The Nanosatellite Revolution: 30 Years and Continuing

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“*Hope lies in dreams, in imagination and in the courage of those who dare to make dreams into reality*”

Jonas E. Salk (1914–1995)

Foreword

On March 17, 1958, Vanguard 1 was launched, becoming the fourth satellite to orbit the Earth and the first to have solar electric power. With a mass just under 1.5 kilograms, Vanguard 1 was also the first of what we would later come to know as *nanosatellites*, unwittingly planting the seeds of a technological revolution that was still decades away from fruition.

Today, we are fortunate to be able to look back on that momentous flight and recognize its significance in the long arc of satellite development. Just as exciting is our ability to look forward and dream of the untold advancements that await us.

Through the tireless efforts of scientists and engineers dating back to the early 1990s, nanosatellites have steadily evolved from technology demonstration testbeds to practical and commercially viable devices poised to form the backbone of many emerging space architectures. Along the way, they've carved the path for countless innovations and served as an accessible entry point for researchers, entrepreneurs, students, and others to begin experimenting with satellites of their own.

This book, the fifth in a series on this subject, chronicles the progress and promise of the nanosatellite revolution. It serves as a testament to the many great achievements that have brought us to this place in history and offers a tantalizing glimpse of what's still to come. The pages ahead speak to the dedication and perseverance that have taken an initial vision from 30 years ago and turned it into a reality benefitting the global space community.

The Aerospace Corporation is proud of the role its people have played in helping shape and advance the nanosatellite revolution, and of our continued efforts to push the state of the art for what nanosatellites can accomplish.

From Earth observation to communication to navigation, the possibilities of what can be done on orbit by ever-smaller satellites are seemingly boundless. As launch costs continue to drop, even more nanosatellites will take their place among the stars and the scale of their impact will only multiply. And while this growth will lead to new challenges to overcome and solutions to be developed, the nanosatellite community is more than up to the task.

The innovative spirit that has propelled the nanosatellite field forward for decades still shines brightly. May it continue to serve as a beacon to all those seeking to advance humankind and our place in the skies above.

Steve Isakowitz
President and CEO
The Aerospace Corporation

Acknowledgments

The editors would like to thank the contributing authors and their supporting organizations who have appeared in these pages. They have shared with us their insight, successes, and failures. The nanosatellite industry stands on the shoulders of these contributors and others who do not appear in this book. They have pushed the idea that small satellites and nanosatellites can contribute to the better understanding of not only our near-Earth space environment but perhaps also to those worlds not yet touched by humankind.

A book such as this does not come into existence without the unfailing support of the people and the organization sponsoring it. Given the length of time it has taken to produce this book, delayed and marred by events surrounding the COVID-19 pandemic, it is a testament to the commitment of the sponsoring organization who insured its publication. The editors are indebted to The Aerospace Corporation who sponsored this work, the Aerospace senior management Sherrie Zacharius (retired) and Sabrina Steele, along with Bryan Tsunoda (retired), who maintained the ethic that we finish what we start. To Denise Betts who guided the production having little resources in the way of a printing press, to Richard Lindsey for his meticulous editorial services to ensure that the written words were consistent and as effective as possible, to Joseph Hidalgo and Julia Kopischke for the creative design of the book cover that, in one picture, reveals the astonishing achievements of the nanosatellite.

Finally, and on a personal note, the editors would like to thank their families and friends for their patience during the assembly of this fifth codex on the topic of miniaturizing space systems and nanosatellites.

Preface
"The Nanosatellite Revolution: 30 Years and Continuing"

This work assembles chapters from contributors across our planet to document technologies, applications, missions, licensing requirements, and lessons learned by individuals and organizations that have participated in the nanosatellite revolution. This book is not intended as a "how to" or as a university reference to design, build, and fly nanosatellites but as a deeper-level reference on what has and hasn't worked in previous nanosatellite programs. Like our previous compendium, *Small Satellites: Past, Present, and Future*, this book provides details on small-satellite efforts, in this case nanosatellites, from the perspective of the individual chapter authors. Many chapters act as a historical reference for particular programs. We realized that some important efforts such as the outstanding nanosatellite work at the NASA-Ames Research Center and in Russia and China were missing from the previous book, so we solicited and received chapters on these efforts. Our previous book was published in 2008, and we wanted to assemble an updated work to cover new advancements in this exploding field. If you plot yearly nanosatellite launch rates vs. launch year using a logarithmic scale on the vertical launch rate axis, you will discover that a tsunami-like second wave of nanosatellite launches started in 1997, with exponential growth that doubles every 2.44 years. The graph, shown simplistically on the cover, validates the use of the term "nanosatellite revolution." Note that the 1997 start date was determined by analyzing launch rates through 2022, and this could change by a few years as we add more data each year.

This book is organized into four sections: a section on missions, a section on technologies, a section on policy, and a final section on future perspectives. In reality, nearly every contribution has elements relating to all three sections. Mission investigations show that nanosatellites or CubeSats (synonymous to us) have evolved from serving as technology demonstration testbeds to providing practical and commercially useful data from space. Nanosatellites were never intended to replace large satellites, except when used in constellations. Companies and governments will continue to permeate low Earth orbit (LEO) with small, micro-, and nanosatellites to form mega-constellations, and inadvertently increase the probability of accidental collision between satellites and debris objects. The problem is further exacerbated if a significant number of satellites arrive partially or totally disabled on orbit. We believe that the future of nanosatellites remains positive and that industry in collaboration with government organizations will self-police to ensure safe access and operations in space. One radical approach to actively reduce the density of ~10-cm scale orbital-debris objects is given in Chapter 24.

Nanosatellites were the first spacecraft the United States attempted to launch in response to the former Soviet Union successfully orbiting the Sputnik-1 and -2 microsatellites (10 to 100 kg mass). Unfortunately, the Vanguard TV-3 and -TSG nanosatellites had launch failures. Explorer-1 became the first U.S satellite, a microsatellite, to reach orbit in 1958, followed by the first U.S. nanosatellite, Vanguard-1. Satellites were launched by government agencies, and the early flight success rate was miserable; only 55% for the Soviet Union and 37% for the United States between October 1957 and April 1960. Emphasis soon shifted to manned spaceflight, and satellite launch masses grew considerably in the 1960s and 1970s as launch vehicles evolved in reliability and throw-weight capability to support manned operations in LEO, and then, in cis-lunar space.

From the start of the Space Age in 1957 through 1994, only 54 active nanosatellites were launched, yielding a miniscule average launch rate of 1.42 nanosatellites per year. More than 500 passive nanosatellites were launched or ejected on orbit, primarily by the Soviet Union, to reflect light or radio waves to calibrate ground-based sensors and to monitor atmospheric density through orbital decay, but these were just structures without any electronic systems (e.g., energy conversion and storage, communications, command, and control, etc.) required by a true satellite. The highest launch rate of eight active nanosatellites per year occurred in 1965 and in 1967. After that, nanosatellite launch rates declined rapidly and dropped to zero per year between 1973 and 1989. Nanosatellites re-emerged in the 1990s with a meager average active nanosatellite launch rate of 1.8 per year. No one noticed the start of the nanosatellite revolution during the 1990s, or even through most of the 2000s (2000–2009) with an average launch rate of only 3.3 per year. The nanosatellite revolution started slowly, fueled by advancements in miniaturized electronics and microelectromechanical systems for the consumer market, small satellite flight experience gained by the Amateur Radio Satellite Corporation (AMSAT, a not-for-profit organization dedicated to amateur radio enthusiasts that had flown more than 45 small satellites, mostly microsatellites, by the year 1997), and access to affordable space launch opportunities using the truly revolutionary CubeSat containerized satellite concept that was born in Silicon Valley. The nanosatellite revolution started in universities and government labs, but then spread to for-profit commercial companies to provide game-changing services in LEO to a variety of civilian and governmental customers. Planet Labs (now Planet) developed the audacious plan of flying hundreds of CubeSats in LEO to provide 5-meter ground resolution imagery, with daily revisit times, to anyone who would buy the data. Entrepreneurs saw a new market, and new launch service providers were born. The availability of launch on an almost monthly basis, from multiple vendors to moderate cost, spurred the development of even more nanosatellite service providers, resulting in hundreds of nanosatellites being launched each year. *Vive la révolution!*

Our nanosatellite revolution started at The Aerospace Corporation when three intrepid researchers (S. W. Janson, E. Y. Robinson, and H. Helvajian) assembled a community of interest to study miniaturization technologies prevailing at the time to reduce satellite mass. One output was the radical concept of the kilogram-mass integrated-silicon nanosatellite formally presented at the 1993 International Astronautics Federation Conference in Graz, Austria. This was followed by four books and technical publications that focused on miniaturization technologies, development of nanosatellite concepts and technologies, and the presentation of results from small-satellite missions—both successful and failed. The last work was an edited book, *Small Satellites: Past, Present, and Future*, containing 24 chapters on small satellites from U.S., Canadian, Japanese, German, Dutch, and British authors. This new fifth work, and likely the last from these editors, continues our tradition by documenting results from selected nanosatellite missions and technologies, and governmental requirements to launch and fly missions. We expanded our international coverage to include Russian, Chinese, and Singaporean authors, and significantly expanded the gender diversity of our chapter authors. Similar to our prior works, this book also reflects on the future to not only identify driving technologies that will propel further advancement, but also to highlight impending issues spawned by the nanosatellite revolution such as a rapid increase in the orbital debris environment.

Nanosatellite and small-satellite capabilities will continue to increase over time due to the continuing advances in radio frequency electronics, microelectromechanical systems, photonics, power management and storage, materials development, and the increasing computational processing and data storage capabilities that can be put into a single square centimeter of silicon. Many successful nanosatellite-based commercial space enterprises like Planet, Spire, and Swarm are established or underway, and more are expected in the near future. Nanosatellites initially enabled university-class researchers to inexpensively build and fly space experiments, and now they also enable entrepreneurs and venture capitalists to expand commercialism into LEO, and beyond. The perseverance of nanosatellite researchers worldwide during the past 30 years has transformed imagination into practical reality. The quote from Jonas Salk in the opening pages of this book serves as a gentle nod to these dedicated researchers.

In conclusion, we make note of additional trends that are worth observation. (1) The increasing sophistication that can be packaged in a nanosatellite bus and the increasing capability of ride-sharing permit use of nanosatellites as robotic probes that can be sent to explore our solar system with far more detail than has been achieved to date, not only to planets, but to moons and asteroids. (2) In a similar vein, nanosatellites can become the mass-producible building blocks for assembling large argosies (a merchant ship or fleet of merchant ships) in space: "the smart brick." In fact, we predict an era of space development that is enabled by self-assembly using smaller, functional units.

Finally, we thank the authors who report in these pages—we thank them for their contributions, their vision, and their perseverance. We know of many more stories that confirm the utility of the nanosatellite as a viable space tool, and we anticipate the next 25 to 30 years to be a watershed for nanosatellite proliferation.

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Dedication

In Memory of Ernest Y. Robinson

This book is dedicated to “Ernie” Robinson, a brilliant engineer and a real “mensch” (a term from Middle High German and Yiddish meaning a person of integrity and honor). Ernie Robinson worked for both NASA’s Jet Propulsion Laboratory and The Aerospace Corporation in Southern California. In the early 1990s, during a serendipitous meeting with the current editors of this book, a trio formed that would begin to champion perspectives that functional satellites of substantially smaller size could be produced. Ernie was impassioned to advocate the concept with superhuman commitment. Bob Twiggs, of Stanford University, was brought into the fold, and then he developed the “killer app” CubeSat form factor. For over a decade, three people at Aerospace, Ernie and the two editors of this book, were mentors and mentees to each other. Ernie passed away since our last book on small satellites, but we are sure he would smile every time a new small satellite is launched into orbit or beyond. Thank you, Ernie.

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