. Blue Origin plans to provide OOR



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capabilities to client satellites with its Blue Ring space mobility satellite, which is slated to launch in 2026.

The U.S. government is driving OOR capability development and adoption, with USSF’s recent announcement that its upcoming RG-XX program (RFP released in January 2026<sup>vi</sup>) will mandate that solutions can be refueled in space.

### 2.3 Technical Limitations

The primary technical challenges facing developers of OOR capabilities reside in testing and validation of integrated systems.

Notable barriers include leakage testing, where terrestrial vacuum chambers must be able to accept contamination from leakage events; the need for testing in microgravity for long enough durations to allow for sloshing and other fluidic behaviors to damp out; the toxicity of many propellants used in satellite propulsion systems (note: high pressure gases and xenon have different testing considerations), which precludes testing in manned space stations and creates barriers to testing on the ground; and limited capabilities to accurately test rendezvous, proximity operations, and docking (RPOD) behavior on the ground. Additionally, electrostatic differences between docking spacecraft, as well as cold-welding in vacuum are concerns that must be mitigated and validated prior to launch.

All these challenges suggest the need for in-space testing and demonstration, which imparts large cost barriers to system qualification and slows capability maturation.



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### 3. Technology Reference Sheet: Fluid Transfer

#### 3.1 Orbit Fab's Rapidly Attachable Fluid Transfer Interface (RAFTI)

##### 3.1.1 Executive Summary

RAFTI represents a standardized approach to space-based fluid transfer operations. RAFTI builds on NASA GSFC technology and was designed for the harshest orbital regimes and for refueling the largest space assets. Orbit Fab, headquartered in Lafayette, Colorado, leads the development with the interface specification defined by a group of 30 companies. The RAFTI Service Valve (RSV) on the passive side was first demonstrated on Orbit Fab's Tanker-001 Tenzing Fuel Depot, which launched to LEO in June 2021. The interface achieved TRL 8 status based on flight qualification of the hardware in 2024, representing the first commercially available refueling interface to reach this milestone.

##### 3.1.2 Technical Considerations

###### 3.1.2.1 Technology Readiness and Flight Status

Technology Readiness Level: TRL 8 based on flight qualification of hardware (on-orbit fluid transfer not yet demonstrated); cooperative docking and refueling interface (low pressure variant; Class 2D high pressure variant under development).

RAFTI is the first spacecraft refueling interface to achieve flight qualification.

###### 3.1.2.2 Physical and Performance Parameters (based on Class 2A configuration):

- Mass: 0.52 kg (1.15 lb)
- Pressure Ratings: 650 psig MEOP for low pressure variant, 3000 psig for Class 2D variant
- Operating Temperature Range: Hardware operates from -40 to 80°C unwetted, with survival range of -60 to 100°C
- Service Life: 15-year operational life capability in LEO and GEO environments

###### 3.1.2.3 Interface Architecture

Two valve cores support transfer of two independent fluids, compatible with bipropellant systems. RAFTI uses a pintle valve design, where the pintle in RSV is actuated via the active coupling half within the Orbit Fab GRIP system. The Grappling Resupply Interface for Products (GRIP) is the active portion of the refueling system that connects to and actuates the passive RAFTI valve.

- Fluid Compatibility Matrix:
  - Low-pressure Applications: MMH, UDMH, water, H<sub>2</sub>O<sub>2</sub>, methanol, kerosene, green monoprops, isopropyl alcohol, HFE, N<sub>2</sub>O



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- High-pressure Applications: Nitrogen, helium, xenon, krypton
- Temperature Range: Operation between -40°C and 120°C
- Safety Architecture: Three inhibits against leaks, triple seal design, passive retractable covers protecting sealing surfaces. External leakage rates less than  $1 \times 10^{-6}$  scc/s, configurable for normally open or normally closed operation.
- Docking Mechanics: Direct docking capability for equivalent masses up to 1,000kg at approach velocities ranging from 0 to 25mm/s. Accommodates misalignment of  $\pm 10$ mm in X & Y axes and  $\pm 5$  degrees in X, Y, & Z axes.

### 3.1.3 Integration and Implementation Considerations

- Spacecraft Modifications: Implementation requires specific keep-out zones, alignment marker placement, and thermal management systems. Integration necessitates surveying fiducial placement within 0.1mm accuracy in all axes.
- Ground Support Equipment: RAFTI Ground Coupling (RGC) provides ground infrastructure interface for launch-site fueling operations, enabling dual-use functionality.
- Operational Environment: Designed for operations from LEO to GEO and cislunar space, with qualification testing per GSFC-STD-7000 standards. VACCO's Orbital Express Refueling Coupling 1.

## 3.2 VACCO's Orbital Express Refueling Mechanism

### 3.2.1 Executive Summary

VACCO designed and delivered the Orbital Express (OE) refueling mechanism, which featured 1/4" and 3/8" hydrazine couplings and successfully demonstrated satellite refueling in orbit. VACCO fuel couplings have flown on many space missions, including Apollo, NASA's Lunar Lander, and the Space Shuttle, among others. VACCO was able to leverage this past experience when developing the Orbital Express Refueling Coupling for the OE mission for DARPA and NASA. OE successfully demonstrated in-space refueling in 2007.

### 3.2.2 Technical Considerations

#### 3.2.2.1 Technology Readiness and Flight Status

Technology Readiness Level (TRL): 9

DARPA and NASA's Orbital Express mission launched in 2007 and demonstrated in-space refueling through a series of autonomous and semi-autonomous operations conducted by two spacecraft: ASTRO (Autonomous Space Transport Robotic Operations), the servicing satellite, and NEXTSat (Next Generation Serviceable Satellite), the client satellite. During the mission, ASTRO approached NEXTSat, connected to it via robotic arm, docked, and transferred propellant to and from NEXTSat's fuel tank. The



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mission successfully demonstrated on-orbit satellite refueling capabilities, demonstrating the ability to extend a client satellite’s operational lifespan.

The demonstration included multiple docking and undocking cycles, the transfer of hydrazine fuel between the satellites, and the exchange of batteries and other components.

### 3.2.2.2 Physical and Performance Parameters

- Mass: Contact provider for information.
- Dimensions: Contact provider for information.
- Ratings: Contact provider for information.
- Interface Architecture Compatibility Matrix (supported systems/fluids/materials): Hydrazine; contact provider for more information.
- Safety Architecture (safety features and redundancy): Contact provider for information.
- Operational Mechanics (connection and operation methods): Contact provider for information.

### 3.2.3 Integration and Implementation Considerations

- System Modifications (required changes): Contact provider for information.
- Ground Support Equipment: Contact provider for information.
- Operational Environment (qualified conditions): Contact provider for information.

This section focuses on mating interfaces specifically. Complete refueling systems require additional technologies such as compressors, quantity gauging and flow measurement systems, and pumps, which are beyond this document’s scope.

## 3.3 Moog’s Fluid Transfer Coupling (FTC)

### 3.3.1 Executive Summary

The Moog Fluid Transfer Coupling (FTC) is an in-space fuel transfer solution using passive and active halves to secure fluid connection and sealing. Moog is developing the FTC through Northrop Grumman for the Gateway program HALO module, with planned demonstration alongside the NASA Docking System. The GSFC FTC was a separate concept developed to PDR level (prototype only). OSAM-1 separately developed the Cooperative Servicing Valve (CSV), which was flight qualified for hydrazine use and installed on the spacecraft before mission cancellation in early 2024, which was slated to demonstrate a number of ISAM technologies before it was canceled in early 2024.



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### 3.3.2 Technical Specifications

#### 3.3.2.1 Technology Readiness and Flight Status

Technology Readiness Level: TRL 6

The FTC is currently un-flown.

#### 3.3.2.2 Physical and Performance Parameters

- Mass: 5.2kg (2.7kg per half)
- Dimensions: Contact provider for information
- Maximum Design Pressure: 207 bar (xenon/pressurant), 138 bar (MMH/NTO/N2H4)
- Proof: 310 bar (xenon/pressurant), 207 bar (MMH/NTO/N2H4)
- Burst Pressure: 414 bar (xenon/pressurant), 276 bar (MMH/NTO/N2H4)
- Internal Leakage: < 0.001 scc/s GHe (gaseous helium)
- External Leakage: < 0.001 scc/s GHe (gaseous helium)
- Flow Rate: 13.6 kg/h (xenon), 34 kg/h (H2O)
- Pressure Drop: <1 bar at flow rates above

#### 3.3.2.3 Interface Architecture

The FTC is a two-piece, stainless-steel design using passive and active halves to secure connection and sealing.

- Fluid Compatibility: Xenon (Xe), hydrazine (N2H4), monomethylhydrazine (MMH), nitrogen tetroxide (NTO or N2H4).
- Safety Architecture (safety features and redundancy): Contact provider for information.
- Operational Mechanics (connection and operation methods): Contact provider for information.
- Mate/De-mate cycles: 25

### 3.3.3 Integration and Implementation Considerations

- System Modifications (required changes): Contact provider for information.
- Ground Support Equipment: Contact provider for information.



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- Operational Environment (qualified conditions): Temperature: -25°C to 77°C operational; contact provider for more information.

### 3.4 Altius' Cryo Coupler

#### 3.4.1 Executive Summary

The Cryo Coupler from Altius (a subsidiary of Voyager Space) is a fluid-transfer interface specifically designed for cryogenic fluids. It uses electro-permanent magnets (EPMs) to make a temporary connection between two tanks, allowing transfer of super-cold liquids or gases between the tanks in space or on the ground.

Altius completed a Phase I NASA Small Business Innovation Research (SBIR) in 2016 and a follow-on Phase II SBIR in 2020 to develop the Cryo Coupler.

#### 3.4.2 Technical Specifications

##### 3.4.2.1 Technology Readiness and Flight Status

Technology Readiness Level: Contact provider for information.

Planned flight demonstration on LOXSAT mission; launch scheduled for early 2026.

##### 3.4.2.2 Physical and Performance Parameters

- Mass: Contact provider for information.
- Dimensions: Contact provider for information.

##### 3.4.2.3 Interface Architecture

- Compatibility Matrix (supported systems/fluids/materials): Liquid oxygen (LOX), liquid hydrogen (LH2); contact provider for more information.
- Safety Architecture (safety features and redundancy): Contact provider for information.
- Operational Mechanics (connection and operation methods): Magnetic latching using EPMs; contact provider for more information.

#### 3.4.3 Integration and Implementation Considerations

- System Modifications (required changes): Contact provider for information.
- Ground Support Equipment: Contact provider for information.
- Operational Environment (qualified conditions): Contact provider for information.



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## 3.5 SpaceWorks Enterprises' FuseBlox

### 3.5.1 Executive Summary

SpaceWorks Enterprises' FuseBlox is a mechanical interface for ISAM which has core docking, power-transfer, and data-transfer capabilities with a modular add-on for fluid-transfer capabilities (FuseBlox Flow for storables and CryoFlow for cryogenics). The Flow and CryoFlow add-ons can be configured on a per-channel basis with up to 4x fluid channels per one FuseBlox connector. Since this section is focused on fluid transfer interfaces, the information presented here is specifically for the fluid-transfer module, not the mechanical or electrical modules.

### 3.5.2 Development History

SpaceWorks began development of FuseBlox in 2019 with a DARPA Phase 2 project aimed at aggregating several small rideshare satellites into a larger, persistent GEO platform. The Air Force Research Laboratory (AFRL) funded the detailed design and ground qualification of the FuseBlox Core to reach TRL 6. In 2022, FuseBlox Flow was chosen for a USSF Phase 1 SBIR program and then selected for a subsequent Phase 2 effort. NASA has also backed Phase 1 and the ongoing Phase 2 for FuseBlox CryoFlow through its IGNITE SBIR program. The next step is to conduct a flight demonstration of FuseBlox Core and complete the formal ground qualification of both Flow and CryoFlow. Multiple benchtop prototypes have already validated the concept.

### 3.5.3 Implementation Case Studies

Although FuseBlox has not yet flown, its design is based on specifications from NASA standards as well as planned and current space missions. The DARPA study on persistent space platforms heavily influenced the requirements for FuseBlox, especially concerning in-space assembly functions. Additionally, SpaceWorks' mission analysis and design efforts for various government and private clients have iteratively shaped use cases and features in FuseBlox. Recent assessments for deorbit-as-a-service, lunar surface exploration infrastructure, and future commercial LEO destination providers have further refined the design specifications based on actual missions.

### 3.5.4 Technical Specifications

#### 3.5.4.1 Technology Readiness and Flight Status

Technology Readiness Level: FuseBlox Core is TRL 6, FuseBlox Flow is TRL 5, and FuseBlox CryoFlow is TRL 4.

FuseBlox has not flown yet. Initial flight for FuseBlox Core (passive half) is expected in Motiv/NASA Fly Foundational Robots mission in 2027. Initial flight for FuseBlox Flow or CryoFlow is expected no earlier than 2027.



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### 3.5.4.2 Physical and Performance Parameters

- **Mass:** For the active half, which is necessary for fluid transfer, FuseBlox is 2.6 kg with approximately 1.0 kg additional per fluid channel. The passive half is estimated at 0.5 kg Core + 0.5 kg additional per fluid channel.
- **Dimensions:** FuseBlox has a length of 20 cm in all active configurations. For the Core configuration, the cross-sectional dimensions are 10 x 10 cm (totaling 2U), with an additional 4 cm on each side for each fluid channel (e.g., 18 cm x 10 cm for 2 channels).
- **Ratings Contact:** MEOP for CryoFlow demo: 75 psig. MEOP for Flow demo: 500 psig (operationally up to 6K psig).

### 3.5.4.3 Interface Architecture

- **Compatibility Matrix (supported systems/fluids/materials):**
  - FuseBlox CryoFlow: LOX, LH2, LCH4, common inert pressurants.
  - FuseBlox Flow: High-test peroxide (HTP), water, GN2, hydrazine (N<sub>2</sub>H<sub>4</sub> , MMH), ASCENT, GEM-3, GHe, GOx, xenon.
- **Safety Architecture (safety features and redundancy):** The majority of the safety and flow processing functionalities are delegated to the servicer spacecraft's feed system. As an independent interface, FuseBlox augments the servicer spacecraft's compliance with standards such as AFSPCMAN 91-710. Additionally, several proprietary features currently under development allow for emergency disconnection of two FuseBlox interfaces. FuseBlox Flow and CryoFlow are both designed as a dry-break interface, ensuring no leakage upon separation, and meets the typical space-grade GHe leak qualification standards.
- **Operational Mechanics (Connection and Operation Methods):** SpaceWorks has developed a patented docking architecture for Flow and CryoFlow, allowing for precise mating once the FuseBlox Core is docked. The FuseBlox Core features a significant docking offset tolerance, eliminating the need for additional guidance, navigation, or control (GNC) requirements to mate with the Flow/CryoFlow interface after the Core is docked.

### 3.5.5 Integration and Implementation Considerations

- **System Modifications (required changes):** FuseBlox's design philosophy for commercial off-the-shelf variants is to provide only what is necessary to perform the function and do so safely. The Core, Flow, and CryoFlow models have sufficient yet minimal, plug-and-play features like essential mechanism power drivers and fault detection/mitigation to minimize SWaP while ensuring compatibility with virtually any servicer spacecraft. Advanced integrated functionalities like navigation devices, spacecraft guidance, flow throttling, and flow sensing are managed by the servicer spacecraft. Nonetheless, SpaceWorks has the in-house expertise to customize designs or add features as needed.



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- Ground Support Equipment: The FuseBlox unit can be operated utilizing standard software on a Linux-based laptop and interfaces with harnesses that adhere to standard pinout configurations. SpaceWorks supplies a test graphical user interface (GUI) for standalone testing and a software development kit to integrate command and control functionalities with the servicer spacecraft's compute devices.
- Operational Environment (qualified conditions): FuseBlox is rated to typical LEO and GEO environments and lifespans. Docking performance specifications are export-controlled and available from SpaceWorks.

### 3.6 Atomos' Refueling Connector

#### 3.6.1 Executive Summary

The Atomos refueling connector is most likely a proprietary docking and refueling interface designed for autonomous orbital transfer vehicle operations, supporting a 10,000-kg payload transport capacity. Atomos Space was founded in 2018 to provide space-resident orbital transfer vehicle services. In April 2025, Katalyst Space Technologies acquired Atomos Space to integrate the technology into a combined in-space servicing platform.

#### 3.6.2 Technical Specifications

##### 3.6.2.1 Technology Readiness and Flight Status

Technology Readiness Level: The refueling connector launched in March 2024 during the Mission-1 flight test aboard SpaceX's Transporter-10, likely placing the interface at approximately a TRL 7-8. Prior to flight, the company reported that propulsion, rendezvous, docking, and refueling systems were space-qualified.

The Singing Astronomer demonstration mission deployed two spacecraft: the Quark-LITE orbital transfer vehicle and the Gluon client spacecraft, to perform rendezvous, docking, refueling, and orbital transfer demonstrations. The mission encountered issues such as spacecraft tumbling and communication glitches, and refueling and orbital transfer had not been demonstrated as of early 2026.

##### 3.6.2.2 Physical and Performance Parameters

The interface is capable of connecting 10,000-kg payloads for transport. There is no publicly available information regarding specific mass, dimensions, or flow rate specifications for the refueling connector itself.

##### 3.6.2.3 Interface Architecture

The interface is designed to support automated refueling operations between Quark and Gluon support vehicles, though specific valve architecture details are not publicly available.



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- **Compatibility Matrix:** The Mission-1 demonstration was intended to validate ammonia electric propulsion and in-space refueling. There is no publicly available information on specific propellant types beyond ammonia nor material compatibility specifications.
- **Safety Architecture:** There is no publicly available information on safety architecture.
- **Operational Mechanics:** The Quark OTV is designed with a Split Stewart Platform robotics system for capture and control of unprepared client spacecraft. Operations are designed for fully autonomous execution without requiring external robotic arm assistance.

### 3.6.3 Integration and Implementation Considerations

- **System Modifications:** There is no publicly available information on specific servicer spacecraft modifications required to accommodate the refueling interface on client vehicles.
- **Ground Support Equipment:** There is no publicly available information on propellant loading hardware, ground test fixtures, or launch site interface equipment.
- **Operational Environment:** There is no publicly available information on qualified thermal ranges, vacuum exposure limits, vibration qualification levels, or radiation tolerance specifications.
- **Data protocols:** There is no publicly available information on data protocols.

## 3.7 Northrop Grumman's Passive Refueling Module (PRM)

### 3.7.1 Executive Summary

The Northrop Grumman Passive Refueling Module (PRM) represents a government-owned standardized refueling interface for military satellites, comprising passive docking hardware and intake valve mechanisms that mate with an Active Refueling Module (ARM). Space Systems Command (SSC) has been studying the PRM since 2021 and in January 2024 selected it as the first preferred refueling solution interface standard for use across SSC satellites.

### 3.7.2 Technical Specifications

#### 3.7.2.1 Technology Readiness and Flight Status

**Technology Readiness Level:** The PRM has completed a critical design review level of maturity and is preparing for a test campaign to become qualified, likely placing the interface at TRL 6-7.

The PRM will be integrated on the company's Mission Robotic Vehicle (MRV), providing a passive refueling port for potential future on-orbit refueling demonstrations. The PRM completed critical design review in 2024 and is undergoing qualification testing, with first flight planned for the Mission Robotic Vehicle launch in 2026.

Separately, in April 2025, USSF awarded Northrop Grumman the Elixir refueling payload program contract to design, build, and integrate a refueling payload onto a space vehicle and demonstrate refueling



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with a demonstration client satellite. The Elixir program, targeting a 2026 GEO refueling demonstration, represents the most likely near-term on-orbit exercise of the PRM.

### 3.7.2.2 Physical and Performance Parameters

The companion Geosynchronous Auxiliary Support Tanker (GAS-T) will carry up to 1,000 kilograms of hydrazine fuel and deliver it to client satellites on demand. There is no publicly available information on the mass, dimensions, pressure ratings, or flow rates of the PRM interface itself.

### 3.7.2.3 Interface Architecture

The PRM includes both an intake valve mechanism and a docking system to allow a refueling spacecraft to inject the fuel. The ARM and the PRM are designed to work together as the active and passive halves for docking and refueling. The system employs a male-female architecture, with the PRM serving as the passive receiver port and the ARM providing active connection and propellant transfer capabilities. There is no publicly available information on specific latching mechanisms or valve types beyond this basic architecture.

- **Compatibility Matrix:** The system is designed for hydrazine propellant transfer in geosynchronous orbit. SSC intends to make the technical specs of the PRM module available to the industry at large, enabling other manufacturers to produce compatible hardware. There is no publicly available information on PRM's compatibility with other types of propellants.
- **Safety Architecture:** There is no publicly available information on safety architecture.
- **Operational Mechanics:** The MRV will likely utilize cameras and lights to enable monitoring of refueling operations status, with robotic arms available for correcting any docking anomalies. The PRM is designed for cooperative operations where both client and servicing vehicle participate in the docking sequence.

### 3.7.3 Integration and Implementation Considerations

- **System Modifications:** Future satellites could be designed with an interface like the PRM to receive fuel while in space. The PRM was put under SSC engineering configuration control as a government-owned design, allowing satellite builders to incorporate the standard into new spacecraft designs. There is no publicly available information on specific structural mounting requirements, propellant system modifications, or avionics integration details.
- **Ground Support Equipment:** There is no publicly available information on GSE.
- **Operational Environment:** The system is designed for operations in geosynchronous orbit, and the system will likely undergo environmental testing to validate its performance there. There is no publicly available information on specific operational environment limits.
- **Data protocols:** There is no publicly available information on data protocols.



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## 3.8 Enduralock's OneLink

### 3.8.1 Executive Summary

Enduralock's OneLink is an integrated satellite connector that combines mechanical latching sufficient for in-space transport, simultaneous data and power transfer, and fluid transfer capability in a single standardized interface.

In 2022, Enduralock was awarded an Orbital Prime Phase I STTR in collaboration with Southwest Research Institute to develop a multi-contact electrical and mechanical connector to assemble satellites on orbit from modules. The OneLink connector evolved from this work, and in June 2025, Enduralock was selected for a SpaceWERX Direct-to-Phase II SBIR contract aimed at using the OneLink connector system to enable modular in-space servicing.

Space Ocean Corporation intends to adopt Enduralock's passive male receive port as a core interface across its fluid delivery and servicing ecosystem, and Enduralock is under NDA with several other companies to support applications from orbital research platforms to refueling depots.

### 3.8.2 Technical Specifications

#### 3.8.2.1 Technology Readiness and Flight Status

Technology Readiness Level: The interface is currently at TRL 5, with ground qualification testing underway.

The OneLink interface has not yet flown. Ground qualification testing is in progress under the 2025 SpaceWERX contract, with flight demonstration anticipated in the 2026-2027 timeframe. Flight hardware is not yet manifested on a specific mission, though the passive male port is available for immediate design integration into assembly, integration, and test activities.

#### 3.8.2.2 Physical and Performance Parameters

The passive male connector envelope measures 15 in x 12 in x 8 in with a mass of 9 lbs, while the active female connector measures 15 in x 12 in x 7 in with a mass of 12 lbs. The system accommodates permissible radial misalignment of +/- 1 in diametrically, permissible yaw misalignment of 10 degrees biaxially, and permissible roll misalignment of 20 degrees. The interface is designed for Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) Class, ESPA Grande Class, and medium-sized satellites. The docking preload between connections is 1,500 lbs, with permissible loads including maximum static bending of 14,000 lbs, maximum compressive load of 30,000 lbs, and maximum torsional load of 50,000 lbs (structural components can be redesigned to increase these values).

#### 3.8.2.3 Interface Architecture

The OneLink employs a male-female architecture with spring-loaded soft dock latching mechanism arms on the male connector to constrain satellites from separating upon contact. The system uses a ball-pin connection for hard docking, with the female cone axially translated to establish secure connection. For fluid transfer, the system uses separate interfaces for fuel and pressurant transfer.



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- **Compatibility Matrix:** The fluid transfer interface supports propellants including ASCENT, hydrazine, and water through one nozzle, with a separate nozzle designed for pressurants like helium. Tubing and valve materials include Ti6AlV and stainless steel.
- **Safety Architecture:** The docking process employs a 3-stage sequence: soft dock assisted by passive alignment features and spring-loaded latching arms; hard dock through ball-pin connection engagement with electrical data connections established; and finally preload application before fluid line connection. Custom-designed spring-energized seals and internal face seals provide sealing to prevent leakage.
- **Operational Mechanics:** During soft dock, the conductively plated latching arms on the male connector and cam on the female cone establish a resistive grounding path to mitigate electrostatic discharge, followed by linear translation of the female cone to force partial ball-pin engagement. The female cone is then axially translated to establish full ball-pin connection and hard dock, activating electrical data connections. Following preload application, the ejection sleeve is actuated linearly to initiate fuel line connection. Undocking reverses this sequence.

### 3.8.3 Integration and Implementation Considerations

- **System Modifications:** The OneLink system requires servicer spacecraft to incorporate either the passive male or active female connector hardware, depending on servicer or client role. Internal spacecraft modifications include propellant and pressurant line tie-ins, electrical bus connections to power ports, and data bus connections. Ground Support Equipment: Specifications for GSE required for OneLink are still under development.
- **Operational Environment:** The OneLink is designed for all space environment operations with materials selected for space durability. Data protocols: The 16 data transfer pins support Ethernet protocol with redundancy, operating at 100 Mbps data speeds with 100 MHz bandwidth. The system provides six power transfer ports capable of 28 VDC bus voltage at maximum 100 A current.



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#### 4. State of Interfaces: Structural

With the increasing debris strike and conjunction risk, spacecraft sustainability has become a key application for satellite servicing. In the event that a satellite becomes debris—due to a failed de-orbit solution or a mission loss prior to the planned end-of-life—servicing satellites acting as tugs are one of the few methods to deorbit defunct satellites to prevent them from collision with other assets. Relocation can also allow satellites to achieve orbits outside their designed regime, allowing more mission flexibility and responsiveness. For a servicer to act as a tug for another spacecraft, it must physically connect to it. The structural interfaces covered in this section focus on satellite-to-satellite grapple and docking mechanisms; interfaces between an Orbital Replacement Unit (ORU) and satellite are outside the scope of this section.

This is not a trivial task as the servicer must rely on its rendezvous and proximity operations (RPO) system to approach and align itself with the target, which may or may not be tumbling or otherwise uncooperative. The final piece—docking—requires robust and reliable systems that can accommodate various angular and translational offsets incurred during final approach. Legacy docking systems, like on the ISS, have published standards like the International Docking System Standard (IDSS).<sup>vii</sup> This standard, while thorough in its explanation of human-rated and human-scale systems, falls short in addressing systems compatible for small satellites, which often have a greater degree of autonomy.

Industry has largely led the development of small-satellite structural interface technologies. Some interfaces, such as the Astroscale Docking Plate, are developed according to general guidelines including the Space Safety Coalition’s Best Practices for Sustainability of Space Operations and the Space Sustainability Rating, representing steps towards standardization in small-satellite structural interfaces. The interfaces covered in this section are the Docking Plate (Astroscale), Magnetic Extendable Capture System (Astroscale), Nautilus (Starfish), Orbital Express Capture System (Sierra Space), and REACCH (Kall Morris Inc.). The DogTag interface, developed by Altius Space Machines (now Voyager Space), has over 300 units currently in space.

These interfaces represent high maturity U.S. solutions for in-space structural connection between objects, but the list is not exhaustive. Examining the technologies holistically, one of the largest gaps in structural interfaces is the difference in maturity between prepared and unprepared grapple devices. Some of the interfaces on this list require the target be prepared—or have some pre-defined fixture already integrated on the satellite. These prepared interfaces can be less complex, as they are designed to capture specific client spacecraft and have seen greater history of flight testing. However, these solutions can only relocate objects that have the pre-defined fixture.

Clean-up of existing debris or relocation of any unprepared satellite requires a more robust grapple device, which, due to their complexity, have been slower to achieve flight-qualified status.



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## 5. Technology Reference Sheet: Structural

### 5.1 Astroscale's Docking Plate

#### 5.1.1 Executive Summary

The Docking Plate is a passive, ferromagnetic grappling interface installed on client satellites prior to launch. It serves as a standardized capture point enabling a servicer spacecraft to rendezvous with, identify, and mechanically attach to the client for end-of-life disposal, relocation, or other on-orbit servicing. The plate requires no power, no data connection, and no moving parts on the client side. It simultaneously provides three functions: a navigation aid via fiducial markers and retroreflectors for optical guidance during RPO, a magnetic capture surface using a high-performance cobalt-vanadium ferromagnetic alloy, and a mechanical capture interface via a knurled reinforced rim compatible with robotic manipulators and clasp-type capture tools. The plate is designed to be servicer-agnostic, supporting multiple capture approaches so that satellite operators are not locked into a single service provider.

#### 5.1.2 Technical Considerations

##### 5.1.2.1 Technology Readiness and Flight Status

The Docking Plate is at TRL 9 with on-orbit flight heritage.

The Generation-1 Docking Plate launched aboard the ELSA-d mission in March 2021, where it supported multiple magnetic capture and release demonstrations over a 3-year mission, including both non-tumbling and tumbling target scenarios. In January 2025, the Generation-2 Docking Plate achieved flight heritage aboard SpaceX Transporter-12, integrated on an Astro Digital Corvus-XL satellite bus. In March 2025, Airbus Defence and Space placed an order for over 100 Generation-2 Docking Plates, representing the first large-scale commercial adoption by a major aerospace prime. The ELSA-M mission, targeting a 2026 launch, will be the first commercial multi-client end-of-life service using the Docking Plate interface for Eutelsat OneWeb satellites.

##### 5.1.2.2 Physical and Performance Parameters

- Diameter: approximately 150 mm
- Mass: less than 500 grams
- Truss leg configurations: three off-the-shelf unit heights available (70, 120, and 163 mm) plus a flush-mount option.
- Materials: aluminum alloy body (nickel-plated), cobalt-vanadium ferromagnetic alloy capture surface.
- Design life: exceeds 15 years in the space environment.



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### 5.1.2.3 Interface Architecture

The Docking Plate is strictly a passive interface. The cobalt-vanadium ferromagnetic alloy surface, characterized by low coercivity and high magnetic saturation, enables secure capture by permanent-magnet-based active systems. The knurled reinforced rim provides a textured grip surface for robotic manipulators and enables capture by wrap or clasp mechanisms as a second, independent capture modality. Fiducial markers, including multi-range ArUco markers and retroreflectors, support vision-based relative navigation during final approach.

- Compatibility Matrix: Magnetic and mechanical wrap/clasp capture options.
- Demonstrated compatibility with Astroscale’s Magnetic Extendable Capture System (MECS); designed for third-party servicer compatibility via published interface guidelines.<sup>viii</sup>

### 5.1.2.4 Safety and Operations

The entirely passive design eliminates failure modes from power loss, software faults, or mechanism malfunction on the client side. A de-coupled top plate and structural deck design mitigates thermal stress accumulation over the 15-year mission life. The redundant capture modality (magnetic and mechanical) ensures that loss of one approach does not preclude servicing. Astroscale states alignment with CONFERS best practices,<sup>v</sup> the Space Safety Coalition,<sup>iv</sup> and the Space Sustainability Rating framework.<sup>ix</sup>

### 5.1.3 Integration and Implementation Considerations

- System Modifications: 3-bolt external attachment solution; can be assembled from outside the satellite during AIT without interior access.
- No electrical, data, or thermal interfaces required; integration is purely mechanical.
- Ground Support Equipment: Contact provider for more information.
- Operational Environment: Qualified for radiation, UV, vibration, and shock per standard space environmental qualification protocols.

## 5.2 Astroscale’s Magnetic Extendable Capture System (MECS)

### 5.2.1 Executive Summary

The Magnetic Extendable Capture System (MECS) is Astroscale’s active solution for satellite capture. It uses an array of permanent magnets on an extendable and retractable arm assembly to magnetically latch onto the ferromagnetic Docking Plate installed on a prepared client satellite. The system enables repeated capture and release cycles without consumables, and the permanent magnets maintain grip without continuous power. It was flight-demonstrated on the ELSA-d mission and is being scaled for multi-client operational service on ELSA-M.



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## 5.2.2 Technical Considerations

### 5.2.2.1 Technology Readiness and Flight Status

The capture system is at TRL 9, having completed a full flight demonstration program on ELSA-d from March 2021 through January 2024. Demonstrations included autonomous re-capture of a non-tumbling client, re-capture of a tumbling client with attitude estimation, target search and inspection fly-around, and manual safety abort testing. The ELSA-M evolution, targeting a 2026 launch, scales the capture capability from the approximately 20 kg ELSA-d client to clients up to 800 kg at altitudes up to 1,325 km.

### 5.2.2.2 Physical and Performance Parameters

- ELSA-d servicer total mass: Approximately 175-184 kg (capture subsystem mass not separately published).
- ELSA-M target capture capacity: Up to 800 kg client mass.
- Magnet type: Permanent magnets in alternating N/S polarity arrangement (no power for grip maintenance).
- Compliant coupling: Coil spring buffer accommodates angular and lateral misalignment during contact.

### 5.2.2.3 Interface Architecture

The system employs a dual-motion mechanism with two independently actuated reciprocating arms on linear bush guides. The first carries a permanent magnet array arranged in an annular pattern with vessel-shaped yokes that maximize attraction on the Docking Plate while minimizing stray field toward the servicer. A central optical aperture through the mechanism allows continuous target tracking during final approach. For release, differential retraction of the two actuated arms produces a gradual peeling-off separation that uniformly decreases magnetic force, preventing uncontrolled tumbling of the released client.

- Compatibility Matrix: Requires prepared client satellite equipped with Astroscale Docking Plate.

### 5.2.2.4 Safety and Operations

The passive grip requires no electrical power, eliminating risk of capture loss from power failure or software fault. Inner- and outer-circle position sensors provide positive confirmation of successful magnetic engagement before post-capture maneuvers. The compliant contact interface absorbs misalignment forces during capture, and the controlled release sequence avoids abrupt separation impulses. The alternating polarity magnet arrangement minimizes electromagnetic interference with servicer avionics.

## 5.2.3 Integration and Implementation Considerations

- System Modifications: Contact provider for more information.



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- Ground Support Equipment: Contact provider for more information.
- Operational Environment: Contact provider for more information.

## 5.3 Starfish Space’s Nautilus

### 5.3.1 Executive Summary

Nautilus is a universal docking end-effector developed by Starfish Space that uses electroadhesion to capture unprepared spacecraft. Unlike conventional docking mechanisms that require cooperative fixtures on the client spacecraft, Nautilus adheres to flat surfaces of various materials commonly found on satellite exteriors without any pre-installed docking hardware. This is an active-only interface architecture with no passive side required on the client. The system also integrates a backup electromagnet for secondary capture capability.

### 5.3.2 Technical Considerations

#### 5.3.2.1 Technology Readiness and Flight Status

Technology Readiness Level: TRL 7

The Otter Pup 2 spacecraft carrying the Nautilus mechanism launched on SpaceX Transporter-14 in June 2025 and is conducting a docking demonstration against an unprepared D-Orbit ION client satellite in LEO. The earlier Otter Pup 1, launched in June 2023, experienced a deployment anomaly but was recovered via software and completed RPO operations within approximately 1 km of a D-Orbit client. A full-scale Otter servicing vehicle for GEO operations is funded under a \$37.5 million USSF STRATFI contract, with a second vehicle awarded in February 2026 under a \$54.5 million APFIT contract. In January 2026, Starfish Space was awarded the first-ever contracted constellation disposal mission (\$52.5 million) to dispose of Proliferated Warfighter Space Architecture LEO satellites.

#### 5.3.2.2 Physical and Performance Parameters

- Otter Pup 2 spacecraft mass: Approximately 40 kg.
- Nautilus mechanism size: Approximately hand-sized (detailed mass and grip force specifications not publicly disclosed).
- Propulsion: ThrustMe iodine electric propulsion.

#### 5.3.2.3 Interface Architecture

Nautilus generates electrostatic forces between interdigitated electrode pads and the target surface. When voltage is applied, charge accumulation on the target surface creates an attractive clamping force. This works in vacuum and on both conductive and dielectric surfaces including aluminum panels, composite structures, solar panel substrates, and multi-layer insulation (MLI). A backup electromagnet provides a secondary capture mode effective on ferromagnetic surfaces. The system provides dynamic damping of



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relative motion during and after capture and is designed for multi-mission reuse with repeated release and re-engagement cycles.

- Compatibility Matrix: Does not require prepared client (or target) satellite.
- Surface Compatibility: Aluminum, composites, solar panels, MLI.

#### 5.3.2.4 Safety and Operations

Starfish Space has developed an integrated autonomous software stack for capture operations: Cetacean, which provides computer-vision-based relative navigation using optical sensors without requiring cooperative target beacons; and Cephalopod, which provides autonomous GNC for rendezvous, proximity operations, and docking. The electroadhesive capture is non-destructive and leaves no residue on the target surface.

#### 5.3.3 Integration and Implementation Considerations

- System Modifications: Client satellite requires a reasonably flat surface for electroadhesive engagement; no pre-integration of passive hardware required.
- Ground Support Equipment: Contact provider for more information.
- Operational Environment: LEO and GEO; designed for unprepared and non-cooperative targets.

### 5.4 Sierra Space's Orbital Express Capture System (OECS)

#### 5.4.1 Executive Summary

The Orbital Express Capture System (OECS) was flown as part of the DARPA Orbital Express program in 2007 and demonstrated the feasibility of autonomous docking and undocking of independent spacecraft. Originally developed by Starsys Research Corporation under SBIR funding beginning in 1999, the system transitioned through corporate acquisitions to Sierra Space, which now offers it as a commercially available spaceflight hardware product. The OECS provides autonomous grapple, alignment, and rigid structural mating between a servicing vehicle and a client satellite using a 3-arm active-passive mechanical capture architecture.

#### 5.4.2 Technical Considerations

##### 5.4.2.1 Technology Readiness and Flight Status

The OECS is at TRL 9 based on the 136-day DARPA Orbital Express mission, which launched in March 2007 and completed all capture, docking, and separation activities with zero anomalies. The mission demonstrated autonomous satellite capture at distances up to 7 km using passive optical and infrared imaging, autonomous docking via the capture mechanism, on-orbit refueling (14.6 kg hydrazine transferred), and autonomous battery orbital replacement unit (ORU) exchange. The system is commercially available through Sierra Space with an Interface Control Document, CAD models, and user manual available upon request.



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#### 5.4.2.2 Physical and Performance Parameters

- Size: 33 inches x 18 inches diameter (active side); 10 inches x 18 inches diameter (passive side)
- Mass: 22.7 kg active side, 11.3 kg passive side
- Capture time: Less than 10 seconds
- Capture and latch time: Less than 300 seconds
- Misalignment tolerance: +/- 5 degrees pitch/yaw/roll, +/- 2 inches lateral
- Linear contact velocity tolerance: 3 cm/sec

#### 5.4.2.3 Interface Architecture

The active side uses three four-bar linkages actuated by a single motor-driven lead screw. This single-motor architecture simplifies the drive train and reduces failure modes. Push-off rod struts form a three-point kinematic alignment mount for a rigid, deterministic interface. The passive side features a wedge-shaped capture geometry that self-centers the mating to compensate for lateral and angular misalignment. Flight-qualified electrical connectors enable power and data transfer across the mated interface.

- Compatibility Matrix: Capable of adding additional electrical and fluid connectors

#### 5.4.2.4 Safety and Operations

The passive side includes sensors to indicate proper engagement of the grappling arms, providing feedback to the servicer flight software to verify capture state before fluid or electrical connections are attempted. The same mechanism provides shock-less separation for undocking operations. Capture time is less than 10 seconds for initial grapple, with full latch including utility connection completing in less than 300 seconds.

#### 5.4.3 Integration and Implementation Considerations

- System Modifications: Contact provider for more information.
- Ground Support Equipment: Contact provider for more information.
- Operational Environment: Contact provider for more information.

### 5.5 KMI's Responsive Engaging Arms for Captive Care and Handling (REACCH)

#### 5.5.1 Executive Summary

The Responsive Engaging Arms for Captive Care and Handling (REACCH) capture system is a highly adaptable mechanism designed to safely and securely grapple any number of different objects in orbit for the purposes of relocation. It combines two bio-inspired mechanisms: octopus-like compliant tentacle



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arms that conform to irregular geometries, and gecko-inspired dry adhesive surfaces augmented with electrostatic adhesion for a hybrid capture approach. The system is designed for non-destructive, residue-free, reversible capture of unprepared and uncooperative targets across a wide range of sizes and surface materials.

## 5.5.2 Technical Considerations

### 5.5.2.1 Technology Readiness and Flight Status

Technology Readiness Level: TRL 6

REACCH was tested aboard the ISS from November 2024 through May 2025, mounted on a NASA Astrobee free-flying robot. Over the course of six test sessions and eight months of operations, the system completed 172 capture cycles against a target cube fitted with interchangeable faceplates simulating spacecraft surface materials including acrylic, aluminum, crumpled aluminum, and multi-layer insulation. KMI reported that results significantly exceeded expectations. Development has been funded through USSF SpaceWERX STTR Phase I and Phase II contracts, with research partners at the University of Southern California, Stanford, and MIT. The full-scale Laelaps spacecraft with an eight-tentacle REACCH variant is planned for a 2027 launch.

### 5.5.2.2 Physical and Performance Parameters

- ISS demonstration configuration: 4 compliant tentacle arms, approximately 0.46 m arm length each
- Operational configuration (Laelaps): 8 tentacles, approximately 25% larger than ISS demo
- Capture diameter range: Approximately 250 mm to 6.5 m
- Detailed Mass and Power Specifications: Contact provider for more information.

### 5.5.2.3 Interface Architecture

REACCH is an active-only end-effector. Eight compliant arms deploy outward and conform to the target geometry on contact. (Note, only four arms were demonstrated on ISS.) Gecko-adhesive tiles use synthetic micro-wedge structures to generate van der Waals adhesion, augmented by electrostatic adhesion in a hybrid configuration that creates a synergistic positive feedback cycle. A centralized pushrod provides opposing force to mechanically lock the captured object. The adhesion is controllable and reversible, enabling selective capture and near-zero-force release without damage or residue.

- Compatibility Matrix: Does not require prepared client satellite.
- Validated Surface Materials: Acrylic, aluminum, crumpled aluminum, multi-layer insulation.



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#### **5.5.2.4 Safety and Operations**

The non-destructive capture approach generates no secondary debris, unlike harpoon or net-based systems. Compliant arms absorb contact dynamics, reducing impact loads on both the client and the servicing spacecraft. The system passed NASA ISS safety review for intravehicular operation aboard Astrobe. Selective release with near-zero separation force prevents unintended momentum transfer to the released object.

#### **5.5.3 Integration and Implementation Considerations**

- **System Modifications:** REACCH is designed as a modular end-effector; the operational Laelaps spacecraft is ESPA-compatible for rideshare launch.
- **Ground Support Equipment:** Contact provider for more information.
- **Operational Environment:** LEO and GEO; designed for unprepared, uncooperative, and tumbling targets.



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## 6. State of Interfaces: Communications

The state of communication technology for space applications has advanced significantly with the maturation of optical communication systems, software-defined networking, and reusable flight software frameworks. This document provides technical analyses of three key technologies: TESAT’s Laser Communication Terminal (LCT) series, MTI Systems’ 5G User Equipment for lunar communications, and NASA’s Core Flight System (cFS) software framework. Each technology represents a different level of development, readiness, and industry adoption, addressing diverse mission needs from high-data-rate inter-satellite links to lunar surface communications and standardized flight software architectures for modern and future spacecraft and their missions.

Core Flight System (cFS) stands out as a highly mature and widely adopted software framework with a technology readiness level (TRL) of 9, having been successfully deployed on over 40 NASA missions. As both an open-source and community-driven platform as well as an adopted framework by major aerospace primes, cFS has demonstrated its value in reducing development time, cost, and risk for a broad range of space missions. Furthermore, not only does cFS provide a robust architecture for spacecraft applications, but it also has a rich ecosystem of tools, ground systems, and community support that enhances its usability and integration.

Tools like COSMOS<sup>x</sup> and ITOS<sup>xi</sup> facilitate ground operations, preconfigured virtual environments enable development without flight hardware, and simulators like NOS3<sup>xii</sup> allow for comprehensive testing and validation. It is an excellent example of sharing development risks and benefits across multiple missions and organizations and is well-positioned to support future space endeavors. Lunar 5G User Equipment (UE) from MTI Systems<sup>xiii</sup> is an emerging technology currently at TRL 5-6, aiming to leverage terrestrial 3<sup>rd</sup> Generation Partnership Project (3GPP) standards for lunar surface communications. While it has not yet been deployed in space, the technology is being actively developed under NASA SBIR funding, with plans for demonstration on Artemis missions.

While it is not as mature as cFS, the adoption of open standards and an Open radio access network (RAN) architecture position it well for future lunar infrastructure development, enabling interoperability and scalability. 4G/LTE technology has been partially demonstrated on the lunar surface by Nokia in March 2025<sup>xiv</sup>, marking a significant milestone for cellular communications in space; 5G technology is expected to follow in the coming years. However, 4G and 5G technologies are largely well understood and the main challenges lie in radiation hardening, thermal management, dust mitigation, and ensuring spectrum allocation, which are still to be fully addressed. Nonetheless, it has a clear path to maturity and adoption for lunar missions and there is low risk in planning for its use in the near future.

TESAT’s Laser Communication Terminal (LCT) and Scalable Optical Terminal (SCOT) series<sup>xv</sup> represents a highly mature optical communication technology at TRL 9, with extensive flight heritage since 2007. TESAT LCTs have been successfully integrated into a variety of spacecraft platforms, including GEO relay satellites, LEO Earth observation satellites, and large LEO constellations. The terminals support high data-rate inter-satellite and space-to-ground links, utilizing coherent laser transmission for robust performance. TESAT’s active participation in international standardization efforts, such as the Consultative Committee for Space Data Systems (CCSDS) and the U.S. Space Development Agency (SDA) OCT Standard, ensures that their terminals remain compatible with evolving industry practices, facilitating interoperability and adoption across diverse space missions.



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The technology’s proven reliability, extensive operational hours, and successful link demonstrations underscore its readiness for current and future space communication needs. There are a wide variety of ISAM missions planned for the coming decades that will require advanced communication technologies to support high data rates, low latency, and robust connectivity across multiple orbits and environments. The analyzed technologies each address different aspects of these needs, from the software frameworks that enable rapid development and deployment of flight software (cFS), to the physical layer communication systems that provide high-throughput links (TESAT LCTs), to the emerging cellular technologies that will facilitate surface communications on the Moon (MTI 5G UE).

Together, these technologies form a comprehensive toolkit for future space missions, enabling more complex, data-intensive operations in cislunar space and beyond.



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## 7. Technology Reference Sheet: Communications

### 7.1 Core Flight Software: Technical Analysis of NASA’s Reusable Flight Software Framework

#### 7.1.1 Executive Summary

The Core Flight System (cFS)<sup>i</sup> is a platform-independent, reusable software interface framework that provides standardized application programming interfaces (APIs) and software bus architecture, enabling spacecraft applications and components to communicate seamlessly across diverse hardware and operating systems. With a TRL of 9, cFS is fully operational and has demonstrated robust, reliable performance on over 40 NASA missions—including CubeSats, flagship observatories, and deep space platforms—amassing millions of operational hours in LEO, GEO, lunar, and deep space environments.

#### 7.1.2 Development History

cFS was developed at NASA GSFC in 2004 to enable code reuse across the Solar Dynamics Observatory and Lunar Reconnaissance Orbiter missions. Instead of mission-specific architectures, engineers created a layered framework. The layered architecture, described below, is used to conceptualize hardware and support application portability. After successful use on these missions, cFS was refined and expanded for broader NASA use. Released as open source in 2014 (initially under NASA Open Source Agreement, later Apache 2.0), cFS has since become a widely adopted standard, earning NASA’s Software of the Year award in 2020 and supporting government, commercial, and international space programs.

#### 7.1.3 Implementation Use Cases

cFS serves as the foundational architecture for spacecraft flight software, enabling standardized command and data handling, attitude control, communications, and payload processing across missions and hardware platforms. Its modular, reusable design allows rapid integration and prototyping for both flight and ground systems, significantly reducing development time, cost, and technical risk. Widely adopted by NASA and international partners, cFS streamlines mission approval, lowers maintenance complexity, and supports fast deployment for a broad range of space missions.

#### 7.1.4 Technical Considerations

##### 7.1.4.1 Technology Readiness and Flight Status

cFS is at a TRL of 9, with operational deployment across 40+ NASA missions. It is flight-qualified for radiation environments up to high-dose deep space missions and has demonstrated compatibility with radiation-hardened processors including LEON3/4, RAD750, and commercial processors.

##### 7.1.4.2 Physical and Performance Parameters

- Memory: 128 KB to 2 MB ROM, 256 KB to 8 MB RAM (configurable)
- CPU: 10-30% load on modern space processors



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- Boot: 2-15 seconds (platform/app dependent)
- OS: VxWorks, Linux, RTEMS, FreeRTOS, bare-metal
- Processors: PowerPC (RAD750/5500), LEON3/4, ARM Cortex, x86/x64
- Protocols: CCSDS (Space Packet, CFDP), MIL-STD-1553, SpaceWire, Ethernet, RS-422, CAN
- Dev tools: GCC, Clang, Green Hills, Wind River
- Host: Linux, macOS, Windows (development/simulation)

### 7.1.4.3 Interface Architecture

cFS employs a 3-layer architecture, isolating applications from hardware dependencies. The Operating System Abstraction Layer (OSAL) provides standardized APIs for file systems, task management, inter-process communication, timers, and hardware interfaces, enabling identical application source code to run on VxWorks, Linux, RTEMS, or bare-metal environments without modification. The Platform Support Package (PSP) handles processor-specific initialization, memory management, and exception handling.

The Core Flight Executive (cFE) provides the Software Bus with messaging infrastructure, enabling publish-subscribe communication between applications, time synchronization services across distributed systems, event management for anomaly reporting, table services for parameter updates without software recompilation, and executive services for managing application lifecycle.

### 7.1.4.4 Safety and Operations

cFS ensures robust software safety and operational flexibility through mechanisms such as application isolation (via memory protection when supported by the real-time operation system (RTOS)), watchdog monitoring with automatic restarts, exception handling to prevent fault propagation, and configurable health monitoring applications. The Software Bus validates messages and prioritizes critical commands, while error checking and graceful degradation maintain system integrity. Applications communicate using a publish-subscribe model, allowing modular updates without system disruption.

Ground operators interact through standard command and telemetry interfaces, enabling remote updates, application management, and real-time monitoring, with support for autonomous operations via event-driven scripting and stored command sequences.

### 7.1.5 Integration and Implementation Considerations

System Modifications and Operational Environment: Integrating cFS requires minimal hardware-specific changes due to its abstraction architecture; users typically adapt the Platform Support Package for their processor/board, configure the OSAL for the target operating system, and develop mission-specific applications using cFS APIs. Ground support commonly uses NASA's COSMOS or ITOS systems, with lightweight alternatives like cFS-GroundSystem available for smaller missions.



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The framework supports development with preconfigured virtual environments and cross-compilers, enabling software testing without flight hardware. cFS is qualified for a wide range of operational environments, including LEO, GEO, deep space, and lunar missions, with demonstrated resilience to launch loads, radiation, thermal extremes, and vacuum conditions.

### 7.1.5.1 Data Protocols and Implementation Examples

cFS applications commonly use CCSDS Space Packet Protocol<sup>xvi</sup> for telemetry and command exchange, with the CCSDS File Delivery Protocol (CFDP)<sup>xvii</sup> supporting reliable file transfers. Software Bus messages are transmitted over various physical layers, including SpaceWire, MIL-STD-1553, and Ethernet, while the Interoperability Plug-In (IOP) allows integration with legacy protocols. Notable implementations include OSIRIS-REx<sup>xviii</sup>, which used cFS for complex deep-space operations, the Global Precipitation Measurement mission (GPM)<sup>xix</sup> for long-term Earth observation, and RainCube<sup>xx</sup>, which demonstrated cFS's adaptability to CubeSat-class resource constraints.

### 7.1.6 Standardization Analysis

NASA maintains the authoritative cFS repository with community contributions reviewed by NASA Goddard Space Flight Center technical leads, ensuring core framework stability while enabling innovation through application-layer extensions. The cFS open-source community includes over 1,000 registered developers spanning NASA centers, Department of Defense organizations, commercial aerospace companies (including Blue Origin, Sierra Space, and Maxar), and university research programs across 15+ countries. NASA's cFS Community Workshop convenes annually with 100-200 participants sharing lessons learned and coordinating framework evolution.

The cFS ecosystem includes partnerships with major aerospace primes (e.g., Lockheed Martin, Northrop Grumman, and L3Harris) who have developed mission-specific applications while contributing generic capabilities back to the community repository. Ground system vendors, including Kratos and AMERGINT, provide cFS-compatible products, enabling end-to-end system integration.

## 7.2 Lunar Access Network: Technical Analysis of MTI Systems' 5G for Lunar Communications

### 7.2.1 Executive Summary

MTI Systems is developing a 5G User Equipment (UE) software stack based on 3GPP 5G New Radio (NR) technology, specifically adapted for the lunar environment under a NASA SBIR Phase II project. Targeting TRL 6 by project completion, the effort aims to deliver a fully functional prototype demonstrated with flight-like hardware and emulated gNodeB base stations, using an Open RAN approach to foster a competitive, interoperable ecosystem for Artemis missions. While this represents significant progress beyond Phase I feasibility studies, the technology remains in laboratory development with no flight heritage and has not yet been deployed or tested in space.

It is distinct from Nokia's 4G/LTE Lunar Surface Communications System, which achieved a brief first lunar deployment in March 2025 on the IM-2 mission.



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## 7.2.2 Development History

MTI Systems, Inc. was founded in 2008 by Colleen McGraw, who served as a NASA Systems Engineer for approximately 20 years (1988-2008). The company is headquartered in Lothian, Maryland, and maintains approximately 30 employees with expertise in software-defined networking, 5G systems, satellite operations, and space communications. MTI's primary customers include NASA Goddard Space Flight Center, NASA Glenn Research Center, and commercial entities such as Google and Meta. The Lunar Access Network project began with a Phase I SBIR award in 2023, which established lunar 3GPP RAN requirements, resource requirements for lunar 5G NR processing, and development plans.

Phase II was awarded in August 2024 with funding of \$849,794 under contract 80NSSC24CA158, extending through February 2026.

## 7.2.3 Implementation Use Cases

The 5G lunar network technology is designed to meet NASA Artemis program needs by enabling high-definition video streaming from astronaut suits, reliable telemetry and command links for rovers and vehicles, and direct device-to-device communications for backup and emergency scenarios. Leveraging 3GPP standards, the system supports data rates up to 100 Mbps over distances of up to 10 km, and allows integration of hardware through a software bus architecture. The Open RAN approach supports scalable, multi-vendor infrastructure, enabling incremental expansion to sustain long-term lunar operations and commercial activities.

## 7.2.4 Technical Considerations

### 7.2.4.1 Technology Readiness and Flight Status

The technology is currently at TRL 5, soon to be TRL 6 upon Phase II completion. It has not yet been deployed in space, with laboratory testing ongoing using flight-like hardware and emulated base stations. The first lunar deployment of 3GPP technology occurred in March 2025 using Nokia's 4G/LTE system on the IM-2 mission.

### 7.2.4.2 Physical and Performance Parameters

- Radio Access: 3GPP 5G NR (Rel.15+) and LTE (Rel.12+) standards; 5G NR preferred for scalability.
- Spectrum: SFCG 32-2R5 bands: 2.505-2.655 GHz, 3.5-3.8 GHz; <2 GHz restricted for radio astronomy.
- Coverage/Data Rate: Up to 10 km range; data rates and SNR depend on terrain; Artemis III demo targets 2 km.
- SWaP: Achieving low Size, Weight, and Power with space-qualified components is a major challenge.



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### 7.2.4.3 Interface Architecture

MTI Systems employs an Open RAN architecture to foster a competitive, multi-vendor ecosystem of interoperable communications equipment, accelerating development and ensuring rapid maturation for human-rated lunar applications. The core network element, known as a Network in a Box (NIB), integrates radio frequency (RF), baseband, and core network functionalities into a compact, SWaP-optimized unit suitable for deployment on Human Landing Systems (HLS) and Lunar Terrain Vehicles (LTV). Both 4G Evolved Packet Core (EPC) and 5G Core Network (5GC) architectures are supported, with 5GC providing enhanced scalability and advanced features for future lunar infrastructure needs.

### 7.2.4.4 Safety and Operations

The system is engineered to operate reliably in the lunar environment, requiring all hardware to withstand radiation exposure, extreme temperature cycles from -280°F to +260°F, vacuum conditions, and pervasive lunar dust. Reliability is achieved through the use of space-qualified or radiation-characterized commercial components. The technology is designed for seamless integration with NASA's LunaNet architecture, ensuring interoperability within the internationally coordinated lunar communications, navigation, and networking framework.

Ongoing evolution of 3GPP standards (Releases 17-19) continues to enhance Non-Terrestrial Network (NTN) capabilities, with Release 19 introducing features such as regenerative payload support and GNSS-independent operation, both highly relevant for future lunar applications.

## 7.2.5 Integration and Implementation Considerations

System Modifications and Operational Environment: MTI's 5G lunar network technology is not yet widely usable, as it remains a Phase II SBIR project targeting TRL 6 and lacks flight heritage or broad accessibility. The first lunar cellular demonstration occurred in March 2025 with Nokia's 4G/LTE system on the IM-2 mission, which validated basic operations but was limited in scope. NASA is advancing 3GPP adoption through Artemis III (2027) with a 4G/LTE demonstration in AxEMU spacesuits and plans for operational 3GPP use on Artemis V (~2030) with the LTV. Full 5G deployment is projected for 2028-2032, with recommendations to align lunar communications with near-current commercial 3GPP standards.

Parallel efforts include EpiSys Science's 5G-MOSAIC project for mission-critical sidelink communications and ongoing NASA testing of LTE/4G, 5G, and Wi-Fi at Johnson Space Center, while Nokia Bell Labs leads lunar cellular technology development under NASA's Tipping Point program and recent systems engineering studies.

### 7.2.5.1 Data Protocols, and Integration Considerations

Lunar 5G systems must comply with International Telecommunication Union (ITU) and Space Frequency Coordination Group (SFCG) 32-2R5 spectrum regulations, as some terrestrial LTE/5G bands are not permitted for lunar use. For example, Nokia's IM-2 mission operated under a temporary waiver; permanent deployments require formal spectrum allocation via ITU World Radio Conferences before Artemis V. Mission teams must adapt Platform Support Packages for their hardware, configure the system for the lunar environment, and develop mission-specific applications. Ground integration must



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ensure compatibility with NASA’s Communications Demonstration Test Objectives and LunaNet interfaces.

### 7.2.6 Standardization Analysis

MTI’s 5G lunar network technology implements open 3GPP standards using an Open RAN architecture, enabling multi-vendor interoperability and leveraging the extensive terrestrial 3GPP ecosystem and technologies, which benefits from over \$100 billion in annual global investment. By adopting commercially proven international standards rather than proprietary solutions, and integrating with NASA’s LunaNet framework, the technology supports collaborative, incremental lunar infrastructure development by both public and private organizations.

## 7.3 TESAT Laser Communication Terminal (LCT) Series: Technical Analysis

### 7.3.1 Executive Summary

TESAT’s Laser Communication Terminal (LCT) series is an operationally mature optical communication hardware interface in space, enabling coherent laser-based inter-satellite and space-to-ground links at data rates from 100 Mbps to 100 Gbps across LEO, medium Earth orbit (MEO), and GEO. With TRL 9 for its heritage LCT135 and SCOT80 product lines, TESAT terminals have demonstrated extensive flight heritage since 2007, supporting critical systems like the European Data Relay System (EDRS) Space Data Highway and the U.S. SDA Proliferated Warfighter Space Architecture. As of 2024, TESAT terminals have accumulated over 500,000 operational hours and performed more than 51,000 successful optical links, with 62 SCOT80 terminals currently operational in orbit.

### 7.3.2 Development History

TESAT-Spacecom originated in 1949 when AEG’s telecommunications division moved to Backnang, Germany. The company became AEG Telefunken (1967), ANT Nachrichtentechnik (1983), Bosch SatCom (2000), and was acquired by EADS Astrium in 2001, becoming Tesat-Spacecom GmbH & Co. KG. Now an Airbus Defence and Space subsidiary with over 1,100 employees, TESAT began laser communication development in the early 2000s with the German Aerospace Center (DLR) and European Space Agency (ESA) support. The first LCTs launched in 2007 on TerraSAR-X and the US NFIRE satellite, conducting the first operational LEO-to-LEO inter-satellite laser link. This heritage underpins all later TESAT optical communication products.

### 7.3.3 Implementation Use Cases

TESAT LCTs enable high-throughput data relay for geostationary missions such as the SpaceDataHighway (EDRS) and provide near-real-time transmission of Earth observation data from LEO satellites to ground stations via GEO relay satellites. In addition to supporting GEO relay, TESAT LCTs are integral to mesh networking within large LEO constellations—including the SDA Transport and Tracking Layer, Telesat Lightspeed, and Kepler AETHER by establishing robust optical inter-satellite links that facilitate data exchange across the network. These terminals enhance navigation constellations, such as the GPS III Follow-On program, by enabling high-speed optical cross-links that improve system resilience and data availability.



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## 7.3.4 Technical Considerations

### 7.3.4.1 Technology Readiness and Flight Status

TESAT LCT135 and SCOT80 terminals are at TRL 9, with extensive flight heritage since 2007. The CubeLCT series has also achieved TRL 9 with multiple successful missions. The SmartLCT70 is at TRL 8, having completed in-orbit demonstrations.

### 7.3.4.2 Physical and Performance Parameters

- Data Rates: 100 Mbps to 100 Gbps (varies by model)
- Ranges: Up to 80,000 km (GEO-LEO)
- Mass: 0.36 kg (CubeLCT) to 53 kg (LCT135)
- Power Consumption: 8 W (CubeLCT) to 340 W (SCOT135)
- Apertures: 70 mm to 135 mm
- Transmission: Coherent BPSK at 1064 nm; some models support 1550 nm IM/DD
- Wavelengths: 1064 nm (all), 1550 nm (select models)
- Pointing, Acquisition, and Tracking: Autonomous Coarse Pointing Assemblies with beaconless algorithms

### 7.3.4.3 Interface Architecture

The TESAT LCT architecture uses coherent optical transmission with homodyne BPSK modulation at 1064 nm via space-qualified Nd:YAG lasers, enabling efficient, long-range, high-data-rate links resilient to sunlight and jamming. Newer models like CubeLCT and SmartLCT70 support 1550 nm IM/DD for terrestrial telecom compatibility, while LCT135 enables dual-wavelength (1064/1550 nm) operation for interoperability with EDRS and emerging standards. All terminals have autonomous telescopes with two-axis gimbals and Coarse Pointing Assemblies (CPA), providing hemispherical field of regard and beaconless pointing, acquisition, and tracking (PAT) algorithms proven in over 10,000 in-orbit operations. LCT135 includes a 2 Mbps forward channel for ground-to-satellite tasking via GEO relay.

SCOT80 terminals are fully compliant with the U.S. SDA Optical Communications Terminal (OCT) Standard v3.1<sup>xxi</sup>, with ongoing development toward v4.0, and have demonstrated interoperability through reference modem testing. For LEO direct-to-Earth, CubeLCT implements the CCSDS Optical On-Off Keying (O3K) standard, and TESAT contributes to CCSDS optical communications working groups for global interoperability.



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#### 7.3.4.4 Safety and Operations

TESAT LCT terminals are engineered for long-duration performance in harsh space environments, with LCT135 qualified for operation in GEO, featuring electronics redesigned for high-energy electron radiation tolerance in the outer Van Allen belt, and SmartLCT70/SCOT80 qualified for LEO missions with appropriate thermal cycling and radiation resilience. All terminals are built to withstand launch-induced mechanical loads and operate reliably across a wide operational temperature range suitable for LEO and GEO missions. Operational maturity is demonstrated by extensive flight heritage, a high number of successful laser links on Space Data Highway, and regular execution of optical links.

TESAT operates both autonomous and ground-controlled modes, with comprehensive health monitoring, fault detection, and recovery mechanisms. Ground operators utilize TESAT's Transportable Adaptive Optical Ground Station (T-AOGS) for link management, with established procedures for link scheduling, acquisition, and data handling.

#### 7.3.5 Integration and Implementation Considerations

System Modifications and Operational Environment: TESAT LCT terminals have been integrated into a wide range of spacecraft platforms, including GEO relay satellites (EDRS-A/C), LEO Earth observation satellites (Sentinel-1/2, TerraSAR-X), LEO communication constellations (SDA Transport Layer, Telesat Lightspeed), navigation satellites (GPS III FOC), and CubeSats (CubeLCT). Integration requires accommodation of data interfaces (LVDS, Wizard Link, Ethernet/SpaceFibre), supply voltage (28 V typical), thermal management for waste heat dissipation, mechanical mounting for full hemispherical field of regard via CPA, and spacecraft pointing stability to maintain coherent links.

TESAT provides comprehensive integration support, including interface control documents, test plans, and operational procedures.

##### 7.3.5.1 Data Protocols, and Integration Considerations

TESAT LCTs support various data protocols depending on the terminal model and mission requirements. The CubeLCT series implements the CCSDS O3K (Optical On-Off Keying) standard for LEO direct-to-Earth links, while SCOT80 terminals comply with the U.S. SDA OCT Standard, enabling interoperability with other OCT-compliant systems. TESAT provides reference modems and test equipment to facilitate integration and validation of optical links. Mission teams must ensure compatibility with spacecraft data handling systems, power supplies, and thermal management solutions. TESAT offers extensive documentation, training, and technical support to assist with integration challenges.

#### 7.3.6 Standardization Analysis

TESAT's Laser Communication Terminals and Scalable Optical Terminals actively implement and contribute to international standards for optical communications. Additionally, their data interfaces and mounting requirements align with established spacecraft design practices. TESAT contributes to CCSDS to advance optical communication standards, including O3K and future protocols. The SCOT80 terminal's compliance with the U.S. power and mechanical interface requirements are readily referenceable in the SDA OCT Standard documentation. TESAT's participation in standardization efforts



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ensures that their terminals remain compatible with evolving industry practices, facilitating interoperability and adoption across diverse space missions.



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## 8. State of Interfaces: Electrical

The U.S. space electrical interface sector is characterized by a legacy problem. Mature standards (40+ years old) dominate operational systems while emerging technologies struggle for adoption. Legacy military specifications (MIL-STD-1553, MIL-DTL-38999) provide proven reliability but constrain bandwidth and mass optimization. The domestic manufacturing base has successfully transitioned from NASA-centric development to commercial production, with eight major U.S. suppliers maintaining global competitiveness. However, the industry faces a critical inflection point as next-generation missions demand capabilities that legacy interfaces cannot deliver.

### 8.1 Critical Challenges

#### 8.1.1 Standardization Crisis for ISAM

The absence of consensus electrical interface standards threatens the emerging servicing economy.

Although USSF has designated two refueling port designs<sup>iii</sup> and CONFERS contributed to the publication of ISO 24330,<sup>v</sup> comprehensive electrical interface standardization lags market needs. Competing proprietary solutions (such as Sierra Space’s SPDP, NovaWurks’ SLEGO, and Orbit Fab’s RAFTI/GRIP) fragment the ecosystem. Without interoperability, the promised ISAM marketplace will struggle to scale.

#### 8.1.2 Economic Pressure vs. Reliability Requirements

Space-grade components are 2-to-10-times the cost of commercial equivalents and have 16- to 24-week lead times, creating tension between “New Space” cost structures and traditional reliability expectations. Commercial off-the-shelf (COTS) approaches gain acceptance for LEO commercial missions, but risk-acceptance frameworks remain immature. The industry lacks consensus on appropriate reliability levels for different mission classes.

#### 8.1.3 Capability Gaps Impeding Growth

- Blind-mate electrical connectors lack flight heritage, limiting autonomous servicing.
- Repeated mate/demate cycle characterization is incomplete for space thermal/radiation environments.
- High-bandwidth interfaces (>1 Gbps) require optical solutions with limited operational history.
- Robotic manipulation compatibility is poorly defined (grip forces, alignment tolerances, contamination sensitivity).

#### 8.1.4 Legacy Architecture Constraints

- 1 Mbps MIL-STD-1553 bandwidth is inadequate for modern sensor suites and artificial intelligence/machine learning (AI/ML) payloads.



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- 28V bus architecture limits power distribution efficiency for high-power systems (electric propulsion, active thermal management).
- Physical connector mass penalties are significant for small satellite economics.

## 8.2 Strategic Opportunities

Near-term advantages (2025-2027) include U.S. leadership in rad-hard optical technology (Samtec 28 Gbps, Smiths 150 Gbps) enabling first-mover standardization before international competition matures, automated processing scale-up reducing qualification lead times from weeks to hours, and controller area network (CAN) bus power distribution unit (PDU) standardization through constellation deployments creating ecosystem lock-in. Medium-term opportunities (2027-2030) center on capturing ISAM interface standardization leadership through CONFERS/AIAA similar to how MIL-STD-1553 dominated post-standardization markets, accelerating SpaceVPX adoption via Pentagon resilient space architecture mandates with commercial follow-on, and establishing cislunar electrical interface precedents through Artemis/CLPS that become de facto international lunar economy standards. Long-term positioning (2030+) focuses on high-power interface development for electric propulsion and directed energy (>10 kW, megawatt-class leadership), AI/ML compute infrastructure driving multi-gigabit optical backplane standards, and hybrid optical-RF interfaces for resilient communications in contested environments.

## 8.3 Investment Implications

High-confidence opportunities center on optical transceiver manufacturers (Samtec, Smiths Interconnect) positioned for 10x market growth as bandwidth demands escalate, automated space-qualification processing facilities addressing critical lead-time bottlenecks (PEI-Genesis 4-hour model), and modular PDU suppliers benefiting from constellation standardization. Moderate-risk plays include blind-mate connector development for ISAM (no dominant U.S. product exists), SpaceVPX ecosystem investments contingent on velocity of adoption by national security space, and Gigabit Ethernet infrastructure if the commercial sector moves away from legacy standards.

U.S. space electrical interfaces face a generational transition from Cold War-era military standards to a diverse ecosystem serving commercial, civil, and national security missions. The U.S. maintains technological leadership in emerging areas (e.g., optical and modular architectures) and manufacturing capacity, but risks losing first-mover advantage without accelerated standardization for ISAM applications. The industry's ability to balance cost reduction pressures against reliability requirements will determine competitive positioning against international alternatives. Strategic investments in automation, standardization leadership, and capability gap closure will position the U.S. to dominate the next 30 years of space electrical infrastructure as decisively as MIL-STD-1553 dominated the last 50.



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## 9. Technology Reference Sheet: Electrical

### 9.1 Physical Connector Standards

#### 9.1.1 MIL-DTL-38999 Series Circular Connectors

High-density circular connectors for power and signal applications with bayonet or threaded coupling. Shell sizes 9-25 accommodate 5-100+ contacts depending on configuration. Current ratings range from 5-50A per contact (size dependent) with voltage capabilities up to 1000V DC and temperature range -55°C to +200°C. Space-grade Class G D38999 variants are outgassed and electroless nickel plated per ASTM E595 with non-magnetic options available and NASA MSFC-STD-3012 compliance. Contact ratings: #12 (25-40A), #16 (13A), #20 (5-7.5A), #22 (5A). US manufacturers include Glenair (SuperNine®), TE Connectivity (DEUTSCH D38999), Amphenol (Series Five), ITT Cannon, and PEI-Genesis (outgassing services). Applications include primary power distribution, payload power interfaces, signal connections, external interfaces, and robotic arm power/signal.

Technology Readiness Level: TRL 9

##### 9.1.1.1 Flight Status

MIL-DTL-38999 connectors have been extensively flight-proven across hundreds of space missions since 1970s, with continuous operational use on NASA, ESA, DOD, and commercial spacecraft. Space-grade variants (Class G) have been qualified per MSFC-STD-3012 and ESCC 3401 standards.

#### 9.1.2 Micro-D Connectors

Micro-D connectors are miniature rectangular connectors for mass-constrained applications offering 9-51 contact positions with 3-5A per contact for signal applications.

- Temperature range: -55°C to +125°C with significantly lighter weight than standard D-sub connectors.
- Space features include: Non-magnetic variants (brass shells, gold-over-copper flash), low outgassing materials, and radiation resistance
- U.S. manufacturers include: Glenair, Omnetics Connector Corporation, ITT Cannon, and TE Connectivity
- Applications include: Low-power signal connections, internal module interconnections, CubeSat/SmallSat interfaces, and sensor connections
- Technology Readiness Level: TRL 9

##### 9.1.2.1 Flight Status

Micro-D connectors are flight-proven on numerous space missions including ISS, Mars rovers, LEO and GEO satellites, and deep space probes since early 1970s. QPL-qualified variants are available per MIL-



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DTL-83513, with space-grade versions meeting NASA outgassing requirements and featuring flight heritage on missions such as Curiosity, Galileo, and Sentinel.

### 9.1.3 D-Subminiature Connectors

Traditional D-shaped connectors with space-qualified materials are available in 9-, 15-, 25-, 37-, and 50-position densities (standard and high-density variants).

- Current rating: 5A typical per contact with voltage up to 300V
- Configurations: NM/NMB Series (ITT Cannon) provides non-magnetic, NASA/ESA qualified variants in standard to double-density configurations.
- U.S. manufacturers include: ITT Cannon, TE Connectivity, Amphenol, C&K
- Applications: Internal signal connections, command and telemetry, ground support equipment interfaces, avionics connections
- Technology Readiness Level: TRL 9

#### 9.1.3.1 Flight Status

These connectors have extensive flight heritage dating to 1950s development, with continuous operational use across military and space applications. Space-qualified NM/NMB Series from ITT Cannon provides non-magnetic variants meeting NASA and ESA requirements.

### 9.1.4 SpaceVPX (VITA 78) Connectors

These are modular backplane connectors for space computing systems meeting VITA 78 standard with data rates up to 25+ Gbps per lane, various contact counts, radiation qualification for space environment, and extended temperature range.

- U.S. manufacturers include: Amphenol Aerospace, Smiths Interconnect (SpaceNXT Aurora).
- Applications include: flight computers, payload processors, modular avionics systems, and high-performance computing.
- Technology Readiness Level: TRL 8

#### 9.1.4.1 Flight Status

The ANSI/VITA 78 standard was ratified in 2015, with ongoing revisions through 2022. Flight demonstrations are in progress, with NASA evaluating 3U and 6U form factors. Connectors have passed VITA 72 vibration testing with BER monitoring and meet NASA/ESA outgassing requirements. Operational deployment is expanding across national security and commercial space platforms.



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## 9.2 Power Distribution Interfaces

### 9.2.1 Latching Current Limiters (LCL)

Latching current limiters (LCLs) are switchable protection devices for spacecraft power distribution providing overcurrent protection with trip-off capability, individual ON/OFF command per channel, and current and voltage telemetry monitoring per ECSS-E-ST-20-20C and ECSS-E-HB-20-20A standards.

- Applications include: PDUs, load protection and isolation, bus fault isolation, and controlled power sequencing.
- Technology Readiness Level: TRL 9

#### 9.2.1.1 Flight Status

LCLs are a mature technology with extensive flight heritage across ESA, NASA, and commercial missions. Standardized per ECSS-E-ST-20-20C and ECSS-E-HB-20-20A. LCLs are operational on numerous satellites in LEO, MEO, and GEO orbits with demonstrated reliability in power distribution applications.

### 9.2.2 Power Distribution Unit (PDU) Architecture

PDUs are spacecraft power management systems with standardized electrical interfaces.

- Primary input: 28V unregulated (+22V to +33V range) with regulated outputs at 5V, 12V, 28V typical
- Communication: Via RS-422/RS-485, CAN bus, LVDS, I<sup>2</sup>C; individual LCL protection per channel with dual unit redundancy configuration standard using D-sub or MIL-DTL-38999 connectors
- Typical channel specifications: 4-12 output channels, up to 6-10A per channel, 12-bit voltage monitoring resolution, real-time current telemetry, dedicated heater lines for high-power loads
- U.S. commercial providers include: ZIN Technologies (NASA Commercial Crew heritage), AAC Clyde Space (Starbuck system), Beyond Gravity (Constellation PDU), Space Inventor (PDU-P4)
- Technology Readiness Level: TRL 9

#### 9.2.2.1 Flight Status

PDUs are flight-proven architecture. Operational systems range from 500W to 15kW capacity across LEO, GEO, and deep space missions. Terma PCDU systems have supported missions since the 1970s, including Euclid, Plato, BepiColombo, Galileo, and Rosetta. Airbus PSR 100V MKII has over 80 units in flight.



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### 9.3 Connector Pin Configurations

#### 9.3.1 MIL-DTL-38999 Contact Arrangements

- Shell Size 9: Up to 9 #20 contacts (low-power signal).
- Shell Size 11: Up to 19 #20 contacts (mixed contact sizes available).
- Shell Size 13: Up to 26 #20 contacts (power and signal combinations).
- Shell Size 15: Up to 37 #20 contacts (popular for payload interfaces).
- Shell Size 17-25: 50-100+ contacts (higher power applications).

#### 9.3.2 Power Capacity Examples

##### 9.3.2.1 Standard Spacecraft Bus Voltages

- 28V unregulated (22-35V range) for primary power bus.
- 50V regulated for high-power payloads.
- 100V regulated for very high-power systems.
- 12V regulated for avionics and flight computers.
- 5V regulated for digital electronics and sensors.
- 3.3V regulated for modern digital circuits and FPGAs.

##### 9.3.3 Connector Power Examples

- Single #12 contact at 28V (~700W).
- Paralleled #16 contacts (x4) at 28V (~1450W).
- Full Size 15 with power contacts (multiple kW possible).

### 9.4 Cable Specifications

#### 9.4.1 Power Cables

Insulation types include PTFE (Teflon) insulated wire, silicone-insulated wire (flexibility), and cross-linked polyethylene (space-grade), with typical gauge range 22 AWG to 10 AWG. Wire specifications: MIL-W-22759 (Teflon-insulated wire), MIL-W-16878 (general-purpose hookup wire), or MIL-W-81044 (lightweight aerospace wire).



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## 10. State of Interfaces: Combination

Component repair and replacement are maturing servicing functions that can extend the life of satellites or even augment satellite missions. Future modular satellites could take advantage of their architecture by having servicers replace faulty reaction wheel clusters, sensor suites, or solar arrays, while hosted payloads platforms could swap out their payloads on orbit to achieve new sources of revenue without having to launch another bus. All of these activities require interfaces between the interstitial parts, with more functionality than just structural connection or fluid transfer.

Each modular component or payload requires a robotic interface capable of in-space actuation, which also passes data and power to and from the ORU. In some cases, power and data transfer is also needed for satellite-to-satellite connection, where the servicer satellite can supplement the client’s capabilities directly. This breadth of different types of functions (satellite-to-satellite, satellite-to-ORU, etc.) results in a wide variety of interface sizes and capabilities, as each is developed for a different class of mission. Similar to structural-only interfaces, NASA-led human-rated interfaces capable of data and power transfer go as far back as Gemini, but small-sat robotic interfaces have lagged behind.

Despite this, there are several emerging U.S. interfaces capable of power and data transfer in addition to structural attachment: Aspin-C (Lockheed Martin), FuseBlox (SpaceWorks), GOLD-2 (Oceaneering), and Structural Power and Data Port (Sierra Space). This list is not exhaustive, as internationally there are over a dozen combination interfaces being developed, but this list represents the most mature U.S. technologies in development. The primary differential in the landscape of “structures+” interfaces lies in the wide breadth of possible mission types. Some architectures—like the ISS—include teleoperated robotic arms, which can guide ORUs or visiting vessels to the interface, reducing the need for compliance and large capture volumes.

Other architectures use more autonomy or simply less robotics, in which case the interface carries more of the functional burden. This makes the sought-after “USB for space” difficult to determine, as different missions often require a different set of requirements, even if the transfer media (in this case data and power) are the same.



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## 11. Technology Reference Sheet: Combination

### 11.1 Lockheed Martin's ASPIN and Aspin-C

#### 11.1.1 Executive Summary

The Augmentation System Port Interface (ASPIN) is the combination of docking ports and the needed electronics that enable on-orbit mission augmentations and upgrades. Lockheed Martin describes it as analogous to a USB port for spacecraft, providing a universal connection point for multiple device types and applications to dock, transfer data and power, and be swapped out. ASPIN is built to the Mission Augmentation Port (MAP), an open-source docking standard also developed and publicly released by Lockheed Martin in February 2022. The ASPIN-C is the compact variant, built as an Engineering Development Unit (EDU) to the MAP-C specification for smaller Satellite Augmentation Vehicles.

- Both ASPIN and ASPIN-C have associated standards that Lockheed Martin is advancing: MAP-A (full-size, ESPA-class SWaP) and MAP-C (compact, simplified RPOD requirements)
- Technology Readiness Level: TRL 5
- Not flight-tested

#### 11.1.2 Technical Considerations

##### 11.1.2.1 Technology Readiness and Flight Status

The ASPIN-C EDU is undergoing a test campaign to achieve TRL 6 for on-orbit servicing and augmentation missions. ASPIN has been integrated into the baseline LM 2100 satellite bus, including SBIRS GEO-5 (the first modernized LM 2100 satellite, now under USSF control) and is planned as standard equipment beginning with GPS III Follow-on Space Vehicle 13. The LINUSS CubeSat pair, deployed to GEO in November 2022, demonstrated autonomous proximity operations supporting risk reduction for ASPIN-based servicing. Lockheed Martin is also exploring integration of Orbit Fab refueling technology with the ASPIN docking port for future refueling capabilities.

##### 11.1.2.2 Physical and Performance Parameters

- Size: 13 inches x 11 inches x 8.1 inches
- Mass: 14.97 kg
- Max Power Passthrough: contact provider for more information

##### 11.1.2.3 Interface Architecture

ASPIN uses an active-passive architecture with cup-cone alignment geometry and a Long Range Electropermanent Magnet (LR-EPM) for semi-autonomous docking. The cup-cone geometry provides passive self-alignment during final approach, reducing precision requirements for the RPOD system. The electro-



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permanent magnet creates a persistent latching force without continuous power consumption after initial energization. The MAP standard documentation specifies dimensions of plates and petals for compliant physical mating of docking port halves.

- Data Protocol Passthrough: 1000 Base-T Ethernet
- Electrical interfaces are application specific per the MAP standard.

#### 11.1.2.4 Safety and Operations

- Safety Architecture: Contact provider for information.
- Operational Mechanics: Contact provider for information.

#### 11.1.3 Integration and Implementation Considerations

- System Modifications: Integrated into LM 2100 bus (SBIRS GEO-5, GPS III F SV-13+); MAP standard available as open-source specification for third-party integration
- Ground Support Equipment: Contact provider for information.
- Operational Environment: Designed for GEO on-orbit servicing and augmentation

### 11.2 SpaceWorks Enterprises' FuseBlox

#### 11.2.1 Executive Summary

FuseBlox is a mechanical interface for ISAM which has core docking, power transfer, and data transfer capabilities (FuseBlox Core) with a modular add-on for fluid transfer capabilities (FuseBlox Flow for storables and CryoFlow for cryogenics). The interface features an androgynous design for docking and a fluid transfer interface that is configurable with up to 4x channels.

- Technology Readiness Level: TRL 6 for docking, TRL 4-5 for fluid transfer
- Flight testing planned for 2027

#### 11.2.2 Technical Considerations

##### 11.2.2.1 Technology Readiness and Flight Status

FuseBlox completed ground qualification testing at the AFRL ROC Lab at Kirtland Air Force Base in October 2021, validating axial, lateral, roll, and yaw offset docking with results exceeding target specifications. The first orbital flight will be on the Rogue Space Systems OTP-3 mission in 2026, where FuseBlox will demonstrate docking, power and data transfer, and eventual refueling capabilities. In December 2025, SpaceWorks completed its first commercial ground test with Rogue Space Systems, successfully demonstrating docking, power transfer, and data transfer. A NASA SBIR Ignite Phase II



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contract is funding a CryoFlow prototype for cryogenic fluid transfer, with a liquid nitrogen demonstration planned at NASA Marshall Space Flight Center by October 2026.

### 11.2.2.2 Physical and Performance Parameters

- Size: 1U x 1U x 2U (10 cm x 10 cm x 20 cm) for CORE + 4 cm on each side per each Flow/CryoFlow channel
- Mass: 2.6 kg (Active Half Core) + 1.0 kg per Flow/CryoFlow channel
- Power Transfer: 1120 W nominal, 1500 W maximum

### 11.2.2.3 Interface Architecture

FuseBlox uses a patented design for internal claws to grasp, align, and secure the inactive half during operations. The device symmetry enables four secure, mated configurations (0, 90, 180, and 270 degrees), permitting docking from multiple angles. The androgynous design means either half can serve as active or passive, with roles reversible post-launch. The self-aligning grapple technique accommodates small spacecraft rendezvous misalignments with near-zero momentum transfer during docking.

- Configuration: Active-passive or active-active (Androgynous)
- Data Protocol Passthrough:
  - High speed: Standard is 2x Gigabit Ethernet, but can be configured to support SpaceWire, USB super-speed, or IEEE 1394.
  - Low speed: Standard is MIL-STD-1553, but can be configured to support RS-485, USB 2.0 (or less), ARINC 429, CAN, RS-232, or RS-422.
- Fluid Transfer (FuseBlox Flow and CryoFlow):
  - FuseBlox Flow (storables interface)
    - Working fluids: High-test peroxide (HTP), water, GN<sub>2</sub>, hydrazine (N<sub>2</sub>H<sub>4</sub>, MMH), ASCENT, GEM-3, GHe, GO<sub>x</sub>, xenon
    - Pressures: 500 psig MEOP (demo), 3000 to 6000 psig MEOP (operational vision)
  - FuseBlox CryoFlow (cryogenics interface)
    - Working fluids: LOX, LH<sub>2</sub>, LCH<sub>4</sub>, common inert pressurants
    - Pressures: 75 psig MEOP (demo and operational)



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#### 11.2.2.4 Safety and Operations

- Safety Architecture: Self-aligning with near-zero momentum transfer docking once two halves are within the capture envelope. Most safety and flow processing functions are managed by the servicer spacecraft's feed system. FuseBlox enhances compliance with standards like AFSPCMAN 91-710. It also has features in development for emergency disconnection of interfaces. Both FuseBlox Flow and CryoFlow are dry-break interfaces, preventing leakage upon separation and meeting space-grade GHe leak standards when disconnected.
- Operational Mechanics: SpaceWorks' patented Flow and CryoFlow method enables precise mating with the FuseBlox Core. The Core's docking offset tolerance removes the need for extra guidance or control systems.

#### 11.2.3 Integration and Implementation Considerations

- System Modifications: FuseBlox Core, Flow, and CryoFlow designed to meet minimum mechanism drive, fault detection, and safety functionality. FuseBlox delegates most advanced features (e.g., flow sensing, flow throttling, RPOD GNC, etc.) to the servicer spacecraft.
- Ground Support Equipment: Standard laptop and harnessing. SpaceWorks provides test GUI and a software development kit with every FuseBlox unit.
- Operational Environment: rated to typical launch, LEO, and GEO environments and lifespans. Contact SpaceWorks for full specifications.

### 11.3 Oceaneering Space System's GOLD-2

#### 11.3.1 Executive Summary

The General-purpose Oceaneering Latching Device (GOLD-2) is a payload attachment system that provides mechanical, electrical, and data connectivity for Space Station external payloads. Developed by Oceaneering Space Systems, the device leverages the company's heritage in subsea robotics tool changers and latching devices engineered for remote, harsh-environment operations. GOLD-2 is the standard interface for external payloads on the International Space Station, deployed on both the Bartolomeo external payload platform (Airbus) and the Bishop Airlock (NanoRacks/Voyager Space). Options are available for custom fluid connection.

- Technology Readiness Level: TRL 9
- Flight-tested

#### 11.3.2 Technical Considerations

##### 11.3.2.1 Technology Readiness and Flight Status

GOLD-2 is at TRL 9 and has been operational on the ISS since 2020. It serves as the standard payload attachment interface across multiple ISS external platforms. All payload attachment interfaces on the



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Bartolomeo platform use GOLD-2, and the Bishop Airlock provides six external hosted payload sites each using GOLD-2 connectors with provisions for 120 VDC, 350 W nominal power (700 W max), and 100 Mb/s Ethernet data. The system is stated as ready for deployment in LEO, GEO, and cislunar missions beyond the ISS.

### 11.3.2.2 Physical and Performance Parameters

- Size: Approximately 12 inches wide
- Mass: 7.8 kg
- Payload capacity: Up to 454 kg (1,000 lbs), sized up to 1 cubic meter
- Power passthrough: Up to 800 W
- Data rate: Up to 1 Mb/s downlink
- Extravehicular activity (EVA) kick load tolerance: 125 lbf

### 11.3.2.3 Interface Architecture

GOLD-2 employs an active-passive architecture. The passive assembly integrates with the external platform and incorporates spring-loaded debris-exclusion doors to protect connector interfaces while unoccupied. The active assembly integrates with the payload and features a micro-square fixture for in-orbit grasping by the Dextre SPDM's ORU Tool Changeout Mechanism (OTCM). Baseline electrical connections use Smiths Interconnect L-Series connectors with Hypertac hyperboloid contact technology, supporting blind mating with guided hardware, and rated for up to 100,000 mating cycles.

- Configuration: Active-passive, cup-cone soft-dock with robotic arm actuation for hard-dock
- Data Protocol Passthrough: Contact provider for more information.
- Can be modified for fluid transfer

### 11.3.2.4 Safety and Operations

The active side is intended to be attached to the payload, making the component with a cycle lifetime the replaceable part. Spring-loaded debris-exclusion doors on the passive side prevent contamination of connector interfaces between payload exchanges. The system requires actuation by the ISS robotic arm system (Canadarm2 for gross positioning, Dextre for fine-positioning and latching via the OTCM). Oceaneering also separately developed a Tool Changer and Common Receptacle Subassembly for DARPA's RSGS program, sharing the company's subsea-to-space technology lineage.

### 11.3.3 Integration and Implementation Considerations

- System Modifications: Contact provider for more information.



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- Ground Support Equipment: Contact provider for more information.
- Operational Environment: ISS (current); stated ready for LEO, GEO, and cislunar

## 11.4 Sierra Space's Structural Power and Data Port (SPDP)

### 11.4.1 Executive Summary

Designed as a tool holder for a robotic servicing satellite, the Structural Power and Data Port (SPDP) consists of an active unit and a passive unit that can be mated and locked together or unlocked and demated. The interface was developed for DARPA's Robotic Servicing of Geosynchronous Satellites (RSGS) program, where it functions as the equipment stowage and tool-holding interface on the Mission Robotic Vehicle (MRV). The SPDP provides structural connection along with electrical power and data passthrough across 29 connections, with a 400-cycle mate/demate life designed for the MRV's 15-year operational mission.

- Technology Readiness Level: TRL 8
- Flight testing planned for 2026 on RSGS

### 11.4.2 Technical Considerations

#### 11.4.2.1 Technology Readiness and Flight Status

The SPDP is at TRL 8 with hardware delivered for integration onto the MRV flight vehicle. Sierra Space confirmed delivery in November 2024. The MRV, built on the GEOStar-3 heritage bus by Northrop Grumman SpaceLogistics, is anticipated to launch in 2026 on a Falcon-9 from Cape Canaveral. The Naval Research Laboratory (NRL)-developed robotic payload consisting of two dexterous 7-degree-of-freedom arms has completed thermal vacuum testing and been delivered for MRV integration. Initial MRV customers include Intelsat and Optus satellites.

#### 11.4.2.2 Physical and Performance Parameters

- Size: 10.3 inches x 8.6 inches x 5.5 inches
- Mass: 6.15 kg
- Pass-through harness: 29 total connections (including 6 power pairs, 4 digital signal pairs, and 3 analog signal pairs)
- On-orbit mate/demate cycle life: Up to 400 cycles
- Payload support through launch: Up to 8.25 kg



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### 11.4.2.3 Interface Architecture

The active unit consists of four subsystems: a launch-restraint system that secures the interface during launch loads, electrical pass-through cables routing the 29-connection harness, a payload locking mechanism, and a stepper gear motor for controlled engagement and disengagement. The passive unit has no moving parts and is integrated structurally and electrically to the payload or tool, reducing mass, complexity, and failure modes.

- Configuration: Active-passive

### 11.4.2.4 Safety and Operations

The active unit contains embedded telemetry providing three status indications: ready-to-lock state, locked versus unlocked status, and excessive locking force fault detection. These sensors enable autonomous or supervised-autonomous robotic operations without requiring visual confirmation of interface status. The launch restraint system is distinct from the on-orbit locking mechanism, allowing the on-orbit system to be optimized for the 400-cycle life without being overdesigned for the one-time launch load case.

### 11.4.3 Integration and Implementation Considerations

- System Modifications: Designed for integration with NRL 7-degree-of-freedom (DOF) robotic arms on MRV; tools stowed in equipment stowage ports.
- Ground Support Equipment: Contact provider for more information.
- Operational Environment: GEO (RSGS mission); MRV designed for 15-year operational lifetime.



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- <sup>vi</sup> See <https://breakingdefense.com/2026/01/space-force-envisions-rolling-awards-for-new-rg-xx-neighborhood-watch-satellites/>.
- <sup>vii</sup> *International Docking Standard (IDSS) Interface Definition Document (IDD): Revision E*; NASA, 2016; see <https://ntrs.nasa.gov/api/citations/20170001546/downloads/20170001546.pdf>.
- <sup>viii</sup> For more information about Astroscale and the Generation 2 Docking Plate, including access to the Docking Plate Interface Guidelines document, email [salesDP@astroscale.com](mailto:salesDP@astroscale.com).
- <sup>ix</sup> See <https://spacesustainabilityrating.org/the-rating/>.
- <sup>x</sup> COSMOS, or the Comprehensive Open-architecture Solution for Mission Operations Systems, is an open-software framework designed to primarily support the development, mission operations, and flight software of small spacecraft; see <https://hsfl.github.io/cosmos-docs/pages/1-intro/cosmos-overview.html#:~:text=1.1%20COSMOS%20Overview,and%20removal%20of%20assets/nodes>.
- <sup>xi</sup> ITOS, or the Integrated Test and Operations System, is a comprehensive software framework developed at NASA Goddard Space Flight Center (GSFC) for commanding, monitoring, and testing spacecraft. It was later commercialized by The Hammers Company and is used extensively for ground data systems; see <https://www.techbriefs.com/component/content/article/6727-gsc-14012#:~:text=The%20Integrated%20Test%20and%20Operations,SAMPEX%20and%20eleven%20other%20missions>.
- <sup>xii</sup> NOS3 is the NASA Operational Simulator for Space Systems; see <https://nos3.readthedocs.io/en/latest/>.
- <sup>xiii</sup> See <https://www.sbir.gov/awards/212362>.
- <sup>xiv</sup> See <https://www.iotworldtoday.com/connectivity/nokia-4g-network-lands-on-moon> and <https://www.wired.com/story/nokia-4g-network-on-the-moon/>.
- <sup>xv</sup> <https://www.tesat.de/news/press/934-tesat-successfully-completes-optical-communication-terminal-interoperability-test>.
- <sup>xvi</sup> CCSDS 133.0-B-2: *Space Packet Protocol, Recommended Standard, Issue 2* (Blue Book); published June 2020; see <https://ccsds.org/Pubs/133x0b2e2.pdf>.
- <sup>xvii</sup> CCSDS 727.0-B-5: *CCSDS File Delivery Protocol: Recommended Standard, Issue 2* (Blue Book); published June 2020; see <https://ccsds.org/Pubs/727x0b5e1.pdf>.
- <sup>xviii</sup> See <https://science.nasa.gov/mission/osiris-rex/>.
- <sup>xix</sup> See <https://gpm.nasa.gov/missions/GPM>.
- <sup>xx</sup> See <https://www.jpl.nasa.gov/missions/radar-in-a-cubesat-raincube/>.
- <sup>xxi</sup> *Optical Communications Terminal Standard*, version 3.2.0, Space Development Agency, published 24 Mar 2025; see [https://www.sda.mil/wp-content/uploads/2025/04/SDA-OCT-Standard-v3.2.0\\_FINAL.pdf](https://www.sda.mil/wp-content/uploads/2025/04/SDA-OCT-Standard-v3.2.0_FINAL.pdf).

