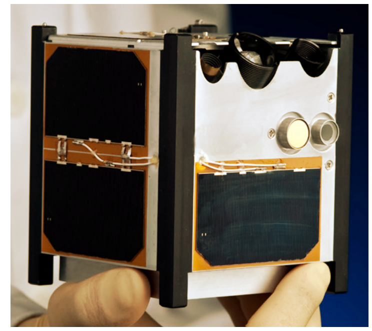
AEROSPACE'S AEROCUBE PROGRAM

Executive Summary

The Aerospace Corporation (Aerospace) has been at the forefront of CubeSat technology and the miniaturization of satellites since before the CubeSat standard existed. Aerospace flew the world's first containerized satellite 20 years ago and has continued to push the state of the art in the 35 plus satellites that we have flown since then. Technologies and CubeSat missions pioneered at Aerospace have been adopted by many organizations in the rapidly growing CubeSat community, enabling Aerospace to have a leadership role in helping shape what is today's CubeSat enterprise.



CubeSats derive their name from the so-called "1U" building block, which is a 10 × 10 × 10 centimeter cube, typically weighing around 1 kilogram.

The long track record of the AeroCube program demonstrates the value of continuous development, with every flight suggesting improvements to be incorporated in subsequent flights. Aerospace's CubeSat program has demonstrated many technological and mission firsts. In addition, multiple publications based on the CubeSat program have had a significant impact on the small satellite industry.

- First tracking and comm from a containerized satellite.
- First 3-axis, stabilized CubeSat to demonstrate 1 degree pointing accuracy.
- First CubeSat to demonstrate orbit control using variable drag profiles.
- First space-to-ground optical communication link from a CubeSat.
- First optical illumination of resident space objects and ground assets from a CubeSat.
- First to demonstrate commercial infrared cameras from a CubeSat to perform military and civilian missions.
- First water-based propulsion demonstration and first CubeSat propulsion system to meet ISS safety standards.
- First demonstration of a solid rocket motor propulsion system on a CubeSat.
- Closest rendezvous and proximity operations (RPO) demonstration for a CubeSat and first CubeSat to collect imagery of another CubeSat as part of an RPO demonstration.
- Developed and published a streamlined assembly methodology for adhering solar cells using double-sided polysiloxane pressure sensitive adhesive (PSA) polyimide film. This Aerospace-developed process has achieved wide scale industry adoption, helping to decrease cost and improve reliability.
- Developed and published shape-memory alloy actuators for small satellites. This innovation enables resettable release mechanisms that resulted in 100% deployment success for Aerospace small satellite missions.
- Of historical significance, the last image taken of a space shuttle on-orbit.

Photo taken by shuttle astronaut of PSSCT-2 deploying from STS-135 in 2011.

In our role as an FFRDC, we've used our CubeSat experience to develop novel space architectures that include a mix of high-value assets and a proliferation of small satellites; we've partnered with industry to advanced their own CubeSat capabilities using our data and experience; and we've worked with academia to help advance a new technology that has transformed how we define an operationally relevant space capability.

PSSCT-2 returning the favor and taking photo of STS-135 in 2011. The last photo captured of a space shuttle in orbit.

Looking to the future, we will press the art of the possible in CubeSats in higher orbits up to GEO, demonstrate operating safely in and around high-value assets, and develop new concepts for miniaturized satellite technology and sensors. By integrating cryptographic solutions, Aerospace plans to add the capability to host classified payloads. Development and promotion of standardized payload interfaces will also help to reduce integration costs and get more high-value payloads to orbit. Aerospace will continue to help rewrite the rules to deliver real missions in small packages.

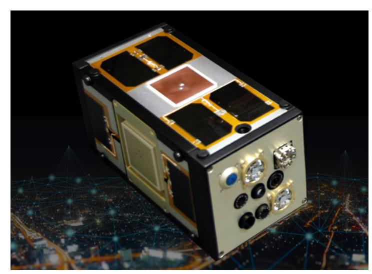
History: Going Small in the 90s

The Aerospace small satellite program began in the mid-1990s, well before the creation of the CubeSat standard. Essentially all containerized satellites developed in the past decade conform to a published CubeSat standard; however Aerospace started flying containerized satellites even earlier. Though our earliest forays into space weren't conventional CubeSats, they played a big role in the development of the AeroCube and in the growth of the CubeSat industry. An Aerospace team worked with Stanford astronautics professor Bob Twiggs to deliver and deploy two of the OPAL PicoSats (OPAL is Orbiting Picosatellite Automated Launcher). Professor Twiggs, utilizing his experience from the OPAL project, went on to be one of the co-developers of the CubeSat concept.

Aerospace flew the world's first containerized satellite known as OPAL PicoSats in 2000. OPAL grew out of a combination of DARPA's strong interest in MEMS (micro electro-mechanical systems) at a time when Aerospace's laboratories were also pursuing the technology. Aerospace suggested we could produce ultra-miniaturized satellites that would be far less expensive to fly than the large satellites that were the norm at that time. The OPAL PicoSats operated for only two weeks (as designed) but were successful and provided a proof-of-principle demonstration showing that it was possible to design, build, test, launch, and deploy very small satellites.

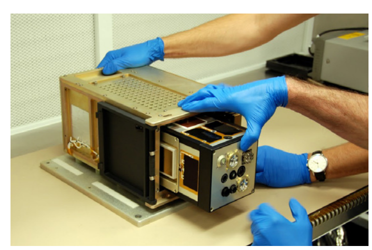
Leading the CubeSat Revolution

When Aerospace started development of PicoSats and AeroCubes, there were no commercial vendors for CubeSat-scale satellite subsystems or components, so Aerospace developed everything in-house. Aerospace published papers on many of the components and subsystems developed, including miniature sun and Earth attitude sensors, miniature star trackers, characterization of MEMS gyroscopes, cold-gas and warm-gas propulsion systems, miniature reaction wheels, GPS-based orbit determination, optical communication transmitters, and characterization of production and experimental solar cells.



PSSCT-2, deployed from STS-135 in 2011.

AeroCube-1 was lost to a launch failure; however, AeroCube-2 was already in process and it flew in 2007. The earliest AeroCubes were focused on developing and demonstrating fundamental bus technologies (power, communications, navigation, attitude control, and propulsion) needed to support future missions. The core foundation of the AeroCube program was based on the PSSCT (PicoSat Solar Cell Testbed), deployed from Space Shuttle Endeavour mission STS-126 in 2008 and the follow-on PSSCT-2, deployed from STS-135, Atlantis, in 2011 which continued to mature the core spacecraft subsystems. AeroCube-4, launched in 2012, established the state of the art for CubeSats by evolving from a technology demonstration platform to a fully functional mission-oriented spacecraft. Demonstrating tracking of ground and space objects with the first 3-axis stabilized control system, AeroCube-4 went on to collect thousands of Earth images over an impressive seven-year mission life. The capabilities demonstrated by AeroCube-4 helped convince both defense and NASA customers that CubeSats could execute real missions.



PSSCT-2 being loaded into launcher.

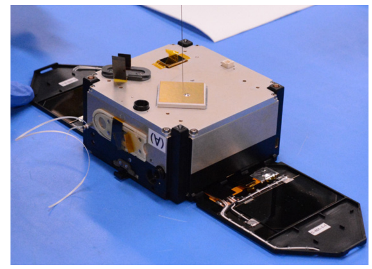
The advancements made up to this point enabled a low-cost, in-space testbed never before realized in this size form factor. Even today we find the CubeSat provides an effective testbed environment for miniaturized sensors, testing commercial parts and systems in an authentic environment and finding affordable access to space as a rideshare enabled by the containerized satellite developed by Aerospace.

Recent Projects and Major Contributions to the Space Enterprise

As the AeroCube platform matured and we were able to demonstrate precision pointing to under 1 degree, AeroCubes started taking on actual mission applications. For example, we were able to use CubeSats as optical tracking targets for space domain architecture demonstrations. In addition to AeroCube-4 and 5 being space-based optical tracking assets, these AeroCubes also demonstrated multiple de-orbit enhancement devices to help find solutions to space traffic management by reducing orbit lifetime after the completion of the primary mission.

Demonstrating the Value of an Affordable Rapid Space Platform

The AeroCube-6 mission was an opportunity to provide on-orbit validation tests for a set of micro-dosimeters developed at Aerospace. This was an early example of the type of affordable and rapid space flight opportunities enabled by CubeSats for new technology. The technology behind these radiation sensors has since been transferred to industry and flown on dozens of spacecraft, including the REACH payloads on the Iridium NEXT constellation and other national security space systems.

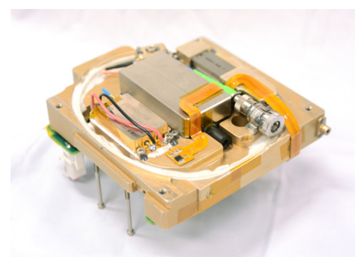


AeroCube-6, the first half-unit CubeSat.

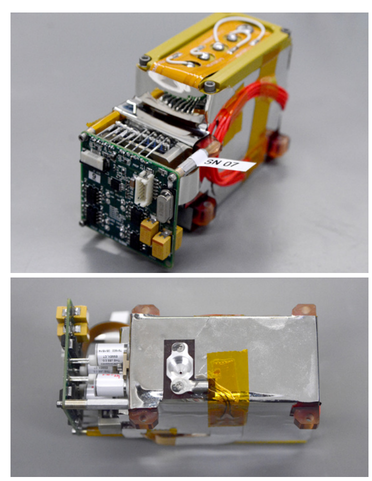
The two AeroCube-6 vehicles, at only 0.5U in size, help drive miniaturization of CubeSats efforts further. Without volume for reaction wheels, the AeroCube-6 vehicles utilized magnetic torque rods for actuation and successfully demonstrated the first use of spin stabilization in a CubeSat form factor. The AeroCube-6 vehicles built on the atmospheric drag control techniques first demonstrated on the AeroCube-4 mission. AeroCube-6 was the first mission to demonstrate that variable atmospheric drag via orientation control could be used to manage relative orbit spacing. This published technique was later adopted by Planet to control the phasing of their satellite constellation.

High Speed Optical Data Links from CubeSats

The Optical Communication and Sensor Demonstration (OCSD), also known as AeroCube-7, originally proposed demonstrating a 5 Mbps optical link from space to ground. The fiber laser transmitter designed and demonstrated for this program achieved 200 Mbps error-free for several minutes during a ground station pass. This technology was later infused into multiple Aerospace-developed CubeSat demonstration missions and is currently used operationally to downlink gigabytes of payload image data. The design for the fiber laser communications transmitter was published and has drawn interest from multiple organizations outside Aerospace. The AeroCube-7 laser transmitter design serves as a foundation utilized by multiple laser communication terminals under development throughout the small satellite industry. Aerospace is an industry leader in the area of optical communications for CubeSats. First demonstrated and published in 2018, nearly three years later, no other company has yet to successfully demonstrate an optical link from a CubeSat. The AeroCube-7 project also developed and published a design for a water-based propulsion system. Commercial developers have since brought products to market based on this propulsion technology. The papers published about the AeroCube-7 program are among the most frequently accessed in the annual Utah State University SmallSat conference archives.



Laser transmitter for the Optical Communications and Sensor Demonstration (OCSD).



Water-based propulsion unit for the Optical Communications and Sensor Demonstration (OCSD).

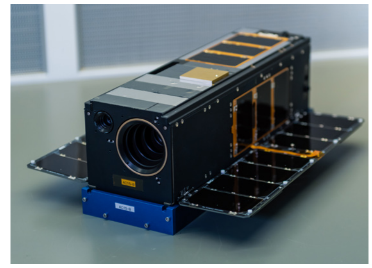
Aerospace also partnered with NASA's Jet Propulsion Laboratory (JPL) to demonstrate the first reflectarray antenna technology on the Integrated Solar Array and Reflectarray (ISARA) spacecraft. This antenna technology went on to enable the communications link with MarCO spacecraft that traveled to Mars, the first interplanetary CubeSats.

Demonstrating Affordable Space-Based Remote Sensing with Commercial Technology

In a series of missions, the AeroCube program has helped advance both visible and infrared imaging capabilities for the space enterprise. The CUMULOS payload (CubeSat Multispectral Observing System), flown on the ISARA spacecraft, was an experiment in the performance of commercial, off-the-shelf (COTS) imaging systems in space, combining visible, short-wave infrared (SWIR) and long-wave infrared (LWIR) cameras into a single system.

The CUMULOS experiment allowed us to perform in-space validation of COTS sensors, to demonstrate techniques for radiometric calibration of these sensors, and to develop a data processing pipeline for CUMULOS that has been used for all subsequent AeroCube imaging programs, including AeroCube-11, which performed in-space validation of new imaging sensor technology and processes.

Most recently, our CubeSat imaging experience was put to use on AeroCube-15 for the US Space Force Space and Missile Systems Center's Rogue-α,β rapid reconstitution demonstration. The Rogue-α,β spacecraft were able to capture visible and shortwave infrared (SWIR) imagery of weather phenomenology such as Hurricane Sally, California wildfires, active volcanos and launch events. The imagery data obtained is being used to inform future experiments and support ground processing algorithm development.



AeroCube-15, a 3U CubeSat.

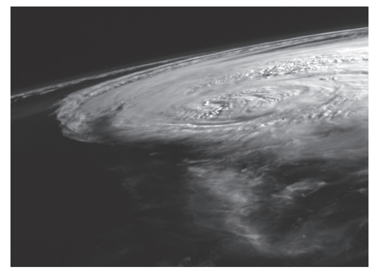


Image of Hurricane Sally, taken by AeroCube-15.

Moving the Laboratory Bench to Space

Aerospace has a strong R&D program related to solar cell technology that has been able to leverage multiple AeroCube missions to provide timely solar cell characterization data from experimental cells produced by domestic and international suppliers. These valuable in-space performance measurements have helped guide advancements in solar cell efficiencies over the past decade. Aerospace is able to share real on-orbit data with suppliers, providing them with unique insight that would have been cost-prohibitive on their own. The AeroCube program provides the largest and most impactful on-orbit solar cell testbed capability in the world.

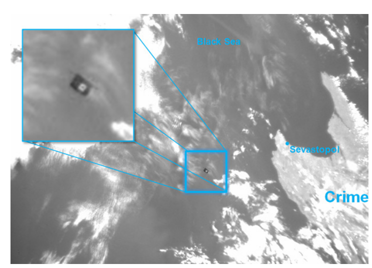
There has been an extended series of flights of eight spacecraft over the past five years as technology testbeds using the AeroCube platform. This testbed program provides an opportunity to invest in research and development of new space technologies, including materials, solar cells, radiation shielding, image sensors, advanced processors, and thrusters, among others. The program can be thought of as an extension of the Aerospace laboratories into space in partnership with industry; the program reaches across Aerospace for ground testing and evaluation of new technologies, and then exercises these technologies in space. The ability to compare in-space results with laboratory results provides a rapid and robust path to raising the technology readiness level (TRL) for technologies possibly not previously considered for space applications. This type of affordable and rapid space flight testbed provides space readiness validation at the leading edge of the technology pipeline. Our customers are highly satisfied with this program and regularly inquire how it might be possible to increase the flight cadence and payload capacity.

Using Affordable Space Test Assets to Advance Space Traffic Management

In addition, AeroCube-10 has an upgraded version of the propulsion system first demonstrated on AeroCube-7, and has been more successful in demonstrating proximity operations, including recently having the two spacecraft approach one another close enough that one was able to obtain a series of photos of the other in orbit at less than 25 meters.

Accelerating the Space Enterprise with Small Satellite Technology

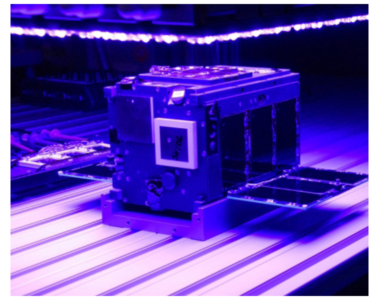
The Aerospace CubeSat program continues to make cutting-edge advances in the capabilities of CubeSats, both in supporting technologies and in mission results. The technology roadmap for the AeroCube program includes significant development in several areas, many of which extend capabilities we've already developed, and some of which will take us in entirely new directions.



AeroCube-10B photographed its twin satellite in orbit from 22 meters away.

In the next five years, the AeroCube program strives to develop and demonstrate several key enabling technologies. The future of the AeroCube program will be focusing on advanced autonomy and maneuverability, onboard processing using AI, space networking technologies, and going to higher orbits, including GEO, where the consequences of mission errors are much higher. Our partners in industry are focused on similar objectives, but as an FFRDC, we will be exploring the full spectrum of technologies to ensure the best innovations in SmallSats are being delivered to the space enterprise. As we have done in the past, we will continue to share and transition these capabilities to our customers and our industry partners. Here are some of the near-term investments and demonstrations planned:

- S-band communications with NSA-certified cryptography that could enable future classified missions and payloads.
- Radiation tolerant onboard computing that is still compact and low power to enable future missions above low Earth orbit.
- Advanced rendezvous and proximity operations capabilities including autonomous formation control. This could enable future distributed aperture collection missions and in-space inspection of other spacecraft.
- Large delta-V propulsion capability, greater than 1 km/s. This could help expand potential rendezvous and proximity operations mission options.
- Advanced optical communication links both from space to ground at higher data rates and crosslinking between CubeSats.
- Standardized payload interfaces that allow for complex payload hosting with stressing power, data, and timing requirements.



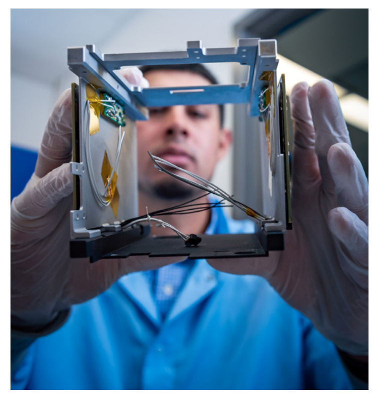
AeroCube-10 being tested in the large area solar simulator in El Segundo.

Conclusion

Aerospace has a rich history of developing and flying CubeSat-scale spacecraft. Aerospace flew the world's first containerized spacecraft in 2000. We've delivered 39 spacecraft to date, with more than 20 still operational on orbit; Aerospace operates the world’s largest fleet of experimental CubeSats, a fleet that is exceeded in size only by the fleets of the commercial operators Planet and Spire.

The technologies developed for the AeroCube program, as well as the broader range of space technologies demonstrated by the AeroCube program, are having a significant effect on the space community. Techniques and technologies developed by Aerospace have been, and continue to be, adopted by others in the CubeSat community, even while we continue to push the envelope of what can be done with CubeSats.

Aerospace has a reputation for taking on the hard problems in space technology development, and our CubeSat program is able to push development of technologies that may not be of readily apparent value to industry. We took a leading role in showing the potential value of CubeSats in the space enterprise and continue to work to extend the boundaries of what can be done with kg-class spacecraft.



A technician begins assembly of an AeroCube.

The Aerospace Corporation

The Aerospace Corporation is a national nonprofit corporation that operates a federally funded research and development center (FFRDC) and has approximately 4,000 employees. The Aerospace FFRDC is aligned to support the most critical programs of the Department of Defense and the nation and to serve as its customers’ innovation partner across the space enterprise. Consistent with the competencies outlined in our sponsoring agreement, Aerospace provides strategic value through independent, intellectually rigorous, relevant, and timely products and services. With three major locations in El Segundo, CA, Colorado Springs, CO, and Washington, DC, Aerospace addresses complex problems across the space enterprise including the DOD, Intelligence Community, civil, commercial, and other areas of national significance.

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