A More Nimble Satellite

A Research Paper submitted to the Department of Engineering and Society

Presented to the Faculty of the School of Engineering and Applied Science

University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree

Bachelor of Science, School of Engineering

Daniel Fisher

Spring 2023

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

Advisor

Kent Wayland, Department of Engineering and Society

Introduction

Since the turn of the century, small satellites have emerged as the most popular platform for conducting space-based operations, including scientific research, commercial solutions, and educational activities. Reflecting this, in 2021, 94% of all spacecraft sent to orbit were small satellites (Halt & Wieger, 2022). A small satellite class of particular interest are CubeSats: small, standardized satellites that come in 10x10x10 cm units (U) and are usually brought to Low-Earth Orbit (LEO) on a ride-share with a commercial launch provider like Lockheed-Martin or SpaceX (Loff, 2015). The rise of the small satellite has been driven by advances in technology, as well as a growing interest in space among a wider range of actors, including universities, start-up businesses, and individuals. This recent phenomenon can be considered a sort of "democratization" of access to space: the process of making space research and orbital access more available to a wider range of actors.

The use of small satellites, especially CubeSats, have the potential to disrupt traditional power structures within the space industry by making orbit more accessible to individuals and organizations. To gain a better understanding of how CubeSats have been a vital component in democratizing space in the past decade, it's important to examine the relationships between the different actors involved in the broader space ecosystem of today. This includes the developers of CubeSats, the governments and institutions that regulate the use of space, the rise of commercial launch providers, and the users of CubeSats for scientific, commercial, and other purposes. Other actors in the space ecosystem include but are not limited to ground-based infrastructure, communication systems, and other satellites in orbit.

This research paper aims to explore the role of small satellite technology, with a focus on CubeSats, in shaping broader social, political, and economic systems surrounding accessing space. This can provide insight into the challenges and opportunities created in this exciting and rapidly-evolving field of space technology. Additionally, an STS approach will be taken to provide a nuanced and critical examination of the implications of the democratization of space through CubeSats and whether we can truly consider “democratization” the reality of what is happening in the field.

Background

Small satellites have been a facet of space technology since the early days of the space age. However, it wasn't until the last decade that they have become a critical component of the growing space economy and an increasingly popular platform for academic research and space-based solutions for global issues. In the early days of space flight, the size of satellites was limited by the amount of mass that could be taken to orbit. The first artificial satellite, Sputnik 1, weighed just 83 kg and had an orbital duration of 22 days (Sweeting, 2018). As the capability to take more mass to orbit increased, national space programs focused on larger, more complex satellites with larger mission scopes. Despite this trend, small satellites continued to be built and implement new technologies as they became available. Amateur radio operators, in particular, played a significant role in the development of small satellites, with notable landmarks including the first small satellite to carry a radio transponder and the first to receive control commands remotely (Baker & Jansson, 1994).

The average mass of satellites continued to increase until the mid-1990s, when interest in small satellites began to re-emerge, driven by a combination of commercial, government, and academic interests. For example, the Air Force Research Laboratory's MightySat program was created in 1994 to use small satellites as a test platform for new space-based technologies (Miller & Davis, 2012). Since then, interest in deploying small satellites as a viable class of spacecraft for conducting commercial, government, and academic research has continued to grow, leading to the rapid expansion of the small satellite market that we see today. In 2021, small satellites made up 94% of all spacecraft sent to orbit, a testament to their increasing importance and versatility as a tool for space exploration and use (Halt & Wieger, 2022). As an example of how small satellites have become integral in addressing issues with global significance, one of the largest technological paradigm shifts occurred at the turn of the century: the emergence of widespread access to the internet. In the early 2000s, it is estimated that only 7% of the global population had access to the internet. Today, it's estimated that over half of the Earth's population has access to the internet and largely through mobile devices (*Measuring Digital Development*, 2020). Especially in the past decade, global demand for internet access has surged and small satellite constellations are being deployed to address this demand (Lal et al., 2017). A noteworthy example in present day of small satellites in this role is the SpaceX Starlink constellation, which is a network of hundreds of small satellites working in tandem with the goal of providing internet access globally (Kosiak, 2019).

Literature Review

Actor-Network Theory (ANT) is a sociological framework that seeks to explain the ways in which technology, society, and humans interact with one another. ANT is concerned with the relationships between actors and the networks they form, considering both human and non-human components (Dolwick, 2009). In ANT, an actor can be defined as any entity that has agency and the ability to act within a network. This can include humans, organizations, technologies, and even non-human entities such as natural resources or the environment. The key concept in ANT is that all actors, whether human or non-human, are considered equally important in shaping the outcome of a network. Actors can also be considered *intermediaries* which is an predictable “input and output” component of the network, while *mediators* are unpredictable elements of change (Latour, 2005, p. 39). Actors can be laid on a spectrum of intermediary and mediator, but most in the non-ideal real world are mediators. For the purposes of this research, we will maintain a dichotomy between the two terms and assign actors as generally either one or the other.

ANT has been used in a variety of fields, including science and technology studies, anthropology, and geography, to analyze the development and implementation of technology. We will use ANT to analyze the space ecosystem surrounding small satellites, focusing on the relationships between actors, including commercial entities, governments, academic institutions, and technological innovations, and the networks they form. From this, we can gain a more holistic understanding of the motivations and factors that have driven the growth of the small satellite and the role of different actors in shaping its development.

Methods

The scope of evidence will be focused on CubeSats because their clearly-defined standards will make it easier to compare and contrast missions. A case study analysis of three CubeSat missions will be conducted: Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) by the Massachusetts Institute of Technology (MIT), AstroBio-CubeSat (ABCS) by La Sapienza University of Rome, and the Phoenix CubeSat by Arizona State University (ASU). These missions were selected because they represent a range of actors involved in the CubeSat ecosystem, including commercial entities, academic institutions, and government organizations. A mixed-methods approach will be used to examine these missions, combining document analysis and observations, to gather data on the development and, if applicable, the launch and operation of these missions. This will include analyzing publicly available documents such as mission proposals, technical reports, and news articles. An ANT perspective will be applied to analyze the relationships between the different actors involved in the development and operation of the CubeSats, including the developers, launch providers, regulators, and users, and the networks they form. Additionally, the influence of non-human actors in the network such as the CubeSats and launch vehicles themselves will be considered. This approach will allow us to examine the cases as complex systems with multiple actors and connections, rather than simply as a collection of individual technologies or institutions. Potential limitations of using ANT as the primary analytical framework include the lack of empirical data and difficulty in identifying key actors in the network we are examining.

Results & Discussion

Before looking at specific CubeSat cases, "mapping the network" generically will help establish broad connections between actors and how they interact or collaborate. In each case, we will find that the center of their networks are the CubeSats themselves and their developers. These include companies and academic institutions that must work closely with launch providers to get their satellites into orbit, often on ride-share with a launch provider such as SpaceX, Rocket Lab, and Arianespace being among the most popular in the industry for this purpose (Halt & Wieger, 2022). Governments and regulatory bodies play an important role in overseeing the use of space and ensuring that CubeSats and other satellites are launched and operated safely and responsibly. Government initiatives such as NASA's CubeSat Launch Initiative are also potential sources of funding for CubeSat projects (Hill, 2017). To make CubeSats useful once in orbit, operators of these satellites rely on ground- and space-based infrastructure providers to establish communication with their satellites and process data. Finally, for the purposes of this research, educational institutions offer programs related to CubeSat development and space exploration and provide resources to researchers and student teams. There are numerous more actors that could be mapped onto the network in examining each case, but highlighting some specific actors will provide a framework for analysis and maintain a reasonable scope.

The TROPICS (Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats) mission is a project led by MIT researchers in collaboration with NASA to study tropical cyclones with a constellation of six 3U CubeSats in Low-Earth Orbit (Blackwell et al., 2018). The researchers chose to use CubeSats because they are low-cost, lightweight, and can be built and deployed quickly compared to traditional government weather satellites (Ranalli, 2018). Additionally, a constellation of CubeSats can gather data over the same spot multiple times on the same day, which is not possible with the standard government weather satellites that typically provide data over the same spot once a week. Data processing and a ground station network will be provided by the University of Wisconsin Space Science and Engineering Center. The project was selected as part of the NASA Earth-Venture Instrument program, which is an initiative seeking rapid development, low-cost mission concepts to conduct Earth science research (Potter, 2021). During a 2022 launch by provider Astra, the payload of two TROPICS satellites was lost due to an upper stage failure (Harwood, 2022).

The network map of the TROPICS mission includes the MIT researchers, the satellites, NASA, the University of Wisconsin Space Science and Engineering Center, and Astra, the launch provider. The CubeSats act as intermediaries that enable the researchers to study tropical cyclones by gathering data over the same spot multiple times on the same day, which is not possible with more conventional operational concepts. The ground station network and data processing provided by the University of Wisconsin Space Science and Engineering Center are also intermediaries that enable the researchers and NASA to receive and process the data gathered by the CubeSats. NASA, through its Earth-Venture Instrument program, acts as a mediator that selects and funds the TROPICS mission. Astra is another mediator that provides the launch service for the TROPICS satellites, but also acts as a potential disruptor if the rocket fails, as it did in 2022 when the TROPICS payload was lost. The failure of the rocket illustrates how the network of actors in the TROPICS mission is not fixed, but constantly changing and vulnerable to disruption. NASA, at time of writing, is still seeking a launch solution to the remaining TROPICS satellites (Foust, 2022).

AstroBio-CubeSat (ABCS) was a project by La Sapienza University of Rome researchers aimed at developing and validating new bio-analytical technologies for manned missions in space (Calabria et al., 2023). The researchers identified a gap in understanding of these technologies and chose to conduct their research in orbit using a CubeSat due to the need to test in conditions beyond the Earth's protective magnetosphere and the limited time the International Space Station crew could dedicate to the research. Ground operations were performed by the School of Aerospace Engineering (SIA) at La Sapienza in collaboration with amateur radio operators and other unnamed ground stations. The project was funded by a 2019 grant from the Italian Space Agency (ASI) and National Institute for Astrophysics (INAF) and was launched as a secondary payload on an Arianespace Vega rocket (Brucato, 2021). ABCS successfully completed its science objectives and delivered telemetry for two weeks past its intended operational life (Messier, 2022).

The ABCS mission involved several actors and intermediaries working together to accomplish its scientific objectives. The primary actors were the researchers from La Sapienza and their partners who developed the mission concept. The satellite itself is more difficult to categorize in this case, since describing it as an intermediary would neglect to take into account its autonomous capability and unexpected operational lifespan; it could be considered a mediator in these circumstances by providing a positive disruption to the network. Similar to the TROPICS mission, ground station operations provided by the SIA and amateur radio operators were also intermediaries that enabled the researchers to obtain experimental data from the spacecraft. Continuing with similarities to TROPICS, ABCS was funded by a grant from the Italian government, which acted in the network to enable the researchers to design and perform this mission. The Arianespace rocket and the primary payload, a larger satellite, were also crucial components in shaping this network, acting as an intermediary to fly ABCS to its intended high orbit.

Phoenix was a CubeSat project developed by an undergraduate group at Arizona State University with a science objective of studying Urban Heat Islands, urban areas that are warmer than their surrounding geography, using onboard thermal imaging instruments (Rogers et al., 2020). The satellite utilized off-the-shelf components in conjunction with custom electronics and structural components designed by the student team using an assortment of software tools. Ground support was provided by an in-house ground station at ASU manned by the student team with a backup station arranged with Embry Riddle Aeronautical University in Prescott, utilizing an encrypted up-link. The project was selected as part of the CubeSat Launch Initiative by NASA, which funds the development and launch of CubeSat missions at educational institutions such as universities (Hill, 2017). The satellite was sent to the International Space Station aboard a Cygnus resupply mission and deployed out of the station, but suffered a communications failure in orbit that rendered it unable to conduct its experiment (Burnham, 2019).

Phoenix is a unique case out of three discussed because it was developed by undergraduate students with the primary objective of providing them a hands-on experience of spacecraft design. Compared to TROPICS and ABCS, the technical report of Phoenix frequently highlighted the prominent role of third parties in providing commercially available off-the-shelf components and open-source software tools such as those created by NASA and GOMspace. In terms of actor-networks, there was a high degree of *proximity* of these actors in this network map. Similar to the other two cases, government and its agencies wield a significant power in being able to decide what projects receive funding and attention, acting as a mediator in the network. Another similarity to TROPICS in particular is a non-human actor causing a disruption to the network, in this case the satellite itself suffered a failure which prevented the student team from fulfilling its science objective.

Understanding the roles of mediators and intermediaries is important in each network map because it helps to identify the dependencies and potential power dynamics between actors in the network. It also highlights the potential for disruption if one or more of these intermediaries or mediators fail or are removed from the network. In examining the three missions, the CubeSats can be seen as intermediaries that enable their operators to achieve their mission goals. The success of these missions, however, were dependent on the actions of other actors, such as ground support, sources of funding, and launch providers. Of particular interest in each network was where the money came from to fund the mission – a common mediator in each case was a source of funding coming from a national government initiative. This reveals a point in the networks in which there is a potential source of conflict and power imbalance. Mediators that provide funding for missions like governments ultimately decide who can manufacture and send their CubeSats to orbit, calling into question whether the CubeSat phenomenon is a reflection of a broad democratization of space.

Conclusion

Based on the three CubeSat case studies and their network maps, it is clear that the democratization of space is not solely the natural outcome of technological advancements or of market forces. As seen in each mission, traditional power structures within the space industry remain the deciding forces in determining what developments in space, especially for CubeSats and other small satellites, occur. While government agencies and established industry players continue to hold considerable power through direct investment and regulation, the emergence of close networks of new entrants working in and around the established order can be considered a sort of democratization. Each network map of the CubeSat case studies was centered around the developers of the mission and showed that the actants within these networks had the ability to shape the development of the mission in significant ways. These networks are also subject to disruptions by actors within the network. Failures such as those experienced by TROPICS and Phoenix highlight the inherent uncertainties and risks involved in space activities, and underscore the need for ongoing innovation and collaboration. The small satellite, especially in its cube-shaped form, has proven to be “the people’s” current way of contributing to the future of space research and exploration. As the space industry continues to evolve, it will be important to continue studying these networks and power structures to understand how they are shaping the industry and to identify opportunities for new entrants like those wielding the CubeSat to contribute and innovate.

References

Baker, K., & Jansson, D. (1994). Space satellites from the world's garage-the story of AMSAT. *Proceedings of National Aerospace and Electronics Conference (NAECON'94)*, 1174–1181 vol.2. https://doi.org/10.1109/NAECON.1994.332909

Blackwell, W. J., Braun, S., Bennartz, R., Velden, C., DeMaria, M., Atlas, R., Dunion, J., Marks, F., Rogers, R., Annane, B., & Leslie, R. V. (2018). An overview of the TROPICS NASA Earth Venture Mission. *Quarterly Journal of the Royal Meteorological Society*, *144*(S1), 16–26. https://doi.org/10.1002/qj.3290

Brucato, J. R. (2021). *AstroBio-CubeSat a new tool for astrobiology in space*. National Institute for Astrophysics. https://indico.ict.inaf.it/event/1515/contributions/8995/attachments/4350/9020/Brucato_ABCS_audizione%20schede%20INAF.pdf

Burnham, R. (2019, August 27). *Mini-spacecraft built by ASU students will study urban heat island effect*. ASU News. https://news.asu.edu/20190827-mini-spacecraft-built-asu-students-will-study-urban-heat-island-effect

Calabria, D., Trozzi, I., Lazzarini, E., Pace, A., Zangheri, M., Iannascoli, L., Maipan Davis, N., Gosikere Matadha, S. S., Baratto De Albuquerque, T., Pirrotta, S., Del Bianco, M., Impresario, G., Popova, L., Lovecchio, N., de Cesare, G., Caputo, D., Brucato, J., Nascetti, A., Guardigli, M., & Mirasoli, M. (2023). AstroBio-CubeSat: A lab-in-space for chemiluminescence-based astrobiology experiments. *Biosensors and Bioelectronics*, *226*, 115110. https://doi.org/10.1016/j.bios.2023.115110

Dolwick, J. S. (2009). "The Social" and Beyond: Introducing Actor-Network Theory. *Journal of Maritime Archaeology*, *4*(1), 21–49.

Foust, J. (2022, August 8). NASA looking for new launch of remaining TROPICS cubesats. *SpaceNews*. https://spacenews.com/nasa-looking-for-new-launch-of-remaining-tropics-cubesats/

Halt, T., & Wieger, A. (2022). *Smallsats by the Numbers*. Bryce Space and Technology Report. https://brycetech.com/reports/report-documents/Bryce_Smallsats_2022.pdf

Harwood, W. (2022, June 12). Low-cost Astra rocket suffers upper stage failure, two NASA satellites lost. *CBS News*. https://www.cbsnews.com/news/astra-rocket-suffers-upper-stage-failure-two-nasa-satellites-lost/

Hill, D. (2017, February 17). *About CubeSat Launch Initiative* [Text]. NASA. http://www.nasa.gov/content/about-cubesat-launch-initiative

Kosiak, S. (2019). *Small Satellites in the Emerging Space Environment: Implications for U.S. National Security—Related Space Plans and Programs*. Center for a New American Security. https://www.jstor.org/stable/resrep20400

Lal, B., Blanco, E. de la R., Behrens, J. R., Corbin, B. A., Green, E. K., Picard, A. J., & Balakrishnan, A. (2017). *Global Trends in Small Satellites*. Institute for Defense Analyses. https://www.jstor.org/stable/resrep22890

Latour, B. (2005). *Reassembling the Social: An Introduction to Actor-Network-Theory*. Oxford University Press, Incorporated.

Loff, S. (2015, July 22). *CubeSats Overview* [Text]. NASA. http://www.nasa.gov/mission_pages/cubesats/overview

Measuring Digital Development. (2020). International Telecommunication Union. https://www.itu.int/en/ITU-D/Statistics/Documents/facts/FactsFigures2020.pdf

Messier, D. (2022, August 3). *Astrobio: A Challenge at High Orbit*. Parabolic Arc. https://parabolicarc.com/2022/08/03/astrobio-a-challenge-at-high-orbit/

Miller, G. B., & Davis, R. J. (2012). *MightySat II: Rapid Access to Space for the Air Force Research Laboratory*. 182–196. https://doi.org/10.1061/40339(206)22

Potter, S. (2021, November 5). *NASA Selects New Mission to Study Storms, Impacts on Climate Models* [Text]. NASA. http://www.nasa.gov/press-release/nasa-selects-new-mission-to-study-storms-impacts-on-climate-models

Ranalli, R. (2018, September 27). *For collecting weather data, tiny satellites measure up to billion-dollar cousins*. MIT News. https://news.mit.edu/2018/for-collecting-weather-data-cubesats-measure-up-0927

Rogers, S., Roberson, C., Flores, S., Barakat, R., Chacko, V., Gamaunt, J., Acuna, A., Bowman, J. D., Jacobs, D. C., & Mall, E. T. (2020). Phoenix: A CubeSat Mission to Study the Impact of Urban Heat Islands Within the U.S. *34th Annual Small Satellite Conference*, 39.

Sweeting, M. N. (2018). Modern Small Satellites-Changing the Economics of Space. *Proceedings of the IEEE*, *106*(3), 343–361. https://doi.org/10.1109/JPROC.2018.2806218