A NITROGEN DIOXIDE MONITORING CUBESAT: INCREASING SPATIAL RESOLUTION OF POLLUTION OBSERVATIONS FROM LOW EARTH ORBIT

USING SATELLITES AS TOOLS TO ADVANCE POLLUTANT RESEARCH AND RESULTING ENVIRONMENTAL POLICY

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By

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The design and development of spacecraft is both an independent field unto itself, as well as a tool within separate areas of inquiry. Environmental scientists and astronomers are taking advantage of our ability to place scientific payloads atop satellites and conduct research from space. Experiments in low Earth orbit provide a unique reference frame of study: the atmosphere can be observed free of the clouds, telescopes can capture signals before certain wavelengths of light are scattered or absorbed, and specified orbits can reach every corner of the globe. Of note is the modern use of complex satellites to observe atmospheric pollutants from orbit (Levelt et al., 2006a) and the recent trends to simplify satellites by way of CubeSats (NASA CSLI et al., 2017). Future missions, undertaken by students at the University of Virginia (U.Va.), aim to further environmental research by creating spacecraft capable of tracing anthropogenic pollution from the source throughout the surrounding atmosphere.

Currently in orbit are two sophisticated instruments observing pollutants such as nitrogen dioxide, ozone, carbon monoxide, and hazardous aerosols: the Ozone Monitoring Instrument (OMI), and the Tropospheric Monitoring Instrument (TROPOMI). Both missions are supported by federal agencies, with OMI onboard the National Aeronautics and Space Administration's (NASA) AURA spacecraft, and TROPOMI onboard the European Space Agency's (ESA) SENTINEL-5P satellite. However, these missions are limited by high altitude orbits and coarse spatial resolutions of 13 km x 24 km and 7 km x 7 km, for OMI and TROPOMI, respectively (Levelt et al., 2006b; Veefkind et al., 2012). Nitrogen dioxide reacts with the atmosphere on short time scales after initial emission, requiring high temporal variability in data collection methods. Likewise, current observing instruments can only resolve spatial gradients at urban scales (Levelt et al., 2006b), while a much finer spatial resolution is required to observe intra-urban variability (Pusede, Skrutskie, & Goyne, 2018; Zhang & Batterman, 2013), as demonstrated in Figure 1 by data collected via aircraft at an altitude of 10 km (Pusede, Skrutskie, & Goyne, 2018). Redder pixels indicate the highest observed concentrations of nitrogen dioxide, which can be attributed to major roadways due to the high spatial resolution of this data. There has been extensive debate on the merits of modeled versus monitored atmospheric data (Garnett, 2017), with modeled data taking an atmospheric chemistry approach, rather than requiring expensive space missions. Nevertheless, the current data set is limited in both temporal and spatial resolution. To better understand the small-scale variability of nitrogen dioxide, novel instruments and their companion spacecraft must be developed to supplement or replace the available data.

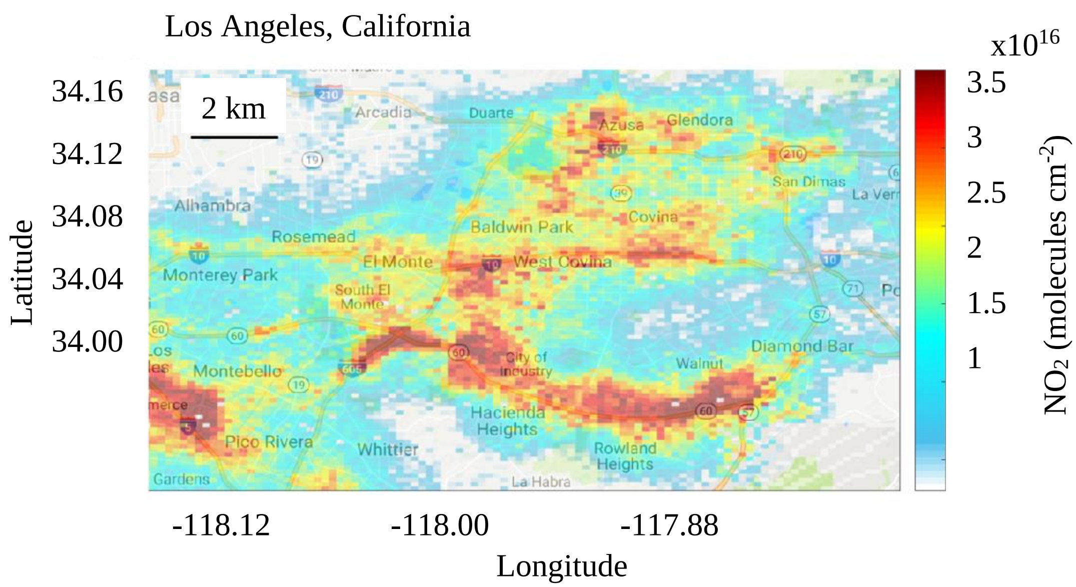

Figure 1: High Spatial Resolution Nitrogen Dioxide Over Los Angeles: Small-scale nitrogen dioxide variability can be captured via instruments used in aircraft flights. This mission aims to achieve similar results at low Earth orbit (Pusede, Skrutskie, & Goyne, 2018).

It is fair to assume that while environmental data is collected to passively quantify the current state of the atmosphere, its collection is motivated by a desire to halt and mend potential negative trends that may arise from data analysis. Unfortunately, pollutant data cannot fix the problems of air pollution, and rarely can the science investigators make direct changes either.

However, environmental data has the power to facilitate great change, providing evidence to legislators and policy makers worldwide (Levelt et al., 2006b; Metz et al., 2005) with data made possible by ongoing satellite observing missions. The objectives of an Earth-observing space mission are not complete after launch, or even after deorbit. The end product of data must be studied for its impact as well as its content. What is this chain of command once data is downlinked from a satellite? How is environmental satellite data processed, disseminated, and digested? How effective is the resultant policy, does it address the relevant issues well, and has it been successfully implemented? Extending the mission timeline to include the effects of its data products is necessary in understanding the true worth of the experiment. In applying Actor-Network Theory, this paper aims to examine a complex web of nodes by mapping the human and non-human actors found in the context of the posed issue.

The U.Va. nitrogen dioxide observing spacecraft mission was originally hypothesized by Professors Chris Goyne, Sally Pusede, and Michael Skrutskie. Professor Pusede is well-versed in atmospheric remote sensing, particularly in relation to vehicle emissions, and teaches within the U.Va Department of Environmental Sciences. Professor Skrutskie has experience in both ground- and space-based astronomical instrumentation, and is the director of the Astronomical Instrumentation Laboratory, part of the U.Va Department of Astronomy. Professor Goyne has led the CubeSat Laboratory and Ground Station over the past five years, and teaches the Spacecraft Design class to fourth years, wherein the development of CubeSats has been a major focus. Professor Goyne holds his position in the U.Va. Department of Mechanical and Aerospace Engineering. Additional instrumentation design work has been done by John Wilson and Matt Nelson of the Department of Astronomy, who serve as the optics specialist and electronics specialist, respectively. A collaborator with this mission is Kelly Chance, a principle investigator for the TEMPO satellite mission, and who conducts research at the Harvard Smithsonian Center for Astrophysics (Pusede, Skrutskie, & Goyne, 2018). Graduate student Angelique Demetillo is contributing to the mission while conducting her studies in the Department of Environmental Sciences with Professor Pusede. Undergraduate student involvement began with the members of Spacecraft Design in the 2018-2019 academic year, and continued in the summer of 2019 with students Kathryn Wason, of the Department of Electrical and Computer Engineering, Connor Segal and Hannah Umansky (author), of the Department of Mechanical and Aerospace Engineering, and Genna Brockett, of the Department of Mechanical and Aerospace Engineering and the Department of Astronomy. These four students are continuing to work on this mission throughout the 2019-2020 academic year. Hannah Umansky is the undergraduate student lead of the project, and manages a team of ten additional students in the capstone course Spacecraft Design. The mission timeline extends beyond the current academic year, as depicted in Figure 2.

Task	Date
Conceptual Design Review	5/2019
Benchtop Spectrograph Testing	8/2019
Spectrograph Proof of Concept	12/2019
Preliminary Design Review	12/2019
Additional Funding Obtained	4/2020
Critical Design Review	5/2020
Build Phase	5/2020 – 5/2021
Integration/Launch	8/2021-12/2021

Figure 2: Mission Timeline: Key milestones of the mission are outlined from 2019 to 2021 (Umansky, 2019).

CREATING A SPACECRAFT FROM SCRATCH

NO BIGGER THAN A BREADBOX

In the past decade, the standard form factor of CubeSats have greatly increased the accessibility of small spacecraft to private companies and academic institutions. Classified by mass as a microsatellite, nanosatellite, picosatellite, or femtosatellite, a standard 1U CubeSat falls under the minimum requirement of nanosatellites at 1 to 1.33 kg. The 1U dimensions of 10 cm x 10 cm x 10 cm allow for reusable deployers, such as the NanoRacks dispenser affixed to the International Space Station (ISS), as well as mass produced, commercial-off-the-shelf (COTS) components. Larger CubeSats are made by simply adding 1U units, resulting in sizes such as 2U, 3U, and 6U. The 3U, seen in Figure 3, has a general size of 10 cm x 10 cm x 30 cm, allowing for triple the volume of a 1U (Agasid et al, 2019).

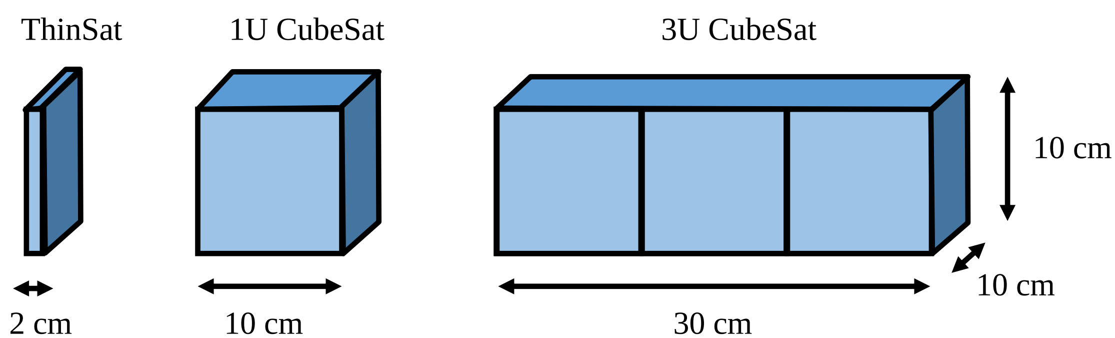

Figure 3: Satellite Sizing: 1U units are combined to create larger satellites within the CubeSat specifications (Umansky, 2019).

A TAILORED DESIGN

The 3U team in the course Spacecraft Design is tasked with developing a small satellite to hold a 1.5U scientific payload. The payload, a custom-built spectrometer, will address the question: how does nitrogen dioxide vary over intra-urban landscapes at high spatial resolutions? Therefore, this project has the problem statement: how can a small spacecraft permit observations of nitrogen dioxide in the Earth's atmosphere at improved spatial resolutions? The solution is divided between the Departments of Mechanical and Aerospace Engineering and Astronomy, such that the former will design the spacecraft bus, while the latter develops a functional spectrometer tuned to detect faint emissions of nitrogen dioxide.

Due to the impossibility of completing an entire space mission in one year, the scope of the 2019-2020 segment will be limited in achieving the Critical Design Review stage of the mission, and acquiring proof-of-concept for the spectrometer, by successfully testing an analogous optical benchtop model.

During the summer of 2019, the undergraduate team worked on evaluating the early component choices made by the previous year's students, and reviewing the overall spacecraft analysis, for example, the mass and power budgets. Further mathematical analysis was taken to understand the pointing requirements of the satellite; in order to take measurements of specific ground locations while quickly passing by, the spacecraft must be able to continually orient itself with respect to the target. Preliminary work was put into the bureaucratic side of space mission design, such as seeking sources of funding, and reviewing the requirements for communications and remote sensing licenses. The August 2019 design can be viewed in Figure 4.

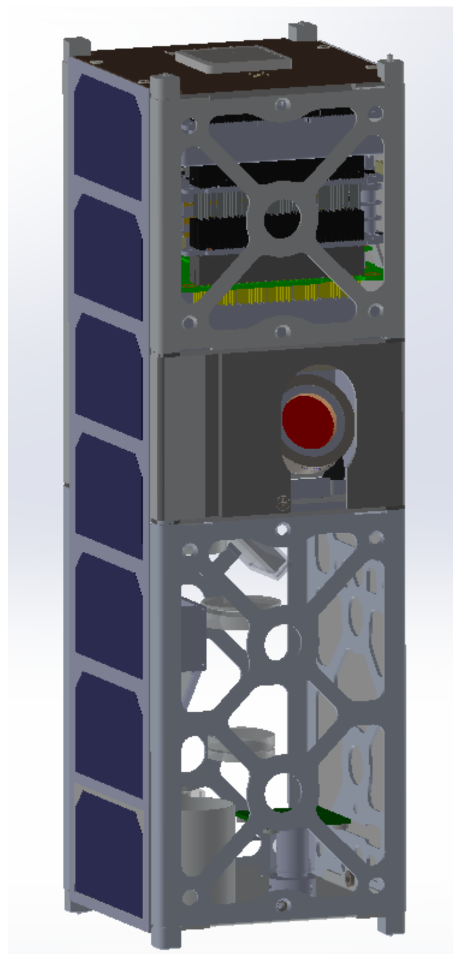

Figure 4: The 3U Spectrograph: Top to bottom, the satellite is comprised of the electronics bus, the control system, and the payload. The final design will include additional side coverage of solar panels (Umansky, 2019).

Throughout the fall semester, the team in Spacecraft Design will analyze the broader conceptual aspects of the mission, as these new student team members are introduced to both the specifics of the 3U project and the more general space mission engineering process. Concurrently, work is being done investigating the thermal environment, possible on-board data processing, and experimentation with the payload benchtop model.

In the spring semester, the undergraduate students will focus more on their respective component sub-teams, and continue to evaluate the compatibility of each aspect of the spacecraft's internal mechanisms. A goal of this year's work is to secure funding, select final components, and prepare for the purchasing and assembly of parts in the summer or fall of 2020. Milestones for future undergraduate teams will then be integration, licensing, launch, and deployment.

The 3U mission was originally funded by the University of Virginia's 3Cavaliers program, created by the Office of the Vice President for Research to promote tri-interdisciplinary research projects. The 3Cavaliers funding allowed for internal research and development by all involved, however, this will not carry into 2020, nor does the allotted amount cover the full cost of the satellite build. External sources of funding are being sought out by the team, with likely candidates being the National Science Foundation or the National Aeronautics and Space Administration (NASA). NASA provides a launch services program entitled the CubeSat Launch Initiative, in which NASA covers the cost of launch and provides manifesting, or scheduling, of the mission onto a launch vehicle in exchange for a share of the mission's results. The previous CubeSat mission at U.Va., a 1U flown with the Virginia CubeSat Constellation, was successful in partnering with NASA for these services.

PEOPLE, POLLUTION, & POLICY

While this mission focuses on detection of nitrogen dioxide, it is only one of many gaseous pollutants that can be tied to the combustion of fossil fuels. As nitrogen oxides interact with the atmosphere, nitrogen dioxide forms and is detected in areas of urban infrastructure, manufacturing, and congested roadways. Unfortunately, air pollutants are not limited to the atmosphere; pollutants have been traced to ingestion via contaminated food and water (Kampa & Castanas, 2008). The proposed CubeSat will be able to provide data on nitrogen dioxide emissions worldwide, at high spatial resolutions not found with current satellite technology. With this finer detail, pollutants from individual roadways and city centers can be mapped to their respective urban features, aiding policy makers and informing environmental scientists, as well as the general public (Mahoney, 2003). Space missions of this kind will be able to aid our understanding of pollution-based public health crises, such as increased doctor and hospital visits, and even effects on mortality rates due to long exposures to automobile emissions (Zhang & Batterman, 2013).

DATA: FROM START TO FINISH

However, just the creation of new data does not solve these public health issues or environmental crises. The aim of this investigation is to reveal the sources of policy making, and to understand the direct, or perhaps indirect link, between data collection and legislative change. It is often assumed that once the data is collected, the scientists have achieved their objective, and the mission can be considered successful. This research will examine the data product lifecycle, and determine its effectiveness with respect to motivating solutions to the problems captured by the data. To understand this lifecycle of information, Actor-Network Theory (ANT) will be applied to identify the influencing factors.

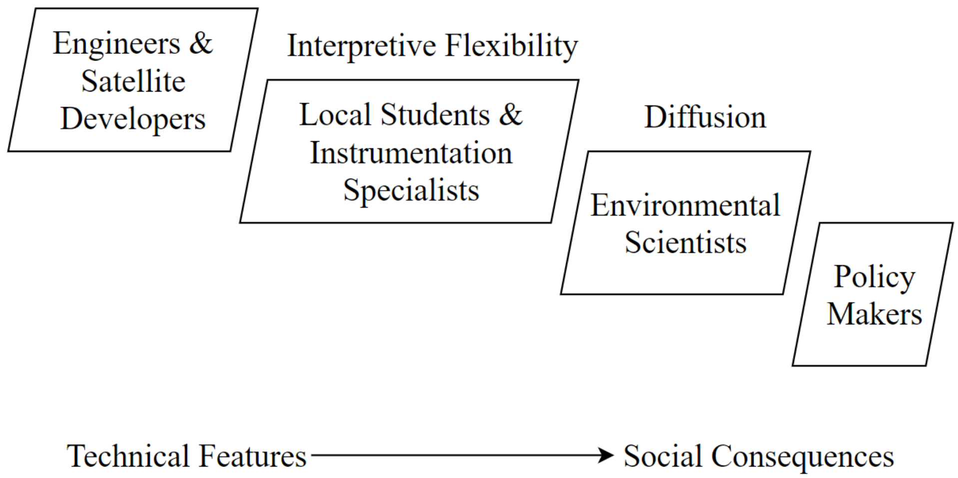

Figure 5: A Linear ANT Model: A simple Actor-Network Theory visualization, depicting four major human actors (Umansky, 2019).

JUST FOLLOW THE MAP

The analysis of the pathway from engineers to policy makers can begin as a simple linear hand-off model, as seen in Figure 5. Depicted within this figure is unidirectional movement through the main human actors in the scope of this research. However, it must be noted that ANT is not limited to examining human actors alone; actors can be, and frequently are, non-human (Fioravanti & Velho, 2010). Within Figure 5, additional socio-technological theories can be applied. Interpretive flexibility, a keystone of social constructivism (Johnson, 2005), arises in the ability of the technical team at U.Va. to customize the CubeSat to the needs of the mission. Though CubeSats must conform to industry-set standards, the device still retains a high degree of flexibility in its properties and internal design. Another socio-technological theory, the diffusion of innovations, occurs when environmental scientists begin to adopt satellite technology as a tool in their research methodologies through their own innovation-decision processes (Rogers et al., 1996). Ultimately, Figure 5 shows a simplified movement from "technical features" to "social consequences" (Jolivet & Heiskanen, 2010).

Yet, though there may be a bias towards analyzing human actors, a full ANT study would be incomplete without acknowledging the power of non-human actors (Latour, 1990). A further mapping of the stakeholders in this study can be seen in Figure 6. Arrows map the path from physical to conceptual actors, as the technology in question undergoes a metamorphosis from a satellite to intangible information. The transfer of data follows the human actors, from engineer to environmental scientist to policy maker. Again, additional frameworks can be imposed on this scenario, as these socio-technical thought processes are not mutually exclusive. The organizational, technical, and social stakeholder categorizations of Pacey's Triangle (Pacey, 1983) can be discerned as the shape of each node shifts from rectangular to superelliptical to circular, respectively.

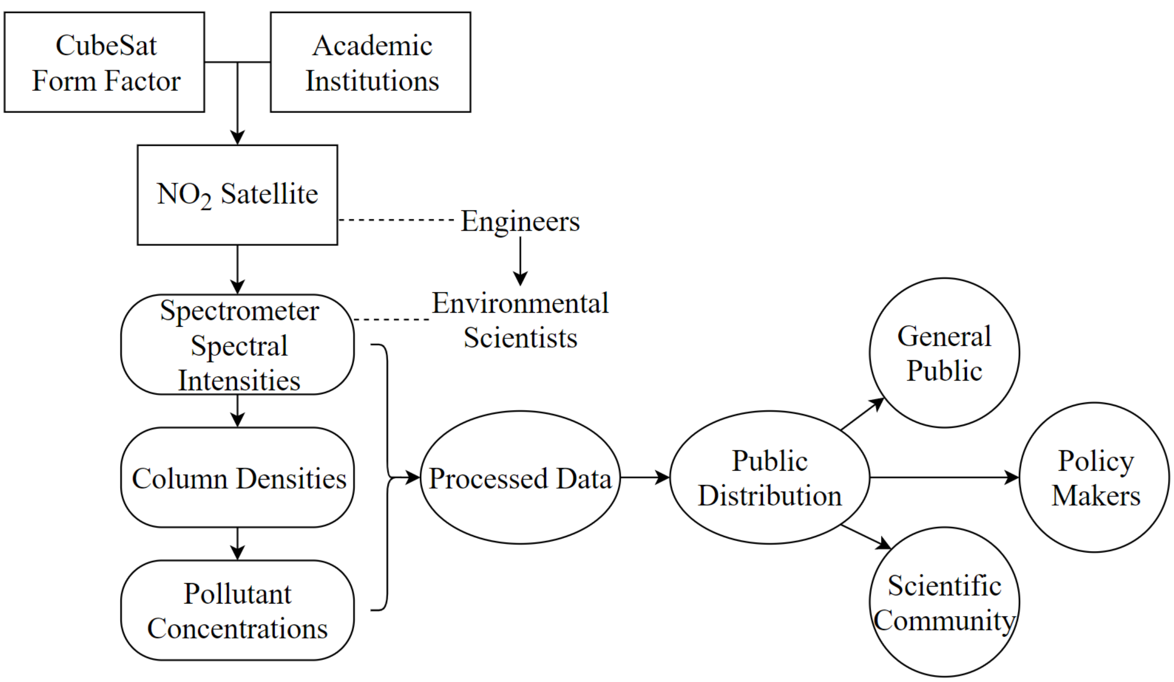

Figure 6: Exploring Stakeholders: The map can be expanded to distinguish between organizational, technical, and social components of the data product lifecycle (Umansky, 2019).

Actor-Network Theory requires the continual searching for influences, ever expanding the network to map all possible actors. In this vein, there is a loss of what is central, global, or local (Fioravanti & Velho, 2010; Jolivet & Heiskanen, 2010). To improve on Figure 5, additional actors are added as the network grows and becomes more complex. The resultant map can be seen in Figure 7. Including the larger network of stakeholders demonstrates the complexity and higher-dimensionality of ANT (Latour, 1990). The once-linear network now becomes bidirectional and even cyclical, as policy makers can inform regulations on the actions of satellite industry, et cetera. The ability to reverse arrow directions creates potential for overflow, as hierarchies dissolve and science becomes a social activity between stakeholders (Fioravanti & Velho, 2010).

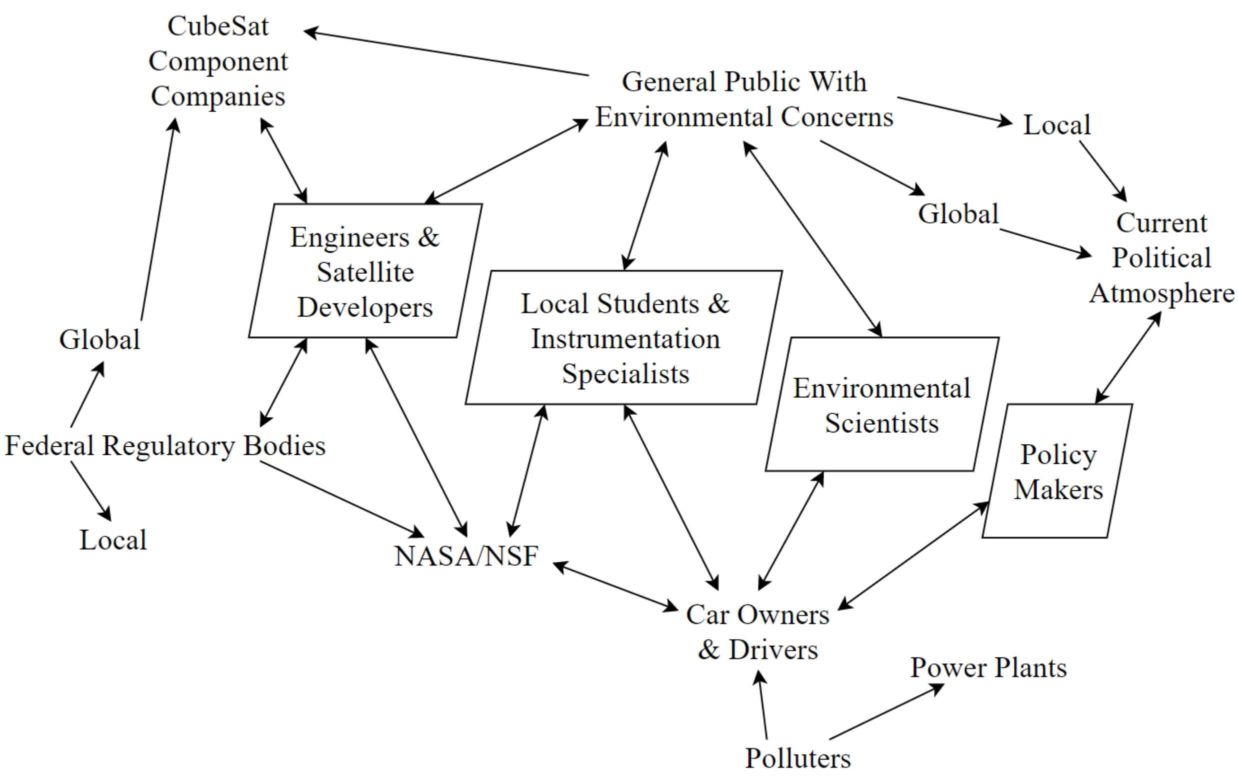

Figure 7: Decentralizing the Problem: By adding additional non-human actors, the ANT model loses its unidirectional constraints (Umansky, 2019).

A positive hypothesis for this study would claim that data is extremely efficient at facilitating legislative change, that policy makers are highly aware of leading-edge data collection methods, and any resulting policy is measurably effective on short and long time-scales. The relationship between satellite-based environmental data and its effect on policy has not been given the proper attention it deserves; by applying the framework of Actor-Network Theory, this study aims to provide an answer.

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