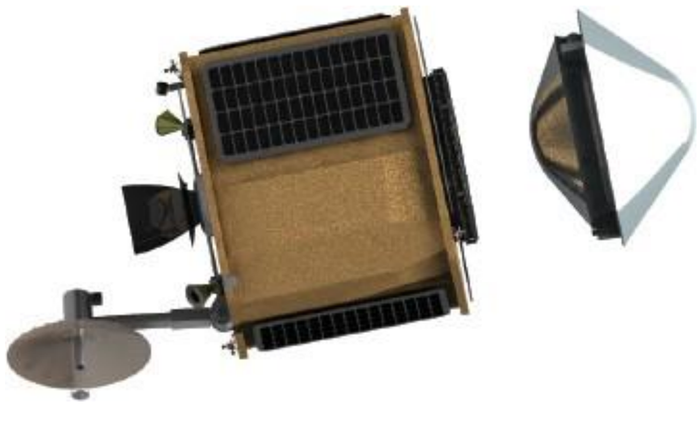
bradford space inc



EXPLORER SPACECRAFT BY BRADFORD SPACE

LOW COST DEEP SPACE TRAVEL

INTRODUCTION

The way that nations, private enterprise, scientists, astronauts, and militaries are accessing and developing space is undergoing rapid change. New technologies, cost points, and funding sources change the calculus on which missions are executed, sometimes with asynchronous cascading effects. New products and approaches become viable faster than organizations can produce them. Two notable changes are the sharp increase in launch availability for small payloads to low earth orbit and increased demand for missions to cislunar and deep space. Bradford Space responds to these complimentary trends with a small spacecraft named Explorer that can conduct missions which start in low earth orbit and travel to cislunar and deep space.

CHALLENGES FOR DEEP SPACE SPACECRAFT OPERATIONS

The heart of the Explorer spacecraft is the propulsion system, powering an integrated system of advanced avionics, communications, and computing suitable for deep space applications. Bradford Space possess the competencies and partnerships to develop and integrate advanced subsystems suited for the operational modes and environments specific to deep space such as:

- High radiation
- Interoperability with distant ground-based communication infrastructure
- Autonomous, untended operation
- Resilience to high energy solar events
- Survival of extreme thermal environments
- Extended periods of dormancy

CHALLENGES FOR SMALL SPACECRAFT LAUNCH

Beyond these requirements for a deep space mission, the Explorer is highly compatible with the burgeoning opportunities for small spacecraft launch:

- Rideshare or small launcher compatible
- Easily shipped
- Easily processed, integrated, and fueled
- Non-hazardous / non-toxic subsystems
- Low cost
- Compliant to standard Interfaces

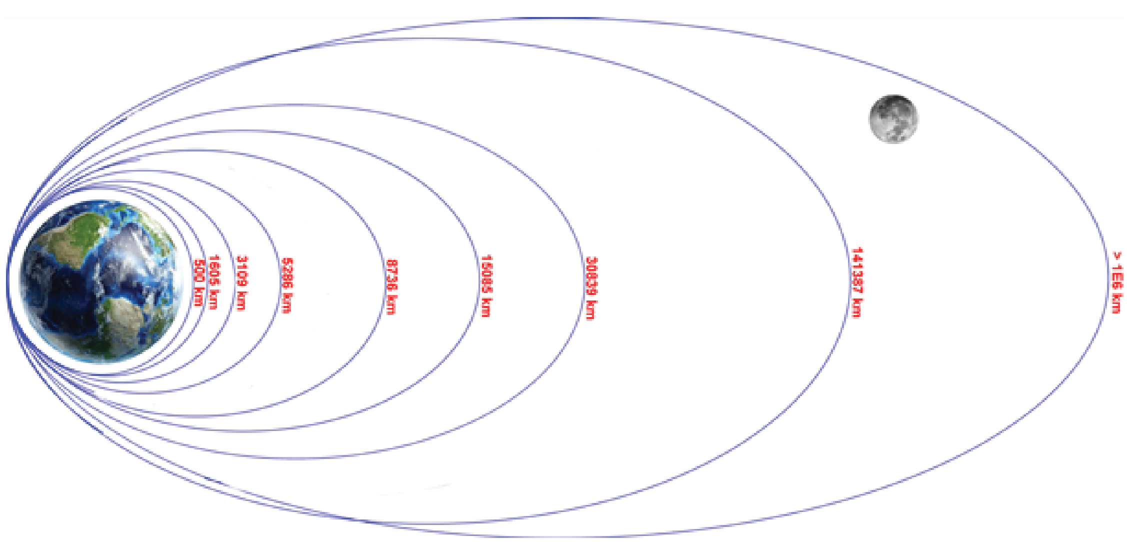


Figure 1: From low earth orbit to cislunar space with Explorer's chemical Propulsion

ONE SPACECRAFT FOR BOTH DEEP SPACE AND RIDESHARE

Bradford works with customers to configure and deliver a mission-specific Explorer configuration whose subsystems are sized for the demands on the mission for: propulsive capability, the particular environment where the mission will operate, and the needs of the payload instruments. This document describes a reference Explorer architecture. It also conveys the latitude about the reference architecture from which customers can expect to benefit. With additional investment and in response to customer requirements, the Explorer can be configured for aeroassist, flyby, rendezvous, and orbital operations at planetary bodies and asteroids throughout the inner solarsystem.

BASELINE EXPLORER CONFIGURATION

The baseline Explorer configuration is a 1 meter cubed spacecraft weighing 300 kilograms, shown in Figure 2. The Explorer employs a breakthrough hydrocarbon/peroxide propulsion system and accommodates standard 24 or 15 inch launch interfaces. The launch interface can be installed on either the forward or aft deck of the spacecraft, and the spacecraft can be configured to withstand launch loads in any mounting orientation. The subsystems of the Explorer are designed to withstand the harsh environment and operating conditions of deep space with specialized power, communications, avionics, thermal, and propulsion.

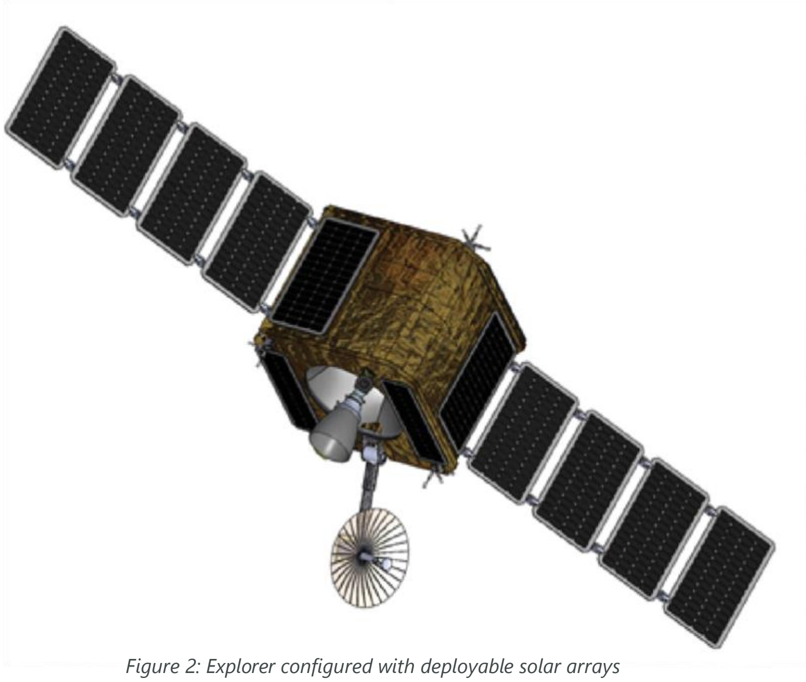


Figure 2: Explorer configured with deployable solar arrays

Constraining Factor	Constraining Opportunity	Constraint	Baseline Explorer
Available spacecraft volume	ESPA-Grand in 5m fairing	100X115X125 cm	100X100X100 cm
Allowable spacecraft mass	ESPA-grand ring	465 kg	300 kg
Propellant Impulse Density	Hydrocarbon/HTP blend	350 sec * gr / cc	350 sec * gr / cc
Payload Instrument Mass	Typical smallsat instrument	30 kg	30 kg
Required Delta V	E.g. LEO to NEO Rendezvous	E.g. 4 km / sec	5 km / sec

Table 1: Design drivers

PERFORMANCE

The opportunity to conduct deep space missions on rideshare and small launch is possible only through high performance propulsion technology. Bradford Space develops such propulsion technology, including both the Meteor and the ECAPS propulsion systems. Not only do these systems have high I_{sp} and sufficient thrust, but they also meet hazard and safety requirements of rideshare missions. Performance of Explorer spacecraft with varying propellant and payload masses are shown in Figure 3.

A customer can influence the necessary performance (and spacecraft configuration) in several ways. Propellant mass, payload mass, and delta-v can be traded against each other to take full advantage of mission design optimization and available launch service capability.

The chemical propulsion systems of the Explorer are high thrust as compared to electric propulsion systems. A high thrust to weight ratio is necessary for many trajectories to deep space. Spacecraft employing higher thrust chemical propulsion spend less time in Earth's radiation belts and can arrive at their destinations sooner. Insertion at the final destination is also greatly simplified, and even enabled in some cases, by having a higher thrust to weight ratio than electric propulsion can afford.

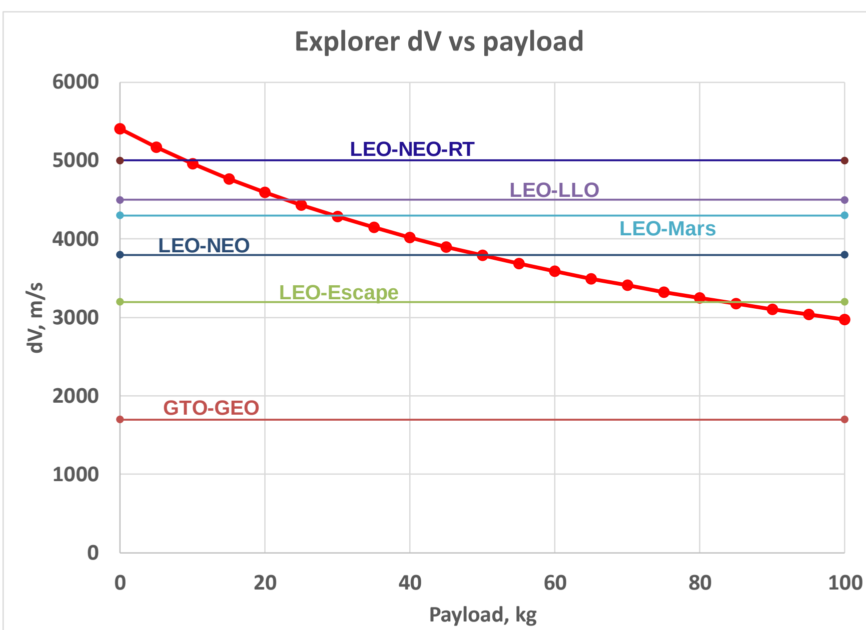


Figure 3: Total delta-V capability vs payload mass allocation along lines of constant mass

PAYLOAD INTERFACE

Explorer has two locations for mounting the payload: a 12 U internal volume that is partially protected from incident ionizing radiation, and the forward deck. The “internal” volume is in a recessed frustum in the forward deck. Figure 4 shows the recessed payload volume as well as the forward deck onto which additional payload may be mounted.

Figure 4: Explorer configured with body mounted solar arrays

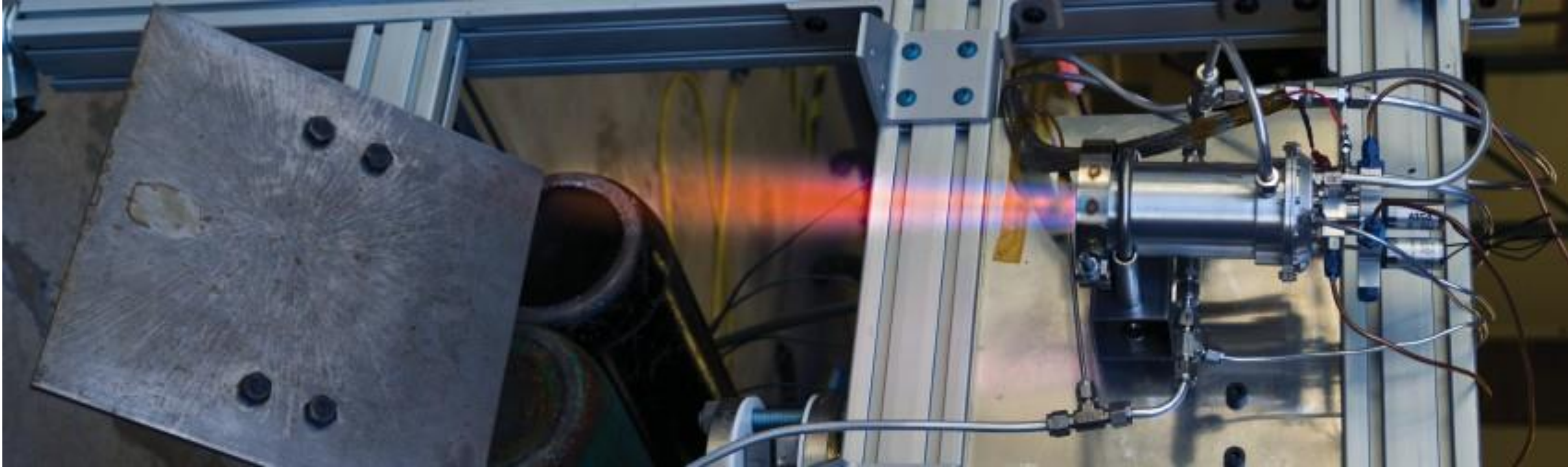


Figure 5: Meteor green bipropellant system under test at Bradford facilities

PROPULSION

The most enabling aspect of the Explorer spacecraft is the propulsion system. Bradford Space propulsion offerings are space storable, easy to handle by ground crews, and possess high density and I_{SP}. The three highest performing propulsion options available for Explorer are:

- Meteor bipropellant (hydrocarbon blend / HTP)
- LMP-103S bipropellant (LMP-103S / HTP)
- LMP-103S monopropellant

These systems vary by thrust level, I_{SP}, current technical maturity, and physical complexity. In addition to the primary propulsion system, the reaction control system thrusters, shown at the corners of the spacecraft in Figure 4, use a propellant mix of gaseous oxygen and hydrocarbon blend on a Meteor system and LMP-103S when used with a LMP-103S primary propulsion system. This means the RCS always shares propellant with the primary propulsion system on Explorer.

The Explorer's Meteor bipropellant fuel tanks are self-pressurizing. The Meteor HTP Oxidizer tank is pressurized from a gaseous oxygen tank, which also provides oxidizer for the Meteor reaction control system thrusters. These thrusters are based on the Meteor igniter. Both of these thrusters have been successfully fired in developmental tests.

For Explorers using LMP-103S green monopropellant, the two possible configurations are bipropellant with HTP oxidizer and a simple, lower performance monopropellant configuration.

Bradford's LMP-103S monopropellant solution has an extensive legacy of both spacecraft primary propulsion and reaction control.

<table>
<tr><th></th><th>Meteor</th><th>ECAPS Biprop</th><th>ECAPS Monoprop</th></tr>
<tr><td>Main Thruster Fuel</td><td rowspan="2">Propane/Butane Blend</td><td rowspan="2">LMP-103S</td><td rowspan="4">LMP-103S</td></tr>
<tr><td>RCS Fuel</td></tr>
<tr><td>Main Thruster Oxidizer</td><td>High Test Peroxide</td><td>High Test Peroxide</td></tr>
<tr><td>RCS Oxidizer</td><td>Gaseous Oxygen</td><td>LMP-103S</td></tr>
<tr><td>Main Engine I_{SP}</td><td>305 s</td><td>320 s</td><td>243 s</td></tr>
<tr><td>Main Engine Thrust</td><td>285 Newtons</td><td>> 200 Newtons</td><td>200 Newtons</td></tr>
</table>

Table 2: Available Explorer propulsion systems

ELECTRICAL POWER SYSTEM

The Explorer power system is built around the Nova power Conditioning and Distribution Unit (PDCU). It has been designed from its inception for the unique environment and operating considerations specific to deep space missions. The configuration of the overall electrical power system is tailored for each specific mission. During spaceflight, the Electrical Power System performs resiliently to respond to changing natural and induced environments. The Nova PDCU is lightweight considering it's high power throughput capabilities.

FLEXIBILITY DURING DESIGN

Relevant variations driving the selected configuration include constraints on the expected spacecraft attitudes relative to the sun, payload power needs, and maximum and minimum expected solar irradiance levels. The final software, component, and physical architecture configuration of the Nova system are optimized for these considerations. In response to these drivers, the physical design can be chosen with different total number of cells per solar array string, and arrays can be deployed or body mounted, large or small. Batteries are sized according to power available, eclipse time, and system power draw.

All sides of the spacecraft include small "keep-alive" solar panels to ensure that the spacecraft will always have enough power to survive contingency situations when primary solar array pointing is not available.

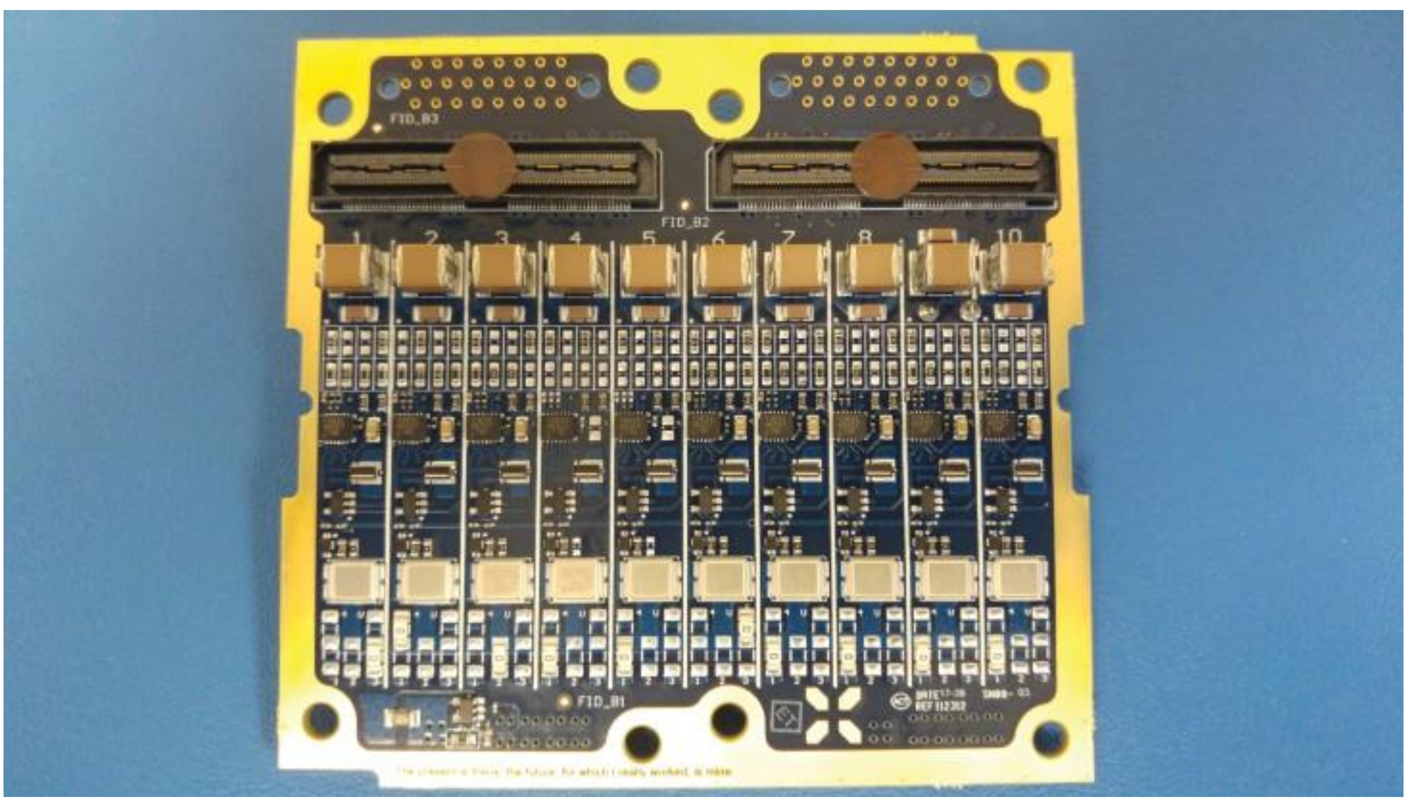


Figure 6: Nova power system peak power trackers

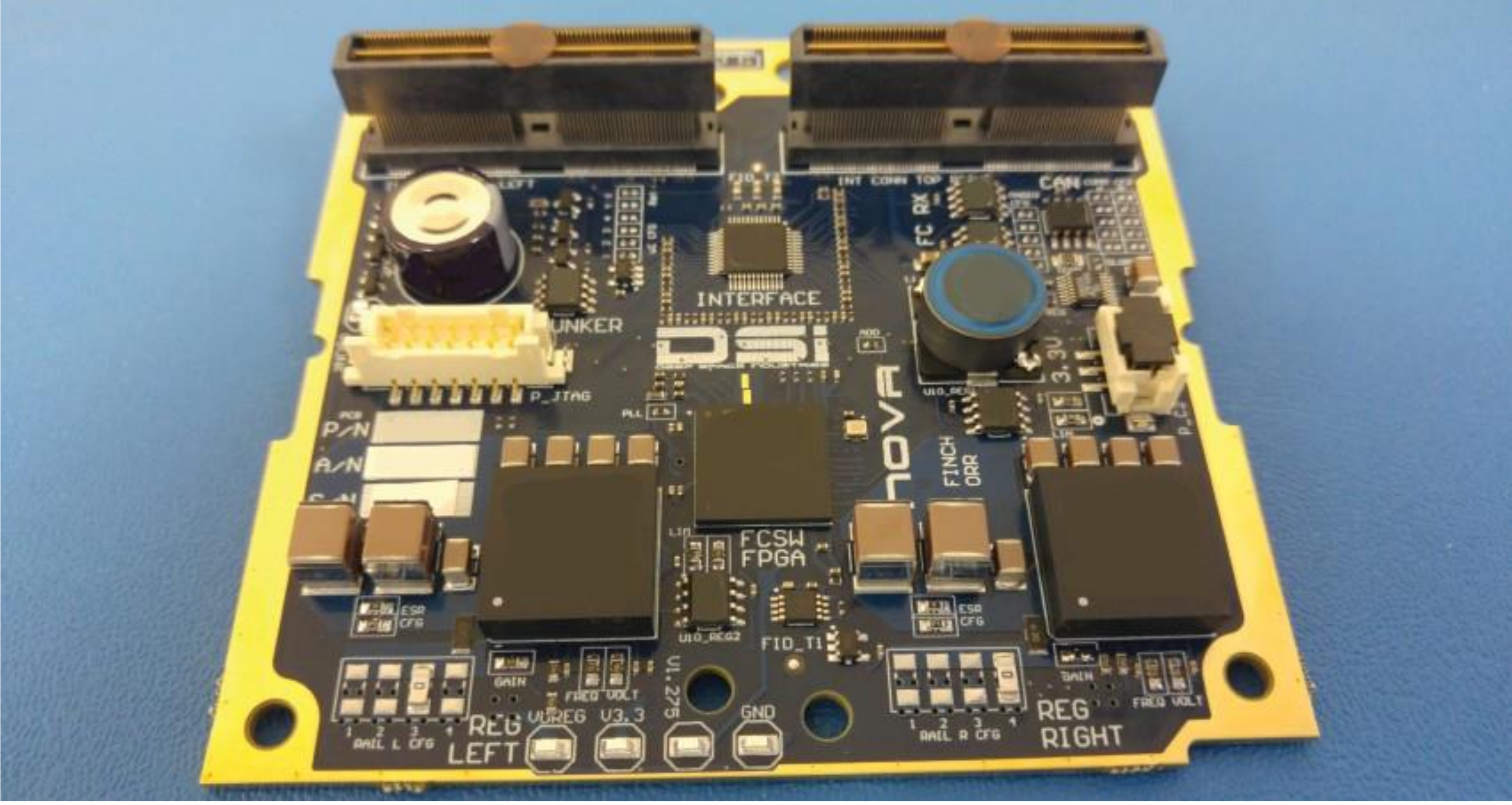


Figure 7: Nova power system scalable power management and distribution systems

FLEXIBILITY DURING FLIGHT

During spaceflight, sophisticated features present in all Explorer spacecraft enable the chosen physical configuration to operate effectively in a number of attitudes, illumination conditions, and thermal environments. The Nova power system employs pairs of synchronized buck-boost converters to regulate voltage without substantial "noise." Peak power trackers ensure optimal charging as the illumination angle and other factors change array charging characteristics. As the spacecraft has multiple arrays, these arrays' peak power trackers are synchronized to operate together despite different instantaneous operating characteristics.

Resettable solid-state switches protect the bus from overcurrent events such as latch-up. Finally, the Lithium-ion batteries are fault tolerant against failure of individual battery cells.

Some spikes in ionizing radiation beyond that typical of the operating environment can be predicted: Ionizing radiation from solar proton events, sometimes called "solar flares," are preceded hours or days by faster-moving electromagnetic radiation. Also, the onset of high radiation flux occurs gradually over a length of time that provides awareness and allows for planned response. When such an event is detected by ground crews or by optional circuitry on the spacecraft itself, Explorer's Nova power system, shown in figure 7, is commanded to enter "Bunker mode." Bunker mode disconnects the main power bus from batteries and solar panels.

High radiation flux can cause damage from collisions of high energy particles, and to a lesser extent electromagnetic and electrostatic effects. All the electronic subsystems, including the primary and secondary onboard computers, are powered off during Bunker mode. This reduces hazards to those systems associated with high radiation flux events.

The NOVA PDCU emits low electromagnetic noise to minimize interference with radio communications and sensitive instrument operation. Also, the NOVA PDCU will be qualified to survive temperatures as low as -196°C, which envelopes lunar nighttime and eclipse temperatures.

AVIONICS

The Explorer possesses a highly reliable and capable avionics subsystem. Key tenants of the Explorer avionics system are:

- Designed redundancy at the subsystem level
- Physical protection from radiation by virtue of being located behind propellant tanks
- Low power consumption
- Open source development tool chain accelerates system configuration and integration
- Survivability of low temperatures and high radiation

ELECTRICAL INTERFACES

The avionics subsystem has a number of available data interfaces, including support of the Controller Area Network (CAN) bus, CMOS sync serial, RS-422 / RS 485 connections, Gigabit Ethernet, LVDS, and USB. This broad array of interfaces provides convenience and interoperability with many instrument providers.

PERFORMANCE

Each onboard computer has a 1 Gigahertz ARM-V7 processor and includes 512 Gb of nonvolatile memory and 256 MiB of volatile memory (RAM.) The common processor architecture enables broad software and hardware compatibility. One of the dual onboard computers is shown in figure 8.

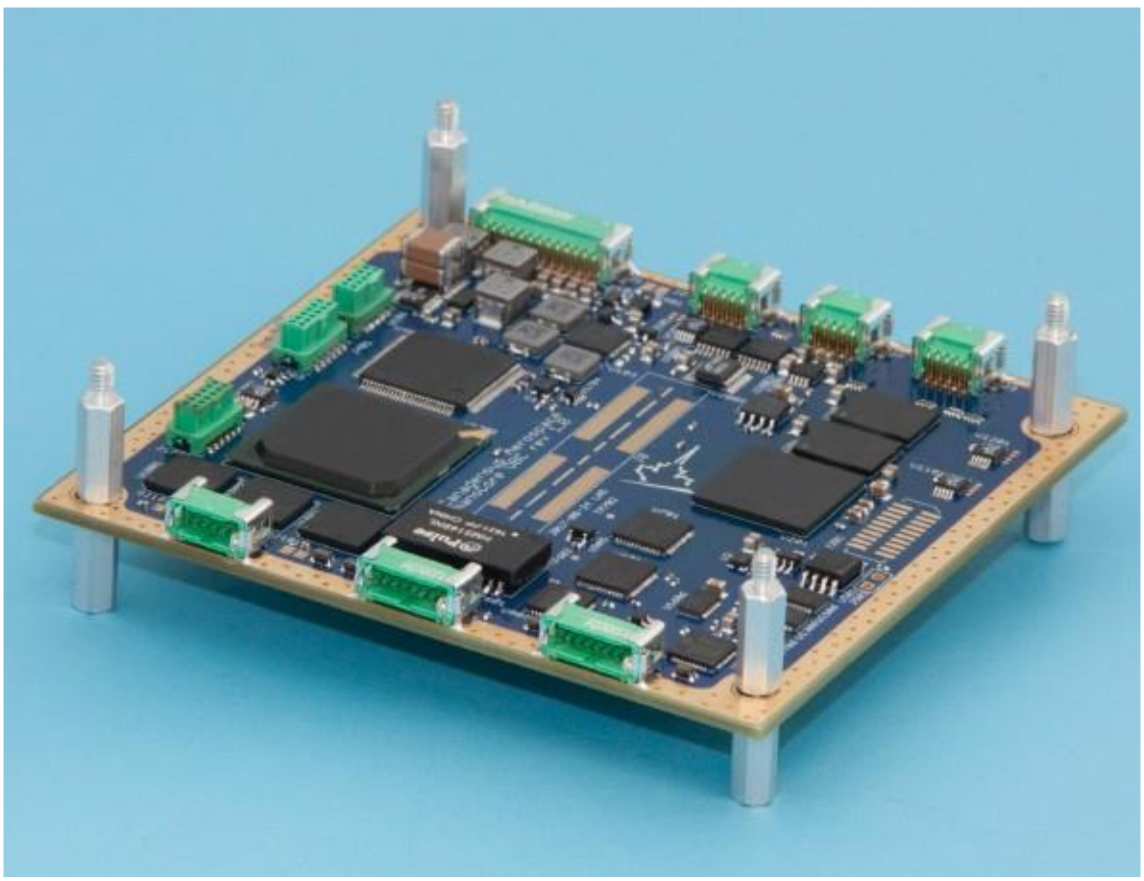


Figure 8: Redundant Explorer onboard computer

Figure 9: Deep Space Network antenna at Canberra, Australia

SURVIVABILITY

One of the hazards encountered by deep space spacecraft are incident high energy particles from deep space or high particle fluxes from solar proton events. These rare yet consequential occurrences can cause “Single Event Effects” such as “latchup” in the circuitry or disruption to computer memory systems. Latch-up causes a circuit to short until the power is reset. Memory disruption is often as simple as a single bit flipping from “1” to “0.” With forethought and careful design, A spacecraft can recover from either of these situations, potentially autonomously, and restored to its original configuration and function. Explorer is designed to have this recoverability. However, some very high energy particles can cause unrecoverable and permanent “burnout” damage to circuitry. For such eventualities, Explorer onboard computers are designed to have redundancy at the board and component level.

The design of reliable spacecraft avionics must be tailored to the operating environment. This design consideration differentiates Explorer spacecraft from spacecraft designed to only operate in low earth orbit. The Explorer onboard computers are designed with redundancy and robustness at the subsystem level. In the event of an unrecoverable failure in one of the computers, the spacecraft enters safe mode and ground controllers can switch the system over to the redundant computer.

ATTITUDE DETERMINATION AND CONTROL

Bradford has provided over one thousand sun sensors which have flown in space of several varieties. Explorer includes six mini fine sun sensors, as well as two Sinclair Interplanetary ST-16RT2 star trackers.
Both units have extensive flight history operating in severe radiation environments. The baseline Explorer configuration achieves attitude control through reaction control system thrusters, although reaction wheel control is also available. Radiometric ranging of the spacecraft with Earth is afforded through the communication system. The spacecraft also includes rate sensors.

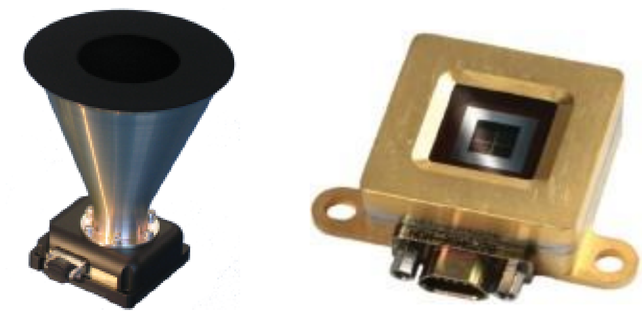


Figure 10: (left) Sinclair Sun tracker, and (right) Bradford mini fine sun sensor

COMMUNICATION

Spacecraft communicating with Earth ground stations from great distances call for specialized transceivers and antennas. In the past, deep space missions communicate with NASA's deep Space Network or ESA's ESTRACK. Explorer will be capable of communicating with such ground infrastructure, but Bradford Space has partnered with commercial ground station networks to develop an alternative solution. While government customers often have specific priorities and goals with regard to ground infrastructure, non-traditional government procurements and commercial customers are willing to find the lowest cost solution without infrastructure constraints. The Explorer is initially available with the flight proven IRIS transponder and deep space Network communication, even while Bradford Space develops a lower cost alternative.

The Explorer has been designed to allow the command of subsystems by direct radio control. Ground controllers can send commands which are decoded by hardware on the spacecraft, as opposed to being decoded by onboard computers. This functionality increases options for recovery from off-nominal situations when the onboard computer is unavailable.

OMNIDIRECTIONAL COMMUNICATION

Explorer is configured with two omnidirectional antennas, providing whole sphere coverage. These are necessary for communications with the spacecraft when the high gain antenna is not pointed at ground stations, such as during recovery or
safe-hold operations.

IRIS TRANSCEIVER AND KAPDA ANTENNA FROM NASA'S JET PROPULSION LABORATORY

IRIS works with the deep space Network and affords both communication and radiometric ranging. As configured for Explorer, the IRIS will provide uplink at 7.2 GHz and downlink at 8.4GHz. Initial Explorer configurations employ a derivative of the successful KaPDA antenna employed on the MarCO CubeSat and Aeneas Colony I CubeSat. Those applications hard mounted the antenna to space primary spacecraft structure, although the size of the Explorer allows for the antenna to be mounted on a deployable boom, should that be called for by mission requirements.

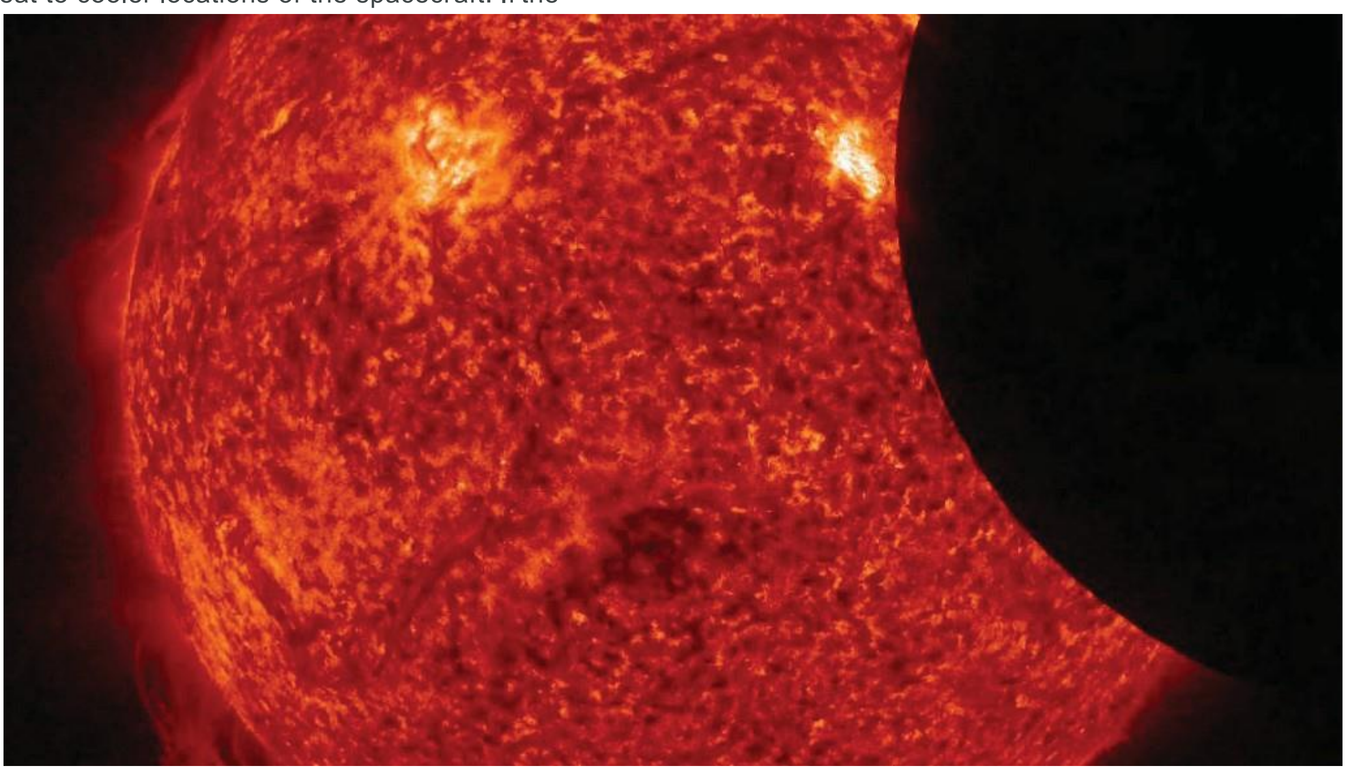
EVOLVED COMMUNICATION SYSTEMS

Costs driven by the communications approach include both the flight hardware as well as the ground infrastructure. Bradford Space is developing a lower cost transceiver and antenna and is working with commercial ground stations which have not previously worked with deep space spacecraft. Closely tied with cost effectiveness, Bradford's performance enhancements include future transceivers that allow for higher power usage. Higher data rates are associated with lower ground station usage durations and cost. Bradford offers the lowest cost communication solution that meets schedule and performance requirements. However, Explorer can be configured per customer constraints on ground infrastructure or flight configuration with respect to wavelength or ground stations.

Bradford Space is also exploring the suitability of laser interconnects and phased array antennas as they may apply to deep space communication.

THERMAL CONTROL

Explorer spacecraft may travel from lengthy eclipses to regions as close to the sun as Venus. Like the power subsystem, the thermal system design is mission-unique. In one example, Multi-Layer Insulation is wrapped around the exterior of the spacecraft to insulate avionics and propellant tanks. Deployable Solar panels are mostly decoupled thermally from the rest of the spacecraft, although shunts can be used to transfer excess solar array heat to cooler locations of the spacecraft. If the spacecraft travels far from the sun, then excess heat from the arrays can be transferred through shunts to components needing heaters. When mission-specific thermal analysis reveals this approach to thermal management insufficient, then individual electric or radioisotope thermoelectric generator spot heaters can be included in the configuration. Battery sizing and required heating power may be impacted by eclipse times of the desired orbit.



Explorer Spacecraft by Bradford Space.

SUMMARY

The Explorer bus solves a significant and outstanding problem: Providing transportation of small payloads to deep space locations. In the past, missions leaving earth orbit required high energy launches or massive spacecraft busses. Today, payloads and spacecraft are trending toward smaller size and mass. Only through use of a small spacecraft with both high performance propulsion and readily processed propellants can the demand for small launch to deep space be satisfied. Bradford Space has anticipated this need and developed the Explorer platform to satisfy the growing demand. Whereas the cost of launch to deep space had been an overwhelming contributor to the cost of previous deep space missions, the Explorer spacecraft lowers the barrier to entry for payload and instrument providers traveling to deep space. The talented team at Bradford can perform the necessary mission specific analysis and configuration to ensure that no matter the destination or mission, Explorer will fulfill customer needs and pave the pathway into deep space.

ABOUT BRADFORD SPACE

Bradford Space is a global space systems group building non-toxic propulsion, space station facilities, deep space missions, and attitude control systems. U.S.-owned and consisting of about 75 staff located in New York, the Netherlands, Sweden and Luxembourg, Bradford Space has a record of building over 2000 products currently flying in space. Bradford is a leading provider of products to aerospace primes, space agencies and venture-backed space companies around the world.

Bradford Space products have either flown on or are currently baselined for a wide variety of deep space or science missions. Missions with Bradford content include:

- BepiColombo mission to Mercury (Reaction wheels, Xenon flow control units, Pressure Transducers)
- ArgoMoon to the Moon (ECAPS 100mN HPGP thrusters)
- LISA Pathfinder to the Earth-Sun L1 point (mini Pressure Transducers)
- JUICE to Jupiter (Sun sensors)
- The SpaceIL Beresheet and the iSpace Hakuto landers to the lunar surface (mini Pressure Transducers)
- Rosetta mission to comet 67P/Churyumov–Gerasimenko and asteroids 21 Lutetia and 2867 Šteins (Pressure Transducers and electronics)

Bradford systems engineers have a long and experienced history with spacecraft design and mission engineering. Bradford Space engineers have been responsible for either the mission design or major subsystems on PurdueSat, TOFSAT, SAOCOM-CS, European Student Moon Orbiter, HawkEye-360 Pathfinder, HawkEye-360 Batch A, Capella and the BlackSky constellation.

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