Exploiting and Exploring Low Earth Orbit: Small Satellites, Hitchhikers, and Smart Links

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ABSTRACT

Breakthroughs the Johns Hopkins University Applied Physics Laboratory (APL) made in small satellites and hosted payloads in 2010–2020 are helping to pave the way for the future in ubiquitous sensing from space. Leveraging its extensive knowledge of space engineering, advanced miniaturization techniques, and a proven capability to meet new challenges, APL is making important contributions that enable a future in which our planet can be managed with prognostic sensing and communication at spatial and temporal scales heretofore unheard of. Small satellites will usher in this new era of utilizing space assets for improving life on Earth and extending humanity's reach into the cosmos, with APL positioning itself to help lead the way with stand-alone, rideshare, and constellation mission concepts.

INTRODUCTION

APL has integrated small satellites into its space portfolio, leveraging a decade of effort in developing small-satellite technology and a strategy for implementing its vision. Small-satellite missions will continue to grow in market share in response to increasing sponsor interest and funding. APL's groundbreaking work is paving the way for the Lab to continue to lead the industry as small-satellite capabilities improve. Dramatic improvements in global coverage, observational resolution, and communication will be achieved in the 2020s by technology breakthroughs developed in part at APL over the past decade (2010–2020). APL is helping to chart the course for use of low-Earth-orbit (LEO) satellites as a replacement for geosynchronous-Earth-orbit (GEO) satellites, at a fraction of the cost and often with greater fidelity. With the cost of each GEO satellite at ~$290 million for design, construction, and launch, and upward of $500 million[1] for subsequent monitoring, an LEO solution can offer an order-of-magnitude savings or more. APL tackled significant hurdles to position itself to take advantage of LEO to improve on GEO solutions, duplicating and even improving on GEO's ubiquitous coverage over specific areas of observational interest. The Laboratory has demonstrated that it is possible to conduct new and exciting science from LEO, at a bargain price, for civil space as well as national security space applications. It has done so by demonstrating reliable CubeSat missions and the technical feasibility of large communications networks that must be created and linked in a delay-tolerant manner to fully utilize LEO.

PRESCIENCE AND FORESIGHT AT THE TURN OF THE CENTURY: CREATING COST-EFFECTIVE NETWORKS OF SENSORS

Commercial companies including SpaceX,[2] Amazon,[3] and OneWeb[4] are developing constellations of over 1,000 small satellites to provide internet connectivity to people all over the world. By 2013, more than half the CubeSat missions were being conducted by industry and the government,[5] and all signs point to the continuing expansion of small-satellite usage for government missions even as university usage continues to increase (Figure 1). In advance of these developments, APL demonstrated the potential of leveraging large constellations and replacing GEO capability at a fraction of the cost with three progressively more capable programmatic accomplishments between 2010 and 2020. The first exploited technical resources currently in LEO spacecraft with the Active Magnetosphere and Planetary Electrodynamics Response Experiment (AMPERE) program by harvesting sensor data from onboard magnetometers on the Iridium constellation. The second created new science and observational opportunities with "hosted payload" instrumentation launched as "ride-alongs" on new commercial constellations. And the third demonstrated the feasibility of a distributed system of nanosatellites in LEO with the possibility of orders-of-magnitude greater functionality and cost savings.

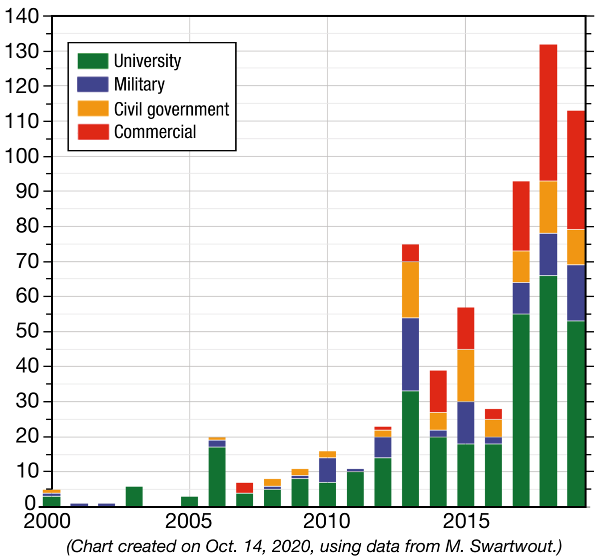


Figure 1. CubeSats by mission type from 2000 to October 2020 (649 spacecraft, no constellations). The number of CubeSat launches continues to increase each year, as does the relative proportion of commercial and government launches. (Reproduced from Ref. 5 with permission of Dr. Michael Swartwout, St. Louis University.)

In Situ: Exploiting In Situ Resources on Constellations with AMPERE

The original Iridium constellation, launched in the late 1990s, was one of the first satellite constellations. Together with its replacement, Iridium NEXT, which launched over 2017–2019, it is part of a dramatic expansion in the prevalence and number of LEO constellations that includes new constellations being developed by SpaceX, OneWeb, and others. Earlier in the space age, Dr. Thomas A. Potemra of APL, working with international colleagues, applied data from the Triad satellite to determine the average distribution of the Birkeland currents linking Earth's ionosphere to the high-altitude solar wind interaction and the amplitude distribution of field-aligned currents at northern high latitudes.[6] In 1996, scientists in APL's Space Exploration Sector (then the Space Department), led by Dr. Brian J. Anderson, leveraged that earlier work when conceiving of the idea to harvest magnetic field measurements from avionics sensors on Iridium Block 1 satellites. The Iridium constellation consists of 66 spacecraft in LEO in circular polar orbits at altitudes of ~780 km in six equally spaced orbital planes with at least 11 satellites in each plane, in principle allowing measurement of the near-instantaneous currents that previously required many months of observations to map.

This work ultimately led to the AMPERE program, sponsored by the National Science Foundation, which started in 2008. Working with Dr. Haje Korth and Robin Barnes of APL, Dr. Anderson developed the data processing and analytical techniques to use measurements from the existing engineering magnetometers installed on every spacecraft of the Iridium constellation to sense the electric Birkeland field (Figure 2a). The AMPERE-processed data show the dense global coverage and scale of the measurements (Figure 2b), providing unprecedented capabilities to measure and track the dynamics of Earth's solar wind interaction on timescales as short as 10 min.[7] This work is continuing on Iridium NEXT, which offers greater sensitivity in these measurements as well as the capability for true real-time monitoring of Earth's geospace environment. The AMPERE work, using existing on-orbit resources, demonstrated the enormous potential for measurements of many types that could be harnessed by placing new resources on spacecraft in constellations.

Stand-Alone: ORS Tech 1 and 2

APL's Space Exploration Sector continues its innovative approach to problem-solving, leveraging the advent of CubeSats that ushered in the era of extremely low-cost missions. The small-satellite revolution essentially began in 1999 with Stanford University's development of the CubeSat form factor (10 × 10 × 10 cm).

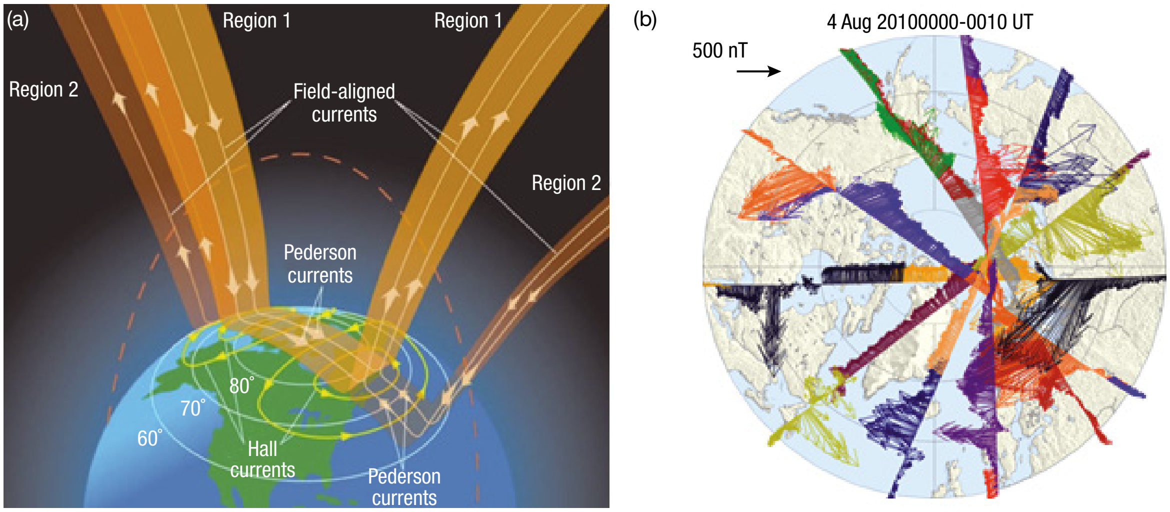


Figure 2. Earth's global upper-atmospheric electrical currents derived from AMPERE. (a) The data processing and analytical techniques use measurements from the existing engineering magnetometers installed on every spacecraft of the Iridium constellation to sense the electric Birkeland field. (b) The AMPERE-processed data show the dense global coverage and scale of measurements, enabling unprecedented measurement and tracking of the dynamics of Earth's solar wind interaction on short timescales.

However, these spacecraft were built for education and simple experiments and were not considered reliable enough for use with critical missions and applications. More than 10 years later, in 2013, APL shifted the paradigm and introduced a new generation of small satellites with the launch of two experimental 3U CubeSats designed for national security and space science operations (Figure 3). The two CubeSats were among 29 others lifted to orbit aboard a Minotaur I rocket from the Mid-Atlantic Regional Spaceport at NASA's Wallops Flight Facility on Wallops Island, Virginia, as part of the US Air Force ORS-3 mission.

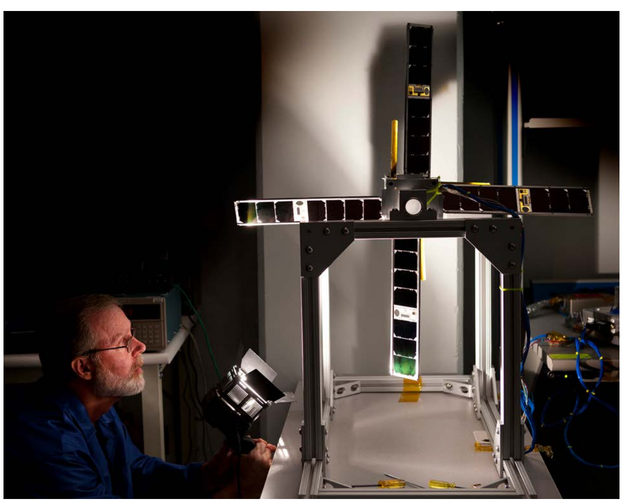


Figure 3. One of the MBD (Multimission Bus Demonstration) CubeSats undergoing inspection at APL. These shoebox-size satellites demonstrated that small satellites can get into orbit inexpensively and be tough enough for critical military and intelligence applications.

The shoebox-size satellites, designated by the sponsoring Operationally Responsive Space (ORS) office as ORS Tech 1 and 2 and known as the Multimission Bus Demonstration (MBD-Vector) within APL, presented a breakthrough capability for the military and intelligence communities, demonstrating that small satellites can get into orbit inexpensively and be tough enough for critical applications in these domains. Phil Huang and Ann Garrison Darrin of APL were the technical lead and program manager, respectively.

Rideshare: Space-Based Kill Assessment-Hosted Payloads Add New Capabilities to Constellation Resources

The Space-Based Kill Assessment (SKA) sensors were designed and constructed and are operated by APL. By 2019, APL's Space Exploration Sector and Air and Missile Defense Sector had deployed SKA. These sensors are hosted aboard commercial satellites and were placed into orbit to improve hit and kill assessment of whether a threat missile has been eliminated by a missile defense interceptor. This demonstration is leading to the deployment of numerous SKA sensors on future satellites to create an ad hoc space-based sensor network that will improve kill assessment. The key here is an improved kill assessment capability that drives a reduction in the number of interceptors needed, thereby dramatically cutting costs. In 2019, the SKA team received the Missile Defense Agency's David Packard Excellence in Acquisition Award. In a ceremony at the Pentagon, Defense Department comptroller David Norquist, performing the duties of deputy secretary of defense, recognized acquisition personnel who saved the US Department of Defense ~$1.7 billion.

GROWING SMALL-SATELLITE PROGRAMS AT APL

Civil Space

Constellation Pathfinder: RAVAN

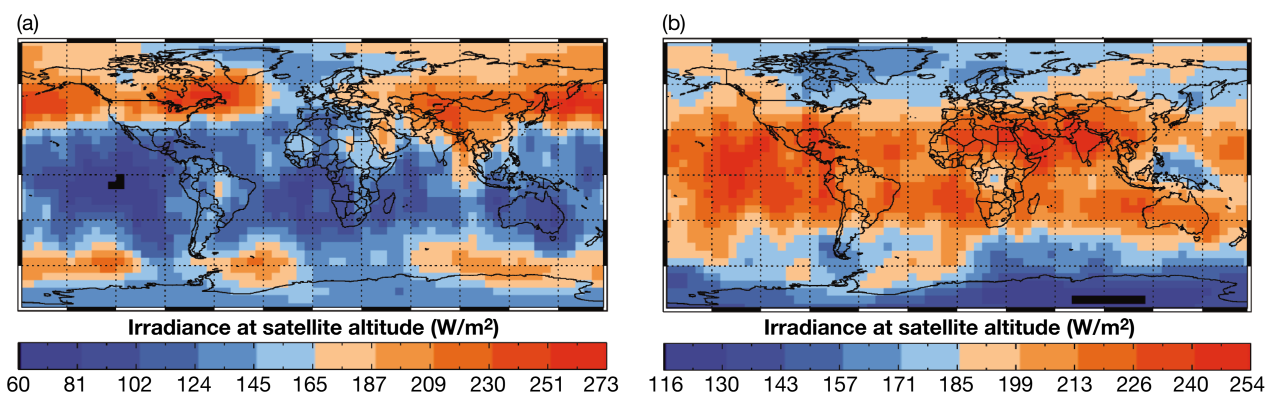
Continuous global remote sensing from LEO requires new lower-cost measurement approaches. A multipoint constellation measuring Earth's energy budget (EEB)—which controls the future course of Earth's climate—could continue long-term measurements made by large spacecraft while enabling new science at high temporal and spatial resolution. RAVAN (Radiometer Assessment using Vertically Aligned Nanotubes) is a technology demonstration that enables broadband measurement of Earth and solar irradiance from small satellites.

As of the end of 2020, the RAVAN 3U CubeSat has been operating for 4 years on orbit, after its successful technology demonstration, and it represents a number of firsts: APL's first science CubeSat, the first CubeSat funded by the NASA Earth Science Technology Office's In-Space Validation of Earth Science Technologies (InVEST) program to reach space, and the first CubeSat bus made by Blue Canyon Technologies, based in Boulder, Colorado, to fly. RAVAN also represents the first use in space of vertically aligned carbon nanotubes, developed in APL's Research and Exploratory Development Department, as absorbers in broadband radiometers. Vertically aligned carbon nanotube forests are arguably the blackest material known and have an extremely flat spectral response over a wide wavelength range, from the ultraviolet to the far infrared. A second technology demonstrated was a pair of gallium phase-change black-body cells that were used as stable references to monitor the degradation of RAVAN's radiometer sensors on orbit. RAVAN's agile 3U CubeSat bus allowed for routine solar and deep-space attitude maneuvers, which are essential for calibrating the Earth irradiance measurements.

RAVAN serves as a benchmark for future EEB science missions and is an important step in the development of science-grade EEB instruments on small-satellite platforms (Figure 4).[8] RAVAN's use of vertically aligned carbon nanotubes as radiometer absorbers has already been duplicated for use on current and planned space missions, and the gallium black bodies are part of a conceptual design of a next-generation EEB instrument. RAVAN was led by principal investigator William Swartz of APL's Space Exploration Sector and leveraged the work of two small commercial partners, L-1 Standards and Technology, Inc., in Manassas, Virginia, and Blue Canyon Technologies.

IT-SPINS

Managed by APL and led by Dr. Gary Bust in APL's Geospace and Earth Science Group, IT-SPINS is manifested by NASA for launch in October 2020 on



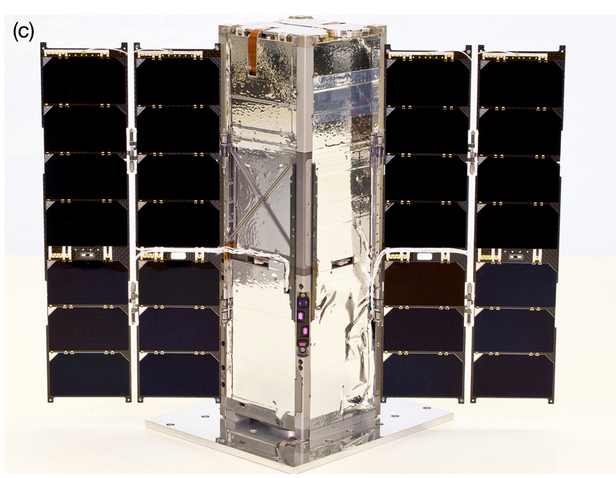


Figure 4. The RAVAN 3U CubeSat and acquired data. RAVAN (c) acquired data to produce maps of Earth's outgoing radiation at shortwave (a) and longwave (b) infrared wavelengths. (Maps adapted from Figure 16 in Ref. 8, an open access article distributed under the Creative Commons Attribution License, https://creativecommons.org/licenses/by/4.0/. RAVAN image, APL/Blue Canyon Technologies.)

a Cygnus International Space Station (ISS) resupply craft as an external payload to be deployed after the ISS departs. IT-SPINS is capable of making an innovative set of measurements that produce continuous nighttime tomographic images of O^+ along the satellite path. The mission concept integrates a high-heritage photometer into a high-heritage bus that rotates about orbit normal at 2 rpm while continually making radiance measurements to create a 3-D profile of O^+ emission. These measurements will demonstrate the feasibility of two primary science objectives: measuring the topside transition region of the ionosphere and measuring the dynamics of mesoscale structures in the ionosphere.

National Security Space

CubeSat Assessment and Test

The Laboratory successfully launched and established communications with two CubeSats, part of an APL-led flight demonstration called the CubeSat Assessment and Test (CAT). CAT is an excellent project to demonstrate APL's heritage of providing trusted and innovative small-satellite solutions both rapidly and at low cost. CAT's principal investigator is Kristin Fretz of APL's Space Exploration Sector. It was delivered to the ISS by the SpaceX CRS-16 Dragon that was launched by a Falcon 9 rocket from Cape Canaveral Air Force Station, Florida, on December 5, 2016. The satellites were released from the ISS on January 31, 2016, at 5:28 a.m. EST (Figure 5). APL used its 60-ft. satellite dish to send and receive data, with the two small spacecraft confirming they were operating as designed at 3:07 p.m. EST. The two CubeSats were among several launched from a NanoRacks CubeSat deployer on the ISS. The 3U CubeSats are commercial off-the-shelf spacecraft measuring 34 cm long and 10 cm square, or ~13.5 in. long and 4 in. square. Each carries a communications payload that was integrated by APL.

Figure 5. CAT (CubeSat Assessment and Test) being deployed from the ISS. Each of the two CubeSats in this APL-led flight demonstration carries a communications payload that was integrated by APL.

PRESCIENCE AND FORESIGHT AT THE TURN OF THE CENTURY: CREATING EFFECTIVE LINKED NETWORKS TO OVERCOME THE CHALLENGES OF LEO

Communications is a critical infrastructure for all space missions. The rapidly expanding population of LEO spacecraft and constellations threatens to strain our outdated networks for satellite communications. Under a multiyear APL independent research and development award, co-principal investigators Edward Birrane and David Copeland looked at LEO satellite communications in a different light, treating LEO communications as a cellular communications problem. With their program, Advanced Network Technology for Integrating Communications in Space (ANTICS), they sought to create a space communications architecture based on proven mobile 4G/LTE technology and to tie in ongoing advances in 5G and the Internet of Things. The ultimate goal of ANTICS is to enable communications capabilities for LEO missions that resemble those in terrestrial networks. These include on-demand access to and from spacecraft, dynamic sharing of resources among users, and roaming among different service providers.

The project team developed standards to enable a marketplace of space service providers that together can provide global access to users. Furthermore, the ANTICS program provides a means to incorporate delay-tolerant networking into the LTE architecture. ANTICS is fundamentally an infrastructure program, intended not to benefit one mission but to enable all users in the LEO environment by allowing seamless communication through standardized approaches. If successful as envisioned, ANTICS will fundamentally change all LEO communication and command and control, moving from traditional, lossy, often low-bandwidth, direct-to-satellite communications to a networked process with excellent reliability and little delay.

APL AT 100

Today, APL is tackling the hard problems that will enable the real-time services of the future. Global coverage, on-demand resources, and smart linkages are all prescience of the future. As of 2020 less than half the world had access to the internet, but by APL's centennial, the internet is predicted to be accessible to the entire world's population,[9] and with this access comes a boost in education and online literacy and the formation of global culture. Artificial intelligence (AI) will combine with ubiquitous global coverage to make it possible to provide resources and services efficiently and effectively around the world.

This access to broadband, whether for defense, science, or consumers and the commercial world, is in some part a result of the cost-effective advances APL is currently developing. As technology continues to get smaller, cheaper, and more connected, APL's Space Exploration Sector will be developing instruments with multiple sensors for rideshare and stand-alone small-satellite missions. These sensor suites will be in smaller form factors but will still be able to support multiple missions, such as detecting, characterizing, and interpreting environmental phenomena. Constellations of thousands of spacecraft will be automated by using future generations of onboard AI to operate, navigate, and communicate between ground stations and each other. APL advancements in space technologies will allow everyone to see anything and everything in the world and out of the world. Data from sensors not even designed yet will coalesce with more conventional data streams, forming a virtual data ocean in LEO that will be so vast that it will be hard to contemplate sending even a small fraction of the data to the ground for analysis.

Instead, onboard AI distributed between satellites will constantly be on the lookout for global and local events, including happenings unthought of by the engineers who programmed the AI. Hyperlocal and accurate weather forecasting will become the norm with sensor suites like those being developed at APL for forecasting ever more dangerous consequences of climate change. Local weather forecasts will drive immediate allocation of resources for coastal communities and inland cities alike. The outbreak of diseases, upcoming famines, and other large-scale human-caused and natural disasters will be forecast and headed off before they even occur. Just how much to empower this AI in the sky so that humanity can enjoy the benefits it provides without being overly vulnerable to the limitation of technology will be the challenge the next generation will have to grapple with.

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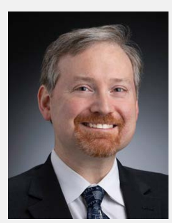

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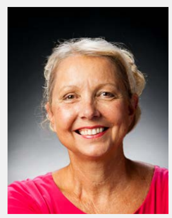

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