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EXPLORING THE USE OF PLANETSCOPE DATA FOR PARTICULATE MATTER AIR QUALITY RESEARCH

by

JEANNÉ LE ROUX

A THESIS

Submitted in partial fulfillment of the requirements For the degree of Master of Science in The Department of Earth System Science to The School of Graduate Studies of The University of Alabama in Huntsville

HUNTSVILLE, ALABAMA
2020
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Submitted by Jeanné le Roux in partial fulfillment of the requirements for the degree of Master of Science in Earth System Science and accepted on behalf of the Faculty of the School of Graduate Studies by the thesis committee.

We, the undersigned members of the Graduate Faculty of The University of Alabama in Huntsville, certify that we have advised and/or supervised the candidate on the work described in this thesis. We further certify that we have reviewed the thesis manuscript and approve it in partial fulfillment of the requirements for the degree of Master of Science in Earth System Science.

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ABSTRACT

The School of Graduate Studies
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Degree Master of Science College/Dept. Science/Earth System Science

Name of Candidate Jeanné le Roux

Title Exploring the Use of PlanetScope Data for Particulate Matter Air Quality Research

Planet, a commercial company, has achieved a key milestone by launching a large fleet of small satellites (smallsats) that provide high resolution imagery of the entire Earth’s surface on a daily basis with its PlanetScope sensor. Given the potential utility of this data, this thesis explores its potential use for air quality applications. Before this data can be utilized for air quality applications, key features of the data including geolocation accuracy, calibration quality, and consistency in spectral signatures need to be addressed. In this study, data from PlanetScope is screened for geolocation consistency, and is compared to Moderate Resolution Imaging Spectroradiometer (MODIS) data over different land cover types, and under varying PM2.5 and aerosol optical depth (AOD) conditions. The data selected for this study was found to fall within Planet’s reported geolocation accuracy of 10 meters (between 3-4 pixels). In a comparison of top of atmosphere (TOA) reflectance over a variety of land cover types, the difference in reflectance between PlanetScope and MODIS ranged from near-zero (0.0014) to 0.117, with a mean difference in reflectance of 0.046±0.031 across all bands. The reflectance values from PlanetScope were higher than MODIS 78% of the time, but no significant relationship was found between surface PM2.5 and TOA reflectance for the cases that were studied. The results indicate that commercial satellite data have the potential to address Earth-environmental issues.

Abstract Approval: Committee Chair

Department Chair

Graduate Dean
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# TABLE OF CONTENTS

List of Figures ............................................................................................................................ vii
List of Tables ............................................................................................................................... ix

Chapter

1. INTRODUCTION ...................................................................................................................... 1
   1.1 Current State of PlanetScope Data ..................................................................................... 5
   1.2 PlanetScope for Air Quality Applications .......................................................................... 9

2. MATERIALS AND METHODS ............................................................................................... 12
   2.1 PlanetScope Data .............................................................................................................. 12
   2.2 MODIS Data .................................................................................................................... 13
   2.3 PM2.5 Data ..................................................................................................................... 15
   2.4 AOD Data ....................................................................................................................... 16
   2.5 Geolocation Comparison ................................................................................................. 17
   2.6 Comparison of PlanetScope and MODIS Spectral Response over Different Land Cover Types .......................................................................................................................... 19
   2.7 Analysis of PlanetScope and MODIS Spectral Response to Varying Surface PM2.5 Conditions ........................................................................................................................................ 20
   2.8 Analysis of PlanetScope and MODIS Spectral Response to AOD ................................... 21

3. RESULTS .................................................................................................................................. 22
   3.1 Geolocation Comparison ................................................................................................. 22
   3.2 Comparison of PlanetScope and MODIS Spectral Response over Different Land Cover Types .......................................................................................................................... 22
   3.3 Analysis of PlanetScope and MODIS Spectral Response to Varying Surface PM2.5 Conditions ........................................................................................................................................ 29
   3.4 PlanetScope and MODIS Spectral Response to AOD ..................................................... 35

4. DISCUSSION AND CONCLUSIONS .................................................................................... 39

APPENDICIES .............................................................................................................................. 43
   Appendix A ........................................................................................................................... 43
   Appendix B ........................................................................................................................... 45
   Appendix C ........................................................................................................................... 50

REFERENCES ............................................................................................................................. 53
LIST OF FIGURES

Figure

Figure 1 Point locations of the EPA AQS PM2.5 monitors utilized for this study. Insets zoom into study areas where data from multiple PM2.5 monitors were used. ................................................................. 16

Figure 2 Schematic illustrating the 5x5 and 10x10 pixel size averages utilized for the TOA reflectance comparison between PlanetScope and MODIS. The inner boxes represent the 5x5 pixel average, whereas the outer boxes represent the 10x10 pixel averages (MODIS to the left and PlanetScope to the right). The difference in size between the MODIS (left) and PlanetScope (right) boxes are not to scale. ................................................................. 20

Figure 3 Comparison of results for (a) a clear day (1/3/2019); (b) and a hazy day (8/7/2018) for water pixels sampled over Millerton Lake near Fresno, CA. Results for the other land cover types sampled in the Fresno and Los Angeles study areas can be found in Appendix A....................... 27

Figure 4 Comparison of results for (a) a clear day (1/3/2019); (b) and a hazy day (8/7/2018) for agriculture pixels sampled near Fresno, CA. Results for the other land cover types sampled in the Fresno and Los Angeles study areas can be found in Appendix A............................. 29

Figure 5 Three hour averaged PM2.5 concentration on the x-axis plotted against (a) blue band TOA reflectance for a 5x5 pixel average; (b) blue band TOA reflectance for a 10x10 pixel average; (c) green band TOA reflectance for a 5x5 pixel average; (d) green band TOA reflectance for a 10x10 pixel average; (e) red band TOA reflectance for a 5x5 pixel average; (f) red band TOA reflectance for a 10x10 pixel average; (g) NIR band TOA reflectance for a 5x5 pixel average; (h) NIR band TOA reflectance for a 10x10 pixel average on the y-axis; for both PlanetScope and MODIS for all 41 data points. PlanetScope points are in color and MODIS points are grey................................................................. 31

Figure 6 Data points from Figure 5 isolated for the SPOKANE - AUGUSTA AVE station for (a) the blue band; (b) green band; (c) red band; (d) and NIR band. Low PM2.5 values are from 4/19/2018 and high PM2.5 values are from 8/14/2018......................................................... 32

Figure 7 Data points from Figure 5 isolated for the Fresno - Garland and Clovis PM2.5 stations for (a) the blue band; (b) green band; (c) red band; (d) and NIR band. Low PM2.5 values are from 1/3/2019 and high PM2.5 values are from 8/7/2018......................................................... 33

Figure 8 Three-hour averaged AOD on the x-axis plotted against (a) blue band TOA reflectance for a 5x5 pixel average; (b) blue band TOA reflectance for a 10x10 pixel average; (c) green band TOA reflectance for a 5x5 pixel average; (d) green band TOA reflectance for a 10x10 pixel average; (e) red band TOA reflectance for a 5x5 pixel average; (f) red band TOA reflectance for a 10x10 pixel average; (g) NIR band TOA reflectance for a 5x5 pixel average; (h) NIR band TOA
reflectance for a 10x10 pixel average on the y-axis; for both PlanetScope and MODIS for all 10 data points. PlanetScope points are in color and MODIS points are grey.

**Figure B1** Results from section 3.2 for pixels sampled over a bright urban area in the Fresno study area on 1/3/2019.

**Figure B2** Results from section 3.2 for pixels sampled over an urban area in the Fresno study area on 1/3/2019.

**Figure B3** Results from section 3.2 for pixels sampled over clouds in the Los Angeles study area on 8/4/2018.

**Figure B4** Results from section 3.2 for pixels sampled over the ocean in the Los Angeles study area on 8/4/2018.

**Figure B5** Results from section 3.2 for pixels sampled over an urban area in the Los Angeles study area on 8/4/2018.

**Figure C1** Data points from Figure 8 isolated for the Sigma_Space_Corp AERONET site. Data points from the 5x5 and 10x10 pixel average plots are combined. Lower AOD values are from 3/22/2017 and higher AOD values are from 7/14/2018. Plots are separated by (a) blue band; (b) green band; (c) red band; (d) NIR band. PlanetScope values are in color and MODIS values are in grey. The image in (e) shows a screenshot of the AERONET site location in Google Earth.

**Figure C2** Data points from Figure 6 isolated for the GSFC AERONET site. Data points from the 5x5 and 10x10 pixel average plots are combined. Lower AOD values are from 3/22/2017 and higher AOD values are from 7/14/2018. Plots are separated by (a) blue band; (b) green band; (c) red band; (d) NIR band. PlanetScope values are in color and MODIS values are in grey. The image in (e) shows a screenshot of the AERONET site location in Google Earth.

**Figure C3** Data points from Figure 6 isolated for the MD_Science_Center AERONET site. Data points from the 5x5 and 10x10 pixel average plots are combined. Lower AOD values are from 3/22/2017 and higher AOD values are from 7/14/2018. Plots are separated by (a) blue band; (b) green band; (c) red band; (d) NIR band. No AERONET data was available for the 500nm band on 3/22/2017 (b), so only values from 7/14/2018 are plotted for the green band. PlanetScope values are in color and MODIS values are in grey. The image in (e) shows a screenshot of the AERONET site location in Google Earth.
LIST OF TABLES

Table

Table 1 Summary of the differences between the three most recent generations of PlanetScope, adapted from Planet’s Imagery Product Specification document (Planet.com 2020). All sensors collect data at 12-bit depth with an approximate ground sampling distance of 3.7 meters. The revisit time is reported to be daily at nadir.................................................................6

Table 2 PlanetScope and MODIS data acquired for this study. The first column lists the location and dates of the Dove-Classic (PS2) PlanetScope imagery acquired, with dates ranging from 3/22/2017 to 12/15/2019. The second column lists the MOD02HKM tile overlapping most closely to the acquired Planet data. The third and fourth column list the acquisition time of the respective PlanetScope and MODIS imagery, and the last column lists the approximate temporal offset between the two, which ranged from 2 minutes at the Baltimore, MD study area on 7/14/2018 to 68 minutes at the Bismarck, ND study area on 8/11/2018...............................14

Table 3 Summary of AERONET data utilized for this study..............................................17

Table 4 Bandwidths of the MODIS, PlanetScope and AERONET bands used for comparison. 17

Table A1 Sources of the ArcMap basemap imagery overlapping control points in each study area used for the geolocation comparison (section 2.5 and 3.1)..........................................................43
CHAPTER 1

INTRODUCTION

A commercial company called Planet has achieved a key milestone by launching a large fleet of small satellites (smallsats) that provide high resolution (sub 5 meter) imagery of the entire Earth’s surface on a daily basis. Surpassing the spatiotemporal coverage offered by most existing environmental satellites, this data has the potential to benefit a wide range of application areas. Given the potential utility of Planet’s smallsat data, this paper introduces the smallsat concept, summarizes the current state of Planet’s smallsat data, and explores its potential use for air quality applications. Before this data can be utilized for air quality applications, key features of the data including geolocation accuracy, calibration quality, and consistency in spectral signatures need to be addressed. This paper also presents the results of an exploratory study conducted to assess these aspects.

Smallsats, defined as satellites with a mass of 500 kilograms or less, have become an increasingly popular platform for space-borne observation (Valinia et al. 2019; Wekerle et al. 2017). This momentum was initiated by the success of the CubeSat standard, which was launched in 1999 as a collaboration between California Polytechnic State and Stanford University (Martin et al. 2014; The CubeSat Program 2014). Originally developed to make space more accessible to university students, the CubeSat standard provides a cost effective, off-the-shelf method for space observation and has since been adopted by organizations worldwide (The CubeSat Program 2014). The standard CubeSat unit, 1U, measures 10x10x10 centimeters and can be extended to larger sizes such as 1.5U, 2U, and etc. Based on their size, CubeSats are considered to be either nanosatellites or picosatellites, in terms of commonly used smallsat categories (Laufer & Pelton 2019):

- Minisatellite: 100 - 500 kg
- Microsatellite: 10 - 100 kg
- Nanosatellite: 1 - 10 kg
- Picosatellite: 0.1 - 1 kg
- Femtosatellite: <0.1 kg

CubeSats and other smallsat designs have become competitive against traditional satellites due their accessibility. Traditional satellites are often designed to carry highly specialized technologies that require years of research and development effort (Wekerle et al. 2017). Traditional satellites also tend to be large, heavy, and therefore expensive to launch (Wekerle et al. 2017). Smallsats, however, tend to employ commercially available off-the-shelf (COTS) technologies. With recent advancements in the miniaturization of electronics, COTS have become smaller, lighter, cheaper, and more readily available (Wekerle et al. 2017). As a result, smallsats are much cheaper to develop and launch, although the availability of launch vehicles remains a hurdle (Martin 2018). These aspects also make smallsats resilient. In the event of mission failure, less resources are lost on a smallsat compared to a traditional satellite. With the use of COTS, replacement satellites can be developed relatively quickly. It is also becoming common for smallsats to be launched as a constellation of multiple coordinated satellites (Valinia et al. 2019). If one part of the constellation fails, the remaining satellites can continue to collect data and fulfill mission requirements. Traditional satellites, in comparison, carry the risk of being a single point of failure since they are not commonly flown in constellations and cannot be as easily replaced.

The accessibility of smallsat technology has also opened the industry to the private sector. While smallsats were once primarily developed by universities and research institutes, approximately 51% of smallsats today are produced by private companies (NASA.gov; Nanosats.eu). One of the most established commercial smallsat companies is Planet (formerly Planet Labs). Based out of San Francisco, Planet’s mission is to “image the entire Earth every day and make global change visible, accessible, and actionable” (Planet.com). Planet’s mission is attractive since there is typically a trade-off between temporally frequent and high spatial resolution observations with data from traditional satellites. For instance, consider NASA’s
Moderate Resolution Imaging Spectroradiometer (MODIS). Flying on the twin Aqua and Terra satellites, MODIS can image the entire Earth’s surface every one to two days, but does so at a resolution of 250 to 1,000 meters. At this resolution, finer-scale details needed for tracking regional and local trends are not resolvable. The Landsat mission, which is a joint venture between NASA and the USGS, provides data at a much finer 30-meter spatial resolution. The revisit time for Landsat, however, is 16 days, leaving large gaps in the coverage needed for time-series analyses. This effect is further exacerbated in cloudy locations where usable imagery may not be available for extended periods of time (Houborg & McCabe 2018a).

The more recent European Space Agency (ESA) Sentinel-2 mission has improved upon these shortcomings. Sentinel-2 competes with Landsat by providing data at a 10 to 60-meter resolution in comparable spectral bands, with a revisit time of 2-3 days at mid-latitudes and 5 days at the equator (USGS.gov; ESA.int 2013). This is accomplished via a constellation of two identical satellites offset by 180 degrees in a polar orbit. ESA and NASA have also entered a collaborative agreement to cross-calibrate Sentinel-2 and Landsat’s multispectral sensors, paving the way for the Harmonized Landsat and Sentinel-2 surface reflectance (HLS) series of merged data products (ESA.int 2013). When completed, HLS will offer global surface reflectance data at a 30-meter spatial resolution every 2-3 days (Claverie et al. 2018).

High spatial resolution (sub 5 meter) satellite imagery has only been produced by commercial companies to date. IKONOS, launched by DigitalGlobe in 1999, was the first commercial satellite to produce sub-meter resolution data via its 81cm resolution panchromatic band. Now part of Maxar Technologies, DigitalGlobe offers data with a resolution as high as 31cm from its WorldView-3 and WorldView-4 satellites. WorldView, and similar high resolution commercial satellites such as GeoEye-1 and QuickBird, utilize the traditional single-sensor satellite design. These satellites offer high-quality, high resolution data with revisit times as frequent as daily or better to its paying customers. The coverage provided, however, is not consistent since these satellites are tasked to focus on certain areas of the globe based on customer requests. For
instance, Maxar currently advertises that approximately 60% of the Earth’s surface is imaged on a monthly basis among its fleet of high resolution satellites (Maxar.com).

Despite recent innovations, traditional satellite missions have yet to provide daily, global high resolution coverage. Planet, however, has managed to accomplish this by launching what is currently the largest smallsat constellation in operation. This constellation is composed of approximately 130 CubeSats (Doves), each equipped with a sensor called PlanetScope that collects imagery in blue (455 - 515 nm), green (500 - 590 nm), red (590 - 670 nm) and near infrared (NIR) (780 - 860 nm) bands at a 3-5 meter spatial resolution (Planet.com 2020). The first Dove was launched in Kazakhstan as a proof of concept on April 19, 2013 as a secondary payload on board the Soyuz-2.1b rocket. A second Dove, also a proof of concept, was launched two days later from Wallops Island, Virginia (EOportal.org). These initial launches proved to be successful, and Planet announced its “Mission 1” to “image the entire Earth’s surface every day and make global change visible, accessible and actionable” shortly thereafter in 2014 (Planet.com). On February 15, 2017 Planet broke a world record for the largest constellation of satellites to launch on a single rocket when a fleet of 88 Doves (collectively referred to as “Flock 3p”) were launched successfully from an Indian Space Research Organization (ISRO) launch vehicle. In combination with Planet’s separate constellation of five RapidEye satellites, this milestone allowed Planet to image the entire Earth daily using only Planet assets (Safyan 2017). Mission 1 was officially completed a few months later on July 14, 2017 when Planet added an additional 48 Doves to its constellation (Planet.com).

U.S. government agencies including NASA, NOAA and the NGA have expressed interest in acquiring commercial smallsat data in order to complement their existing data assets. All three agencies have pursued some form of data purchase agreement with commercial smallsat vendors, including Planet (The White House 2016). One example is NASA’s Commercial Smallsat Data Acquisition Program (CSDAP), launched in 2017 to “identify, evaluate, and acquire data from commercial sources that support NASA’s Earth science research and applications goals.” Under
the program, eligible vendors submit a proposal to enter a purchase agreement with NASA to have their data evaluated over a 12-18 month period. As part of the evaluation process, NASA scientists test out the data and report on its utility for their area of expertise. The evaluation results dictate whether NASA will continue to procure data from the vendor (Earthdata.nasa.gov).

CSDAP’s pilot project awarded contracts to Planet and two other commercial companies. The evaluation report for the pilot project concluded that PlanetScope data was useful for augmenting and complementing existing NASA activities, and 22 out of 28 NASA scientists recommended that the agency continue to buy Planet data. The report showed high utility scores for single date imagery analysis, however, PlanetScope data had a low utility score for monitoring long term trends due to issues with calibration and geolocation (NASA Earth Science Division 2020).

1.1 Current State of PlanetScope Data

PlanetScope is a 3U form factor (10x10x30cm) CubeSat. Several iterations of the PlanetScope sensor have been launched, and there are currently three generations of PlanetScope in orbit including the Dove-Classic (PS2), Dove-R (PS2.SD) and the SuperDove (PSB.SD). The original PlanetScope sensor, Dove-Classic, has been deployed in both an International Space Station (ISS) orbit and a Sun Synchronous Orbit (SSO). Based on public launch announcements, it appears that Doves have not been launched into ISS orbit since mid-2016 (Planet.com/pulse). According to Planet’s public satellite operational report, Doves from flocks deployed into ISS orbit are no longer operational (Ephemerides.planet-labs.com 2020). Satellites in ISS orbit flew at an altitude of 400 kilometers with a 51.6 degree inclination angle, and provided maximum latitude coverage of ± 52 degrees. The equator crossing and revisit times were variable, and the ground sampling distance was approximately 3 meters at nadir (Planet.com 2016). Doves in SSO fly at an altitude of 475 kilometers with a 98 degree inclination, collect imagery up to ± 81.5 degree latitude and have an equator crossing time ranging from 9:30 AM to 11:30 AM local solar
time. The revisit time in SSO is daily and the ground sampling distance is 3.7 meters at nadir (Planet.com 2016; Planet.com 2020).

At any given time, the PlanetScope constellation is composed of approximately 130 Doves. The typical lifespan of a Dove is about 3 years in SSO, and new Doves are launched every 3 to 6 months to replenish decommissioned satellites and to infuse new and improved technology into the constellation (Planet.com 2015). Currently, the majority of Doves in orbit are Dove-Classics, however, it is anticipated that all launches moving forward will only consist of SuperDoves. Flock-4a which launched in April 2019 is the only publicly announced launch known to carry Dove-R satellites (Safyan 2019; Doshi 2019). Table 1 summarizes the differences between the three active PlanetScope sensors.

Table 1 Summary of the differences between the three most recent generations of PlanetScope, adapted from Planet’s Imagery Product Specification document (Planet.com 2020). All sensors collect data at 12-bit depth with an approximate ground sampling distance of 3.7 meters. The revisit time is reported to be daily at nadir.

| Characteristic       | Dove-Classic (PS2)                                                                 | Dove-R (PS2.SD)                                                                 | SuperDove (PSB.SD)                                                                 |
|----------------------|----------------------------------------------------------------------------------|---------------------------------------------------------------------------------|---------------------------------------------------------------------------------|
| Sensor Description   | Four-band frame imager; split-frame visible + NIR filter                         | Four-band frame imager; butcher-block filter providing blue, green, red and NIR stripes | Eight-band frame imager; butcher block filter providing blue, green, red, red-edge, and NIR stripes |
| Spectral Bands       | Blue: 455 - 515 nm Green: 500 - 590 nm Red: 590 - 670 nm NIR: 780 - 860 nm       | Blue: 464 - 517 nm Green: 547 - 585 nm Red: 650 - 682 nm NIR: 846 - 888 nm       | Coastal Blue: 431 - 452 nm Blue: 465 - 515 nm Green I: 513 - 549 nm Green II: 547 - 583 nm Yellow: 600 - 620 nm Red: 650 - 680 nm Red-Edge: 697 - 713 nm NIR: 845 - 885 nm |
| Frame Size (Approximate) | 24 x 8 km                                                                        | 24 x 16 km                                                                      | 32.5 x 19.6 km                                                                  |

Dove-Classics acquire data in three broad visible spectral bands and one broad NIR band, covering a range of 60nm for the blue band, 90nm for the green band, and 80nm for the red and NIR bands (Table 1). MODIS bands, in comparison, cover a range of 53nm for the blue band,
38nm for the green band, 32nm for the red band and 42nm for the NIR band. There is some overlap of the relative spectral response between Dove-Classic’s visible bands (Breunig et al. 2020; Houborg & McCabe 2018a). This level of overlap among the visible signals could be a limitation for certain applications. In mid-2019 the Dove-R series was launched with improved imaging capabilities, including narrower spectral bands designed to be more interoperable with Landsat-8 and Sentinel-2. In late 2019, Planet announced capabilities for the next generation of PlanetScope sensor, coined the SuperDove. SuperDoves are also reported to be interoperable with Sentinel-2 and will offer 5-band and 8-band imagery, and introduce new spectral bands such as coastal blue and red-edge designed to make SuperDove data practical to a wider range of applications (Planet News 2019).

Poor radiometric quality of PlanetScope data has been raised as a concern throughout the literature due to inherent differences in individual sensors and imaging under variable illumination conditions (Wang et al. 2020; Houborg & McCabe 2018a; Houborg & McCabe 2018b; Leach et al. 2019). Multiple studies have investigated techniques to correct for radiometric inconsistencies using data from well calibrated satellites such as Landsat, Sentinel-2 and Aqua/Terra MODIS. Some involve using data from other satellites to calibrate or normalize Planet data (Leach et al. 2019; Wang et al. 2020; Houborg & McCabe 2018a; Houborg & McCabe 2018b), whereas others seek to fuse the spectral signals from other satellites with Planet’s high spatiotemporal coverage (Aguilera 2020; Kaplan 2020; Li et al. 2020). Each PlanetScope data product undergoes radiometric correction to account for the relative differences in the radiometric response between sensors. Planet’s user documentation outlines the following efforts for maintaining radiometric accuracy: pre-launch sensor calibration in the lab; regular monitoring and adjustment of calibration coefficients once in orbit; maintenance of radiometric accuracy over time using monthly moon imaging; and continuous processing of calibration data for each satellite using instantaneous crossovers with well-calibrated satellites such as RapidEye and Landsat-8 (Planet.com 2018; Jumpasut 2019). Vicarious calibration accuracy is reported to
be within 5% based on data collected at a ground calibration site (Planet.com 2018). Planet’s radiometric calibration techniques are further outlined in a white paper titled “Absolute Radiometric Calibration of Planet Dove Satellites, Flocks 2p & 2e” which cites the radiometric calibration uncertainty to be 5-6% at 1-sigma (Wilson et al. 2017). This level of radiometric uncertainty is comparable to that of Landsat-8, however, the issue remains inconsistencies between individual sensors and therefore consequent inconsistencies between images (Yaokai et al. 2017).

Satellite data geolocation accuracy is important for any change monitoring application, where it is imperative that the same location be compared between images acquired at different times (Townshed et al. 1992). The accepted level of geolocation accuracy depends on the specific application, although higher accuracies are always ideal. PlanetScope data are geolocated and orthorectified using Digital Elevation Models (DEM) and Ground Control Points (GCP). Planet notes that the location accuracy of imagery depends on the quality of the DEMs and GCPs used and may vary from region to region based on the GCPs available. The location accuracy of orthorectified data products is reported to be a root mean square error (RMSE) of 10 meters (Planet.com 2016). Cooley et al. 2017 found that the mean Euclidean distance between lake centroids imaged by PlanetScope and WorldView were 10.5 ± 3.2 meters, comparable to Planet’s reported 10 meter ground location accuracy. This study also acknowledged that water/non-water classification differences between PlanetScope and WorldView could have contributed to some of the calculated offset, therefore, the geolocation errors reported may have been conservative (Cooley et al. 2017). Houborg & McCabe 2018a found shifts up to 19 meters (i.e. approximately 6 pixels) between PlanetScope images selected for use in a time-series analysis. This study also found that the pixel shifts were independent of orbital configuration (early Dove-Classics orbited in both ISS and SSO configurations). The study provides a methodology to automatically correct for geolocation differences between scenes, citing it as an important prerequisite step for performing meaningful multi-sensor time series analyses at the resolution of CubeSat data.
(Houborg & McCabe 2018a). Other studies found that PlanetScope data were geolocated reasonably well and did not find further geolocation correction necessary (Cheng et al. 2020; Leach et al. 2019).

1.2 PlanetScope for Air Quality Applications

Fine particles or droplets suspended in the air measuring two and a half microns or less in width (PM2.5) are a major air quality and public health concern, as these particles are small enough to reach the lungs via the respiratory tract. Short term exposure can cause a range of symptoms such as coughing, sneezing, and eye and throat irritation, whereas long term exposure is linked to increased mortality (Pun et al. 2017; West et al. 2016). PM2.5 is measured at ground-based air quality monitoring stations, however, many countries do not have any PM2.5 monitoring in place. Even countries that are well equipped, such as much of Europe and the United States, have large gaps in geographical and temporal coverage (Christopher & Gupta 2020). The use of satellite data for indirect PM2.5 estimations has been proposed as a method for filling in these gaps. One key variable that can be derived from satellite measurements is aerosol optical depth (AOD), which is the measure of the extinction of light as it travels through the atmosphere (Kaufman et al. 2002). Higher AOD values indicate the increased presence of aerosols in the atmosphere, and there is a large body of research regarding the estimation of ground-based PM2.5 from satellite derived AOD (Li et al. 2015 and cited works, for example). MODIS, for instance, has been used extensively to study aerosols and their role in the Earth’s climate, and numerous studies have investigated the relationship between MODIS-derived AOD and PM2.5 (Levy et al. 2013; Wang & Christopher 2003; Zhang et al. 2009; Lee et al. 2011; van Donkelaar et al. 2006). Although many studies have found some degree of correlation between MODIS-derived AOD and PM2.5, it is recognized that AOD-PM2.5 relationships are complex and is influenced by a multitude of factors that can vary based on meteorological conditions, region, time of year, land cover composition, and spatiotemporal resolution (Paciorek & Liu
Accounting for day-to-day and location-specific variability in the AOD-PM2.5 relationship has shown to yield significantly better results, however, the process of deriving AOD from satellite measurements relies on certain assumptions which still leave a degree of uncertainty (Lee et al. 2011; Wang & Christopher 2003; Zhang et al. 2009). Spatiotemporal resolution differences between satellite derived AOD and ground-based PM2.5 measurements are also a limitation to verifying these methods. For instance, MODIS AOD products were initially distributed at a 10km resolution, followed by the release of a 3km resolution product in 2014 (Remer et al. 2013). More recently, a 1km AOD product was made available, significantly improving the ability to predict PM2.5 at local scales (Lyapustin et al. 2018). Nonetheless, ground-based PM2.5 conditions can change rapidly and can vary at scales much smaller than 1km. Therefore, higher spatial and temporal resolution satellite measurements are needed to derive an accurate representation of PM2.5 at local scales (Wei et al. 2018; Bai et al. 2016; Di et al. 2019; Xie et al. 2019; Yao et al. 2019; Kloog et al. 2014; Zhang et al. 2018).

PlanetScope data provides the opportunity to estimate PM2.5 at a higher spatial resolution than ever before. Zheng et al. 2020 successfully used PlanetScope data to train a machine learning model to derive PM2.5 at a 200-meter resolution (Zheng et al. 2020). The machine learning approach removes the uncertainties associated with AOD retrieval by predicting PM2.5 directly from PlanetScope’s visual imagery (Zheng et al. 2020). Similarly, Shen et al. 2018 showed that it is possible to use machine learning to estimate PM2.5 directly from satellite top of atmosphere (TOA) reflectance, the starting point for AOD retrieval, rather than first deriving AOD and then using AOD for PM2.5 estimations (Shen et al. 2018). Since PlanetScope data is relatively new, using this data for air quality applications is an emerging area of research. In fact, at the time of this study, Zheng et al. 2020 was the only publication in the scientific peer reviewed literature to utilize PlanetScope data for PM2.5 estimation. Realizing the potential of PlanetScope data for deriving PM2.5 and other air quality indicators, as well as the limited literature on this topic, this study provides a general investigation of PlanetScope data in the
context of air quality applications. Specifically, PlanetScope’s geolocation consistency is assessed, and the spectral response of PlanetScope to MODIS (as TOA reflectance) are compared over a variety of land cover types, and under varying PM2.5 and AOD conditions. MODIS was selected for comparison since it is a well calibrated sensor and extensively used for aerosol and air quality research. Data over eight different U.S. cities, covering a range of seasons and geographical locales, were included in the assessment.
CHAPTER 2

MATERIALS AND METHODS

2.1 PlanetScope Data

PlanetScope data is offered as a basic scene, ortho scene, or ortho tile product. The basic scene product is the closest to raw data that is available. Basic scenes are composed of individual images taken in scanline with sensor and radiometric corrections applied, but have not been geometrically corrected. Ortho scenes are also composed of individual scanline images but are both radiometrically and geometrically corrected. Ortho tiles are simply ortho scenes that have been mosaicked together by Planet. Both ortho scene and ortho tile products are cartographically projected and are available as a visual or analytic product. Visual products are 8-bit depth 3-band (RGB) images designed to be used for visual purposes only. Analytic products are scaled to 16-bit depth and are designed to be used for a variety of applications. The ortho scene analytic product is available in units of scaled TOA radiance (W/m² sr µm) or atmospherically corrected scaled surface reflectance (SR), whereas analytic ortho tiles are only available in units of scaled TOA radiance.

For this study, analytic ortho scenes in units of scaled TOA radiance covering eight different U.S. cities (Table 2) were acquired from Planet (Planet Team 2020). These locations were chosen based on the availability of PM2.5 monitoring stations and to include a variety of geographical regions. Since PM2.5 monitoring typically takes place near population centers, all of the selected study areas include urban/suburban areas, with the inclusion of some surrounding rural/agricultural areas and bodies of water. While some of the imagery initially downloaded contain mountainous regions, these areas were not the main focus of the study. Planet’s Data Explorer were used to identify dates over each city with minimal cloud cover and ample overlap with available PM2.5 monitoring stations. Browse imagery of MODIS AOD data products and Environmental Protection Agency (EPA) Air Quality System (AQS) air quality tile plot data were
used to identify dates over each city with varying air quality levels. From these dates, one clear
day (i.e. low AOD levels shown in the browse imagery) and one hazy day were selected for
download. The locations and dates of PlanetScope data acquired are summarized in Table 2. Only
Dove-Classic data were acquired since it comprised the majority of available imagery at the time
of the study. Pre-processing of the PlanetScope data involved converting the data from scaled
TOA radiance (scaled by a factor of 10,000) to TOA reflectance using conversion coefficients
provided in the metadata for each individual scene, and then mosaicking together the scenes from
the same dates at each location.

2.2 MODIS Data

For each date and location listed in Table 2, MODIS scenes were acquired as closely as
possible to the time of PlanetScope acquisition. The Terra MODIS Calibrated Radiances 5-Min
L1B Swath 500m (MOD02HKM) version 6.1 data product, which is freely distributed by NASA,
were obtained. Table 2 lists the MODIS File ID and image acquisition time, as well as the image
acquisition time of the corresponding PlanetScope scenes. The approximate time difference
between the PlanetScope and MODIS acquisition times at each study area are also provided. Note
that the time difference between corresponding PlanetScope and MODIS imagery is 70 minutes
or less across all dates. For air quality applications this time window is reasonable since most
studies that compare satellite data with surface values use a 3-hour window for comparisons
(Gupta & Christopher 2020; Wang & Christopher 2003). Pre-processing of the MODIS data
consisted of conversion from HDF to GeoTIFF format, and conversion from scaled integers to
TOA reflectance using metadata coefficients. During the HDF to GeoTIFF conversion, the
MODIS tiles were also re-projected to match the projected coordinate system of the
corresponding Planet data.
Table 2 PlanetScope and MODIS data acquired for this study. The first column lists the location and dates of the Dove-Classic (PS2) PlanetScope imagery acquired, with dates ranging from 3/22/2017 to 12/15/2019. The second column lists the MOD02HKM tile overlapping most closely to the acquired Planet data. The third and fourth column list the acquisition time of the respective PlanetScope and MODIS imagery, and the last column lists the approximate temporal offset between the two, which ranged from 2 minutes at the Baltimore, MD study area on 7/14/2018 to 70 minutes at the Chicago, IL study area on 7/13/2018.

| Study Area Location & Date | MODIS File Identifier | MODIS Acquisition Time (GMT) | Acquisition Time of Corresponding PlanetScope Scenes (GMT) | Approximate Temporal Offset |
|---------------------------|-----------------------|-------------------------------|----------------------------------------------------------|----------------------------|
| Baltimore, MD 3/22/2017   | MOD02HKM.A2017081.1520.061.2017313214630 | 15:20:00 - 15:25:00          | 15:09:28 - 15:09:38                                      | 11 minutes                 |
| Baltimore, MD 7/14/2018   | MOD02HKM.A2018195.1615.061.2018196014137 | 16:15:00 - 16:20:00          | 15:17:32 - 15:23:50                                      | 2 minutes                  |
| Birmingham, AL 1/10/2019  | MOD02HKM.A2019010.1550.061.20190111549 | 15:50:00 - 15:55:00          | 16:07:59 - 16:07:56                                      | 15 minutes                 |
| Birmingham, AL 9/3/2019   | MOD02HKM.A2019246.1615.061.2019247011649 | 16:15:00 - 16:20:00          | 16:07:59 - 16:07:56                                      | 8 minutes                  |
| Bismarck, ND 8/11/2018    | MOD02HKM.A2018223.1815.061.2018224074641 | 18:15:00 - 18:20:00          | 17:07:07 - 17:07:11                                      | 68 minutes                 |
| Bismarck, ND 10/30/2018   | MOD02HKM.A2018303.1815.061.2018304073558 | 18:15:00 - 18:20:00          | 17:08:50 - 17:09:02                                      | 67 minutes                 |
| Chicago, IL 3/22/2018     | MOD02HKM.A2018081.1625.061.2018082211719 | 16:25:00 - 16:30:00          | 16:06:21 - 16:14:08                                      | 19 minutes                 |
| Chicago, IL 7/13/2018     | MOD02HKM.A2018194.1710.061.2018195020513 | 17:10:00 - 17:15:00          | 16:00:00 - 16:07:53                                      | 70 minutes                 |
| Fresno, CA 8/7/2018       | MOD02HKM.A2018219.1845.061.2018220074514 | 18:45:00 - 18:50:00          | 18:08:38 - 18:16:46                                      | 37 minutes                 |
| Fresno, CA 1/3/2019       | MOD02HKM.A2019003.1900.061.2019004073319 | 19:00:00 - 19:05:00          | 18:15:19 - 18:20:37                                      | 45 minutes                 |
| Los Angeles, CA 8/4/2018  | MOD02HKM.A2018216.1815.061.2018217074026 | 18:15:00 - 18:20:00          | 18:01:40 - 18:06:21                                      | 14 minutes                 |
2.3 PM2.5 Data

PM2.5 concentration measurements collected from EPA AQS ground monitors were used for this study. Only monitors providing hourly PM2.5 readings, and that had data available co-located spatially and temporally with the PlanetScope and MODIS data listed in Table 2, were considered. Figure 1 shows the location of the 25 AQS PM2.5 monitors which met the criteria to be used in this study.
Figure 1 Point locations of the EPA AQS PM2.5 monitors utilized for this study. Insets zoom into study areas where data from multiple PM2.5 monitors were used.

2.4 AOD Data

Ground-based AOD readings were obtained from the AErosol RObotic NETwork (AERONET). Version 3.0 quality level 2.0 AOD data were obtained from the AERONET website (https://aeronet.gsfc.nasa.gov/). AERONET sites used for this study are summarized in Table 3. Only monitors that had data available co-located spatially and temporally with the PlanetScope and MODIS imagery from Table 2 were considered.
Table 3 Summary of AERONET data utilized for this study.

| AERONET Site Name | Coordinates       | Date(s)        | Study Area |
|-------------------|-------------------|----------------|------------|
| NEON_SJER         | 37.109N, 119.732W | 1/3/2019       | Fresno     |
| GSFC              | 38.992N, 76.840W  | 3/22/2017 & 7/14/2018 | Baltimore |
| MD_Science_Center | 39.281N, 76.612W  | 3/22/2017 & 7/14/2018 | Baltimore |
| Sigma_Space_Corp  | 38.953N, 76.836W  | 3/22/2017 & 7/14/2018 | Baltimore |
| UMBC              | 39.255N, 76.709W  | 3/22/2017       | Baltimore |
| NEON_SERC         | 38.890N, 76.560W  | 7/14/2018       | Baltimore |
| SERC              | 38.889N, 76.556W  | 7/14/2018       | Baltimore |

AERONET measurements of atmospheric optical parameters are taken approximately every 15 minutes at wavelengths ranging from 340nm to 1020nm. For this study, measurements at wavelengths most closely corresponding to PlanetScope and MODIS spectral bands were used for comparison. The bandwidths of the MODIS, PlanetScope, and AERONET bands used for this study are summarized in Table 4.

Table 4 Bandwidths of the MODIS, PlanetScope and AERONET bands used for comparison.

| Band Color | MODIS (nm) | PlanetScope (PS2) (nm) | AERONET (nm) |
|------------|------------|------------------------|--------------|
| Blue       | 459-479    | 455-515                | 440          |
| Green      | 545-565    | 500-590                | 500          |
| Red        | 620-670    | 590-670                | 675          |
| NIR        | 841-876    | 780-860                | 870          |

2.5 Geolocation Comparison

One method for determining geolocation accuracy of satellite data is via ground control points (GCPs). GCPs may be natural or man-made features on the surface of the Earth that can be easily and precisely identified at the satellite imagery resolution, and which have high-quality
(e.g. sub-meter accuracy) location coordinates. Calculating the distance between the coordinates of the GCP in the satellite imagery and the known GCP location yields a measure of geolocation accuracy. Ideally, GCPs should cover a variety of land cover types and latitudes to provide a comprehensive measure of accuracy (Smiley 2009). In the absence of high-quality GCPs, a measure of geolocation accuracy can be obtained by comparing satellite imagery to imagery from another satellite or airborne source with a known location accuracy. In fact, this is a method that Planet employs, reporting the use GCPs derived from 2.5m ALOS basemap imagery to assess the geolocation accuracy of PlanetScope data over most of the Earth’s land mass (Suggula 2018). 1-m resolution National Agriculture Imagery Program (NAIP) imagery, which has an accuracy of 6m at a 95% confidence interval, is used to identify GCPs for PlanetScope imagery over the United States, and Landsat-8 data is used “as a fallback solution over remote polar areas and some small islands” (Fsa.usda.gov 2009; Suggula 2018).

High quality GCPs and high-resolution satellite imagery with a known geolocation accuracy were not available for this study, so basemap imagery from ArcMap was utilized as a best-available alternative to assess the geolocation quality of PlanetScope data. ArcMap is a commercial geographic information system (GIS) software produced by ESRI that uses high resolution data from a variety of sources to create its basemap layer. The sources of the basemap imagery are cited within the software and include the spatial resolution of the underlying imagery as well as the reported spatial accuracy. For the PlanetScope data covering each study area (Table 2), ten control points were selected in ArcMap’s basemap imagery, and each control point was manually compared to the PlanetScope data. Any features in the PlanetScope imagery that appeared shifted from the basemap were investigated further - for these features, the approximate distance between the control point feature in the PlanetScope image and the basemap were measured. Since Planet reports a geolocation accuracy of 10 meters, discrepancies measuring greater than 10 meters were noted. The goal of this method was to use a common reference point (i.e. the ArcMap basemap imagery) in order to identify shifts in PlanetScope imagery acquired.
between the two different dates in each study area. Alignment of the imagery from both dates with the basemap indicate that the PlanetScope imagery geolocation is consistent between the two dates and can be compared. If there is a significant offset for one or both dates of the PlanetScope imagery, then further geolocation correction may be warranted to ensure imagery from both dates are aligned as closely as possible. Since ArcMap basemap imagery are compiled from different sources, this methodology only provides a measure of geolocation consistency between the multi-source basemap imagery and PlanetScope data from two select dates. Nonetheless, agreement between all imagery sources at the same location is a positive indicator of geolocation accuracy. A summary of the ArcMap basemap imagery intersecting each control point surveyed in this study, as well as the cited accuracy for each, are summarized in Appendix A. The resolution of the basemap imagery used for comparison ranged from 0.07m with a 0.73m accuracy, to 0.5m with an accuracy of 5m.

2.6 Comparison of PlanetScope and MODIS Spectral Response over Different Land Cover Types

The Fresno, CA study area (Table 2) was more closely inspected to compare the spectral response, in terms of TOA reflectance, from PlanetScope and MODIS over a variety of land cover types including an inland freshwater lake, urban areas, and agricultural land. For the fresh water and agricultural land cover types, a comparison was also done between imagery from a clear (1/3/2019) and a hazy (8/7/2018) day, to gauge how TOA reflectance varies over the same land cover type but under differing air quality conditions. Imagery from the Los Angeles study area (Table 2) were also inspected for the inclusion of additional land cover types. Samples from the Los Angeles study area include cloudy pixels, ocean water, and an additional urban area sample. Maps detailing the location of each land cover type surveyed are included in Appendix B.

Over each land cover type, four MODIS pixels (500x500m) were randomly selected. For each pixel, the TOA reflectance for MODIS bands 1-4 (red, NIR, blue, green) were recorded. For the corresponding PlanetScope imagery, the mean TOA reflectance for all PlanetScope pixels
falling within the extent of each 500m MODIS pixel were recorded for comparison. This was done for each PlanetScope band (blue, green, red, NIR). Since PlanetScope pixels are at a 3m resolution, approximately 27,778 PlanetScope pixels fall within the extent of a single MODIS pixel. The mean and standard deviation TOA reflectance of the four randomly selected pixels were calculated for each band over each land cover type. The TOA reflectance of each sampled pixel, as well as the mean and standard deviation, are listed in Tables in Figure 3, 4 (section 3.2) and Appendix B.

2.7 Analysis of PlanetScope and MODIS Spectral Response to Varying Surface PM2.5 Conditions

TOA reflectance for corresponding PlanetScope and MODIS imagery (Table 2) were averaged over a 5x5 and 10x10 pixel sized box centered around each PM2.5 ground monitoring site shown in Figure 1. For MODIS, a 5x5 box measures 2,500m by 2,500m and a 10x10 box measures 5,000m by 5,000m. For PlanetScope, a 5x5 box measures 15m by 15m and a 10x10 box measures 30m by 30m.

**Figure 2** Schematic illustrating the 5x5 and 10x10 pixel size averages utilized for the TOA reflectance comparison between PlanetScope and MODIS. The inner boxes represent the 5x5 pixel average, whereas the outer boxes represent the 10x10 pixel averages (MODIS to the left and PlanetScope to the right). The difference in size between the MODIS (left) and PlanetScope (right) boxes are not to scale.
TOA reflectance was averaged over an area surrounding each PM2.5 monitoring site, at two different scales, in order to account for noise in the imagery, and to investigate the effect of scale on the average reflectance value. PM2.5 readings at the EPA AQS monitoring sites used in this study are taken at the top of every hour. In order to account for spatial gradients in the PM2.5 readings, the PM2.5 concentration was averaged over a three-hour window centered as closely as possible to the respective PlanetScope and MODIS image acquisition times. A total of 41 data points were collected, where a data point consists of the 5x5 and 10x10 averaged TOA reflectance centered around a PM2.5 station for an overlapping PlanetScope and MODIS image pair, and the corresponding three-hour averaged PM2.5 concentrations.

2.8 Analysis of PlanetScope and MODIS Spectral Response to AOD

A similar process was repeated for AOD, where TOA reflectance from PlanetScope and MODIS were averaged for a 5x5 and 10x10 pixel sized box centered around each AERONET site listed in Table 3. AOD readings for the wavelengths specified in Table 4 were averaged for a three-hour window centered around the respective PlanetScope and MODIS image acquisition times. A total of 10 unique data points were collected, where a unique data point includes 5x5 and 10x10 averaged TOA reflectance for an overlapping PlanetScope and MODIS acquisition (obtained within 70 minutes of one another), centered around an AERONET site, along with the corresponding three-hour averaged AERONET AOD.
CHAPTER 3

RESULTS

3.1 Geolocation Comparison

Overall, the control points surveyed showed good co-location between the PlanetScope imagery and ArcMap basemap imagery. Nine of the eighty control points surveyed had an offset approximated to be between 6-10 meters (i.e. greater than two pixels), however, this shift was not consistent across all control points within the same study area, or even across imagery from the same PlanetScope overpass. For some control points it was difficult to discern the exact offset due to sun-angle and shadow effects in the imagery. Nonetheless, none of the control points appeared to have an offset significantly greater than 10 meters, aligning with the geolocation accuracy reported by Planet. Imagery over the Spokane, Phoenix, Los Angeles, Fresno and Chicago study areas had zero or very minimal (less than a pixel) offset estimates. The imagery over Bismarck, Birmingham, and Baltimore contained the nine control points estimated to have an offset greater than 6 meters (i.e. two pixels). In most cases, the PlanetScope data appeared to be shifted slightly East or Southeast of the control points. Overall, these results suggest that PlanetScope data are accurate within a 3-4 pixel distance, however, this result is based on a comparison with ArcMap basemap imagery which has a varying degree of accuracy depending on the location. The lowest accuracy cited in the basemap imagery metadata was 5m (i.e. nearly 2 PlanetScope pixels) at a 0.5m resolution, adding an uncertainty of 5m (or nearly 2 PlanetScope pixels) to the results (Appendix A). Based on the results of the geolocation comparison, additional geolocation correction was not pursued for the PlanetScope data used in this study.

3.2 Comparison of PlanetScope and MODIS Spectral Response over Different Land Cover Types

Figure 3 and 4 (continued in Appendix B) show the mean TOA reflectance of the four randomly sampled pixels over each land cover type, for both PlanetScope and MODIS, plotted as
a function of wavelength. The wavelength of greatest spectral response for the 10xx PlanetScope sensor series is used as the wavelength on the x-axis for PlanetScope, and the center wavelength of each MODIS band is used as the wavelength on the x-axis for MODIS. The standard deviation of the four pixels used to calculate the mean TOA reflectance is shown as error bars.

For the samples taken over the Fresno study area, the mean TOA reflectance from PlanetScope trends slightly higher (by 0.06 on average) than that of MODIS across all four bands with the exception of the Millerton Lake hazy day sample (Figure 3b). For the three land cover types sampled over the Los Angeles study area, the spectral response curves for PlanetScope and MODIS trend closer together in comparison (average difference in reflectance of 0.02). A total of 12 pixels were sampled over the Los Angeles study area, and for these samples the mean difference in TOA reflectance between PlanetScope and MODIS was 0.018±0.009 for the blue band, 0.018±0.014 for the green band, 0.021±0.015 for the red band, and 0.043±0.034 for the NIR band; with an RMSE of 0.020 for the blue band, 0.022 for the green band, 0.025 for the red band, and 0.054 for the NIR band. The mean difference in TOA reflectance between PlanetScope and MODIS was slightly higher for the 24 pixels sampled over the Fresno study area, with a mean difference of 0.054±0.030 for the blue band, 0.059±0.027 for the green band, 0.054±0.027 for the red band, and 0.057±0.037 for the NIR band; with an RMSE of 0.062 for the blue and green bands, 0.060 for the red band, and 0.068 for the NIR band. The closer agreement between PlanetScope and MODIS TOA reflectance for the Los Angeles study area could be attributed to the difference in image acquisition time being only ~15 minutes, compared to ~30 and ~40 minutes for the Fresno samples.

A total of 36 samples were taken across both the Fresno and Los Angeles study areas. Across all samples, the mean difference in TOA reflectance was 0.042±0.030 for the blue band, 0.045±0.027 for the green band, 0.043±0.028 for the red band, and 0.052±0.037 for the NIR band; with an RMSE of 0.052 for the blue and green bands, 0.051 for the red band, and 0.064 for the NIR band. For 72% of the blue band samples, the TOA reflectance was higher for
PlanetScope compared to MODIS. The TOA reflectance for PlanetScope was also higher than MODIS for 94% of the green band samples, 92% of the red band samples, and 61% of the NIR band samples. While the TOA reflectance from the PS2 sensor trends slightly higher than MODIS overall, the results could be affected by the small sample size. The offset in image acquisition time between PlanetScope and MODIS, as well as the differences in spectral response functions between the two sensors, are also factors that are expected to contribute to some difference in TOA reflectance.

Figure 3 and 4 (continued in Appendix B) also shows the results as scatter plots with the reflectance of each sampled MODIS pixel on the x-axis, and the mean reflectance of the corresponding PlanetScope pixels on the y-axis. Values from each spectral band are color coded. Tighter clusters of the same color indicate less variability in reflectance across the sampled pixels. The reflectance values generally behave as expected. For instance, the samples over bodies of water show the lowest reflectance in the NIR band, which is expected since water absorbs large amounts of NIR light (Figure 3a, 3b, A4). Reflectance is high across all bands for the sampled cloudy pixels which is expected since clouds scatter light in the visible wavelengths as well as the NIR range covered by PlanetScope and MODIS NIR bands (Figure A3; Schlundt et al. 2011). All samples over urban areas show the highest reflectance in the NIR, followed by blue, green, and red, and the cluster of points is the tightest for pixels sampled over an urban area with many similar, highly reflective buildings (Figure A1). In the Fresno study area, samples were taken over an inland body of water, Millerton Lake, for both a relatively clear day (1/3/2019) and a hazy day (8/7/2018), in order to compare TOA reflectance under the same surface conditions but differing atmospheric conditions (Figure 3). The haze seen in the 8/7/2018 imagery can be primarily attributed to the nearby Ferguson wildfire which burned approximately 392 km² of land north of Fresno in the Sierra and Stanislaus National Forests, and Yosemite National Park between July 13 and August 19, 2018 (Figure 3b, 4b). As expected, the reflectance is higher across all PlanetScope and MODIS bands on the hazy day due to the added aerosols in the
atmosphere from the smoke. The cluster of points also appear to be more spread apart on the hazy day. This could be due to the influence of a variety of aerosols in the atmosphere.
Sample Water Pixels
Millerton Lake (NE of Fresno, CA)
Clear Day 1/3/2019
MODIS imaging time: 19:00:00 – 19:05:00 UTC
Planet imaging time: 18:15:19 – 18:20:37 UTC

Sample Water Pixels
Millerton Lake (NE of Fresno, CA)
Hazy Day 8/7/2018
MODIS imaging time: 18:45:00 – 18:50:00 UTC
Planet imaging time: 18:08:38 – 18:16:46 UTC
Figure 3 Comparison of results for (a) a clear day (1/3/2019); (b) and a hazy day (8/7/2018) for water pixels sampled over Millerton Lake near Fresno, CA. Results for the other land cover types sampled in the Fresno and Los Angeles study areas can be found in Appendix B.

Clear and hazy day samples were also taken over an area of agricultural land located north of Fresno’s city center (Figure 4). TOA reflectance similarly increased across all bands for both PlanetScope and MODIS on the hazy day, with the greatest increase in reflectance seen in the NIR band cluster (Figure 4b). Since the clear day sample was taken in January and the hazy day sample in August, seasonal changes may also contribute to some of the reflectance differences observed. Additionally, the pixels were sampled over the same geographical area but do not overlap exactly between the clear and hazy day samples, which may also contribute to some variability in reflectance.
Figure 4 Comparison of results for (a) a clear day (1/3/2019); (b) and a hazy day (8/7/2018) for agriculture pixels sampled near Fresno, CA. Results for the other land cover types sampled in the Fresno and Los Angeles study areas can be found in Appendix B.

3.3 Analysis of PlanetScope and MODIS Spectral Response to Varying Surface PM2.5 Conditions

Figure 5 shows scatter plots of PlanetScope and MODIS TOA reflectance in relation to PM2.5 concentrations at 25 different PM2.5 ground monitoring locations. Data were collected for 15 different dates over eight U.S. cities. For each study area, two dates were selected to capture a variety of air quality conditions. The x-axis shows the average PM2.5 concentration for a three-hour time period centered around the PlanetScope/MODIS image acquisition time. The y-axis shows PlanetScope and MODIS TOA reflectance averaged for a 5x5 or 10x10 pixel sized box centered around each PM2.5 station location. The 5x5 plots are shown in the left-hand column of Figure 5, and the 10x10 average plots are shown in the right-hand column. Data points from MODIS are shown in grey while data points from PlanetScope are shown in color. The average reflectance of the pixels surrounding each PM2.5 site were used to account for noise as well as potential geolocation errors in the case of PlanetScope.
Figure 5 Three hour averaged PM2.5 concentration on the x-axis plotted against (a) blue band TOA reflectance for a 5x5 pixel average; (b) blue band TOA reflectance for a 10x10 pixel average; (c) green band TOA reflectance for a 5x5 pixel average; (d) green band TOA reflectance for a 10x10 pixel average; (e) red band TOA reflectance for a 5x5 pixel average; (f) red band TOA reflectance for a 10x10 pixel average; (g) NIR band TOA reflectance for a 5x5 pixel average; (h) NIR band TOA reflectance for a 10x10 pixel average on the y-axis; for both PlanetScope and MODIS for all 41 data points. PlanetScope points are in color and MODIS points are grey.

PM2.5 concentrations in the scatter plots range from 0.37 to 69 µg/m³. In order to meet current EPA standards, PM2.5 concentrations should remain less than or equal to 35 µg/m³ over a 24-hour averaged time period. This threshold was exceeded at the Fresno - Garland and Clovis PM2.5 stations sampled on 8/7/2018 as well as the SPOKAN - AUGUSTA AVE station sampled on 8/14/2018. The high PM2.5 readings at these locations can be attributed to nearby wildfire events, including the Ferguson wildfire near Fresno and smoke from local and nearby Canadian wildfires that resulted in unhealthy PM2.5 levels in Spokane. These poor air quality days are visible as small clusters in the right-hand side of the scatter plots. The scatter plots show no apparent correlation between PM2.5 and TOA reflectance. This outcome is expected since many factors influence the TOA reflectance signal, including atmospheric conditions, land surface radiation, the geographic region, and time of year. The points in the scatter plot include samples from a variety of geographic regions, land cover types, times of year, and atmospheric conditions, all of which contribute to the TOA reflectance signal to a varying degree. This is further illustrated by isolating the samples from a clear and extremely hazy day at the same
location. Figure 6 isolates the data points from both the 5x5 and 10x10 scatter plots for the SPOKANE - AUGUSTA AVE station, which saw very low PM2.5 on 4/19/2018 and high PM2.5 on 8/14/2018 due to nearby wildfires.

![Figure 6](image)

**Figure 6** Data points from Figure 5 isolated for the SPOKANE - AUGUSTA AVE station for (a) the blue band; (b) green band; (c) red band; (d) and NIR band. Low PM2.5 values are from 4/19/2018 and high PM2.5 values are from 8/14/2018.

Even with the large difference in PM2.5 concentration, the difference in TOA reflectance is minimal across all bands, indicating that PM2.5 is not the primary factor accounting for changes in TOA reflectance between these two dates. Isolating the data points from the Fresno study area, however, paint a different picture (Figure 7).
Figure 7 Data points from Figure 5 isolated for the Fresno - Garland and Clovis PM2.5 stations for (a) the blue band; (b) green band; (c) red band; (d) and NIR band. Low PM2.5 values are from 1/3/2019 and high PM2.5 values are from 8/7/2018.

Here, there is a noticeable increase in TOA reflectance on the high PM2.5 day compared to the lower PM2.5 day, and the increase appears more pronounced for MODIS compared to PlanetScope. This indicates that, perhaps, PM2.5 had a somewhat larger influence on the TOA reflectance signal at the Fresno sites between the clear and hazy days sampled. The examples highlighted in Figure 6 and 7 speak to the complexities involved in accurately modeling the relationship between satellite data and PM2.5.

For both the 5x5 and 10x10 plots, PlanetScope reflectance trends slightly higher than MODIS (with the most visible overlap in the NIR band), which aligns with the results from section 3.2. Across all 5x5 samples the mean difference between PlanetScope and MODIS
reflectance was 0.044±0.032 for the blue band, 0.052±0.032 for the green band, 0.053±0.035 for the red band, and 0.047±0.036 for the NIR band. Across all 10x10 samples the mean difference between PlanetScope and MODIS reflectance was 0.042±0.028 for the blue band, 0.051±0.027 for the green band, 0.052±0.029 for the red band, and 0.044±0.034 for the NIR band. Across both the 5x5 and 10x10 plots, PlanetScope reflectance was higher than the corresponding MODIS reflectance 91% of the time. Across both the 5x5 and 10x10 plots, the points with the smallest difference in reflectance had a discrepancy in image acquisition time ranging from approximately 7 - 19 minutes, compared to a discrepancy ranging from 42 - 58 minutes for the points with the largest difference in reflectance. This suggests, as would be expected, that the agreement between PlanetScope and MODIS improves if the imagery is acquired closer to the same time. As mentioned in section 3.2, some difference in reflectance is also expected due to PlanetScope’s wider spectral bandwidths compared to MODIS (Table 4). It is important to note that some difference in reflectance is also expected due to the considerable difference in PlanetScope and MODIS pixel size; a 5x5 pixel sized area for MODIS covers 2,500m² compared to only 15m² for PlanetScope.

The difference in reflectance between the 5x5 and 10x10 pixel averages for PlanetScope were minimal, with the mean difference in reflectance equaling 0.006±0.009 for the blue band, 0.007±0.008 for the green band, 0.008±0.010 for the red band, and 0.009±0.008 for the NIR band. The difference in reflectance between the 5x5 and 10x10 MODIS pixel averages were even smaller, with the mean difference in reflectance ranging from 0.002±0.002 for the blue and green band, to 0.003±0.002 for the red band and 0.006±0.009 for the NIR band. These results indicate a negligible difference in reflectance for both PlanetScope and MODIS when averaged between a 5x5 and 10x10 pixel sized area. If the 5x5 values were compared to data averaged over a much larger scale, say 25x25 pixels, the difference may have been more pronounced.
3.4 PlanetScope and MODIS Spectral Response to AOD

Figure 8 shows scatter plots of PlanetScope and MODIS TOA reflectance in relation to AOD collected at seven AERONET sites over three different dates, resulting in a total of 10 PlanetScope/MODIS point pairs (Table 3). All data summarized in Table 2 were assessed for AERONET data availability, however, only select AERONET sites had data available on the selected study dates, resulting in the small sample size. The sample includes data from six sites in the Baltimore study area and one site from the Fresno study area. The x-axis shows the average AOD for a three-hour time period centered around the PlanetScope/MODIS image acquisition time. The AOD average was calculated for the AERONET band most closely overlapping each PlanetScope/MODIS band (Table 4). The y-axis shows PlanetScope and MODIS TOA reflectance averaged for a 5x5 and 10x10 pixel sized box centered around each AERONET site. Data points from MODIS are shown in grey while data points from PlanetScope are shown in color. There are two plots for each band, one for the 5x5 TOA reflectance average, and one for the 10x10 TOA reflectance average.
Figure 8 Three-hour averaged AOD on the x-axis plotted against (a) blue band TOA reflectance for a 5x5 pixel average; (b) blue band TOA reflectance for a 10x10 pixel average; (c) green band TOA reflectance for a 5x5 pixel average; (d) green band TOA reflectance for a 10x10 pixel average; (e) red band TOA reflectance for a 5x5 pixel average; (f) red band TOA reflectance for a 10x10 pixel average; (g) NIR band TOA reflectance for a 5x5 pixel average; (h) NIR band TOA reflectance for a 10x10 pixel average on the y-axis; for both PlanetScope and MODIS for all 10 data points. PlanetScope points are in color and MODIS points are grey.

Plotted AOD values range from 0.008 in the 870nm channel to 0.238 in the 440nm channel. The samples with the highest AOD values were collected at the MD_Science_Center AERONET site on 7/14/2018, and the samples with the lowest AOD values were a tie between the MD_Science_Center site on 3/22/2017 and the NEON_SJER site near Fresno on 1/3/2019. The difference in reflectance between PlanetScope and MODIS was 0.042±0.033 for the blue band, 0.056±0.042 for the green band, 0.059±0.045 for the red band, and 0.037±0.028 for the NIR band, averaged across all 5x5 samples. Across all 10x10 samples, the mean difference in reflectance between PlanetScope and MODIS was 0.036±0.026 for the blue band, 0.052±0.030 for the green band, 0.056±0.033 for the red band, and 0.039±0.015 for the NIR band. 85% of the PlanetScope samples had a higher reflectance than MODIS for the 5x5 averages, and 90% of the PlanetScope samples had a higher reflectance than MODIS for the 10x10 averages, aligning with the results from 3.2. PlanetScope imagery was acquired approximately 47 minutes before MODIS for the Fresno location on 1/3/2019. PlanetScope imagery was acquired approximately 57-58 minutes and 16 minutes before MODIS for the Baltimore sites on 7/14/2018 and 3/22/2017,
respectively. Isolating the data points from 3/22/2017, where the image acquisition was only 16 minutes apart, did not significantly improve the mean difference in reflectance between PlanetScope and MODIS. This could be due to the small sample size or the influence of other factors, such as the difference between PlanetScope and MODIS spectral response, or the scale difference between the averaged pixels, playing a larger role.

Similar to the results from section 3.3, there was no significant correlation observed between TOA reflectance and AOD across all samples. The MODIS NIR band did have a positive linear correlation with AOD at an $r^2$ of 0.40 for the 5x5 pixel average and an $r^2$ of 0.48 for the 10x10 pixel average. The $r^2$ in terms of a positive linear relationship between AOD and TOA reflectance for the PlanetScope NIR band was 0.13 for the 5x5 pixel average and 0.22 for the 10x10 pixel average. The next highest $r^2$ value was 0.11 for the 5x5 pixel average and 0.10 for the 10x10 pixel average for the MODIS green band. The $r^2$ for all other bands, both PlanetScope and MODIS, was 0.06 or less. AOD has been shown to have a positive linear correlation with TOA reflectance when controlled for surface conditions (Sun et al. 2015). This relationship holds true even in urban areas (although to a lesser degree) where surface reflectance values tend to be higher and play a more complex role in the TOA reflectance signal (Sun et al. 2015). Isolating the data points from a single AERONET site, which assumes the surface conditions are the same, did not improve the correlation between AOD and TOA reflectance (Appendix C). In fact, the MODIS values behaved opposite as expected in some cases (negative linear correlation instead of positive), with the exception of the NIR band, when data from the same location is isolated. Further investigation, with a larger sample size, is warranted to determine whether a correlation exists and in order to gain a better understanding of PlanetScope response to AOD.
CHAPTER 4

DISCUSSION AND CONCLUSIONS

Planet’s constellation of CubeSats provides daily global imagery of the Earth’s surface at an orthorectified 3m resolution, providing unparalleled spatiotemporal coverage compared to traditional satellites. Several studies have expressed concern over the radiometric and calibration quality of this data, as well as the limited spectral bands offered by the earlier generations of the PlanetScope sensor. Planet is taking steps to address these limitations and continue to infuse newer sensors into the PlanetScope constellation with improved imaging capabilities. Therefore, it is important to continue to assess the fitness of this data for each unique application, especially as Planet’s commercial data becomes more readily available to the scientific community via avenues such as NASA’s CSDAP.

Satellite observations have emerged as a promising means to fill gaps in ground-based air quality monitoring, and Planet’s high resolution imagery offers the potential to derive air quality parameters, such as PM2.5, at spatial scales localized enough to benefit human health (Chow et al. 2002). A large body of research surrounds the estimation of PM2.5 from satellite derived AOD. More recently, machine learning techniques have been used to derive PM2.5 directly from TOA reflectance without the complexities involved in AOD retrieval (Shen et al. 2018). In this study, PlanetScope TOA reflectance was examined in the context of air quality research.

First, the PlanetScope data selected for the study, which included Dove-Classic data from 2017 – 2019 over eight U.S. cities, was compared against high-resolution basemap imagery in ArcMap to gauge geolocation consistency. This was prompted by concerns raised in Houberg & McCabe 2018a as well as NASA’s CSDAP evaluation report (NASA Earth Science Division 2020). Based on a visual assessment of control points at each study area, there was not found to be any offset greater than ~10m compared to basemap imagery in ArcMap, aligning with Planet’s
reported geolocation accuracy of 10m RMSE. Based on this result, additional geolocation correction to the PlanetScope data was not performed. It is important to note that the basemap imagery in ArcMap comes from multiple sources with varying degrees of spatial accuracy. The lowest accuracy reported in the metadata for the basemap imagery used in the comparison was 5m at a 0.5m resolution, adding an uncertainty equivalent to approximately two PlanetScope pixels to the results. It is also important to note that across the control points analyzed, the topography was relatively flat with elevations ranging from 0m to 804m, with a difference in elevation of no more than 314m within a single study area (the only exception being two control points located at 1220m elevation in the Los Angeles study area). Primarily urban, suburban, and some rural/agricultural areas were sampled. Future work should include an assessment of PlanetScope’s geolocation accuracy in comparison to high-quality (e.g. sub-meter accuracy) GCPs over a wider variety of topography in order to gain a better understanding of the geolocation quality of PlanetScope data.

Next, TOA reflectance from PlanetScope (PS2 sensor only) was compared to MODIS over a variety of land cover types. Some degree of difference was expected due to differences in PS2 and MODIS spectral response functions and the differences in acquisition times (Table 2). MODIS pixels were randomly sampled over each land cover type. The average TOA reflectance of all PlanetScope pixels falling within the extent of each MODIS pixel were used to compare TOA reflectance values. The difference in TOA reflectance ranged from near-zero (0.0014) to 0.117, with a mean difference in reflectance of 0.046±0.031 across all bands. The reflectance value from PlanetScope was higher than MODIS for 78% of all pixels sampled. The spectral bands for Planet’s Dove-R and SuperDove are designed to be more comparable to Landsat and Sentinel-2, so future work should include a similar analysis for Dove-R and SuperDove data in comparison to Landsat, Sentinel-2, as well as MODIS, to assess how new generation PlanetScope data compares with well calibrated traditional sensors (Table 1).
TOA reflectance from PlanetScope and MODIS were also compared to PM2.5 and AOD measurements from ground-based monitors across eight different U.S. cities. TOA reflectance was averaged at two different scales, and PM2.5 and AOD readings were averaged around the respective PlanetScope and MODIS image acquisition time to account for noise. Figure 5 shows TOA reflectance as a function of PM2.5 concentration, for both a 5x5 and 10x10 pixel sized average centered around the PM2.5 ground station locations. Figure 8 displays the results in the same way but for AOD readings across seven AERONET sites located in the Baltimore and Fresno study areas. These results show a similar difference in TOA reflectance between PlanetScope and MODIS (compared to the land cover analysis) with a mean difference in reflectance of \(0.048 \pm 0.032\) across all data points (PM2.5 and AOD combined). For 89% of the samples, the PlanetScope TOA reflectance value was higher than MODIS TOA reflectance. There was no significant correlation between TOA reflectance and PM2.5, across all data points, which is expected since PM2.5 may contribute to the TOA reflectance signal to a varying degree. A slight positive linear correlation between TOA reflectance and AOD was expected, however, no significant correlation was found for either PlanetScope or MODIS. The sample size for the AOD analysis was very small with only 10 data points, and the majority of those points were from the same two dates which did not happen to have a good relationship with AERONET AOD. Further investigation is warranted to gain a better understanding of how PlanetScope responds to varying AOD conditions. The effect of other variables on TOA reflectance, such as reflectance from the land surface, were not controlled for in this study. Furthermore, there was a minimal difference between the 5x5 and 10x10 averaged reflectance values for both PlanetScope and MODIS, showing that this change in scale had a minimal effect on the results. Repeating this analysis for a larger sample size and for a larger difference in scale would be necessary to gain a better understanding of how scale size affects analysis outcomes.

While the mean difference between PlanetScope and MODIS TOA reflectance was found to be relatively small, the pixel-pixel analysis did reveal differences in reflectance up to 0.117.
Samples with a difference in reflectance of 0.05 or greater (i.e. those that would round up to 0.1) consisted of 40% of the pixels sampled. While MODIS is considered to be well-calibrated, PlanetScope is able to resolve details at a much finer spatial scale. Based on the application, the need for higher spatial resolution data may outweigh potential pitfalls in terms of data quality. Higher resolution imagery is needed to make PM2.5 estimation possible at community-level scales, and PlanetScope data has the potential to meet this need (Zheng et al. 2020). Whether it be through fusion with other satellite data or via machine learning, PlanetScope data should continue to be evaluated as a means for PM2.5 estimation.
## Applicability of Existing Basemaps

### Appendix A

| Study Area | Basemap Imagery Source | Date Acquired | Resolution (m) | Accuracy (m) |
|------------|------------------------|---------------|----------------|--------------|
| Baltimore  | Maxar (WorldView-2)    | 9/28/2017     | 0.5            | 4.06         |
| Baltimore  | Maxar (WorldView-2)    | 8/21/2017     | 0.5            | 4.06         |
| Baltimore  | Maxar (GeoEye-1)       | 9/16/2017     | 0.46           | 4.06         |
| Birmingham| Maxar (WorldView-2)    | 3/20/2019     | 0.5            | 5            |
| Birmingham| Shelby County GIS/ALDOT/USGS | 1/19/2020 | 0.0762         | 0.15         |
| Birmingham| Maxar (WorldView-3)    | 11/19/2019    | 0.31           | 4.06         |
| Birmingham| Maxar (GeoEye-1)       | 11/19/2019    | 0.46           | 4.06         |
| Bismarck  | Maxar (GeoEye-1)       | 9/22/2019     | 0.46           | 5            |
| Bismarck  | Maxar (WorldView-3)    | 9/2/2019      | 0.31           | 5            |
| Bismarck  | Maxar (WorldView-2)    | 9/18/2019     | 0.5            | 5            |
| Chicago   | Maxar (WorldView-2)    | 8/5/2018      | 0.5            | 4.06         |
| Chicago   | Maxar (WorldView-3)    | 3/3/2018      | 0.31           | 4.06         |
| Chicago   | Maxar (WorldView-3)    | 10/16/2017    | 0.31           | 4.06         |
| Chicago   | Maxar (WorldView-3)    | 4/29/2018     | 0.31           | 4.06         |
| Chicago   | Maxar (GeoEye-1)       | 8/19/2017     | 0.46           | 10.16        |
| Chicago   | Lake County, IL GIS    | 3/20/2018     | 0.07           | 0.73         |
| Fresno    | Maxar (WorldView-2)    | 9/22/2019     | 0.5            | 5            |
| Fresno    | Maxar (WorldView-2)    | 5/10/2020     | 0.5            | 4.06         |
| Fresno    | Maxar (WorldView-2)    | 8/20/2019     | 0.5            | 5            |
| Los Angeles| Maxar (WorldView-2)   | 9/26/2018     | 0.5            | 5            |
| Los Angeles| Maxar (WorldView-2)   | 7/6/2019      | 0.5            | 5            |
| Los Angeles| Maxar (WorldView-2)   | 1/6/2020      | 0.5            | 4.06         |
| Los Angeles| Maxar (WorldView-3)   | 4/15/2020     | 0.31           | 4.06         |
| Los Angeles| Port of Long Beach    | 12/16/2017    | 0.07           | n/a          |
| Los Angeles| Maxar (WorldView-3)   | 2/4/2020      | 0.31           | 4.06         |
| Los Angeles| Maxar (GeoEye-1)      | 7/20/2019     | 0.46           | 4.06         |
| Phoenix   | Maxar (WorldView-4)    | 6/19/2018     | 0.31           | 5            |
| Phoenix   | Maxar (WorldView-4)    | 11/16/2018    | 0.31           | 5            |
| Phoenix   | Maxar (WorldView-2)    | 1/18/2020     | 0.5            | 4.06         |
| City      | Source                              | Date       | Latitude | Longitude |
|-----------|-------------------------------------|------------|----------|-----------|
| Phoenix   | Arizona State University            | 8/4/2019   | 0.3048   | 0.14      |
| Phoenix   | Maxar (GeoEye-1)                    | 2/12/2020  | 0.46     | 4.06      |
| Spokane   | Spokane Image Consortium            | 4/18/2018  | 0.22     | 0.8       |
| Spokane   | Spokane Image Consortium            | 3/12/2018  | 0.1      | 0.35      |
| Spokane   | Spokane Image Consortium            | 3/18/2018  | 0.1      | 0.35      |

**Table A1** Sources of the ArcMap basemap imagery overlapping control points in each study area used for the geolocation comparison (section 2.5 and 3.1).
Appendix B

Sample Bright Urban Pixels
Downtown Fresno, CA & Vicinity
Clear Day 1/3/2019

MODIS imaging time: 19:00:00 – 19:05:00 UTC
Planet imaging time: 18:15:19 – 18:20:37 UTC

Table 1. TOA Reflectance Values

| Band      | MODIS Urban Pixel 1 | MODIS Urban Pixel 2 | MODIS Urban Pixel 3 | MODIS Urban Pixel 4 | Mean | Standard Deviation |
|-----------|---------------------|---------------------|---------------------|---------------------|------|--------------------|
| Blue Band | 0.082               | 0.085               | 0.087               | 0.091               | 0.086| 0.004              |
| Green Band| 0.180               | 0.190               | 0.180               | 0.190               | 0.185| 0.006              |
| Red Band  | 0.067               | 0.073               | 0.076               | 0.082               | 0.075| 0.006              |
| NIR Band  | 0.170               | 0.180               | 0.180               | 0.180               | 0.178| 0.005              |

Figure B1 Results from section 3.2 for pixels sampled over a bright urban area in the Fresno study area on 1/3/2019.
Figure B2 Results from section 3.2 for pixels sampled over an urban area in the Fresno study area on 1/3/2019.
Figure B3 Results from section 3.2 for pixels sampled over clouds in the Los Angeles study area on 8/4/2018.
Figure B4 Results from section 3.2 for pixels sampled over the ocean in the Los Angeles study area on 8/4/2018.
Figure B5 Results from section 3.2 for pixels sampled over an urban area in the Los Angeles study area on 8/4/2018.
Figure C1 Data points from Figure 8 isolated for the Sigma_Space_Corp AERONET site. Data points from the 5x5 and 10x10 pixel average plots are combined. Lower AOD values are from 3/22/2017 and higher AOD values are from 7/14/2018. Plots are separated by (a) blue band; (b) green band; (c) red band; (d) NIR band. PlanetScope values are in color and MODIS values are in grey. The image in (e) shows a screenshot of the AERONET site location in Google Earth.
Figure C2 Data points from Figure 6 isolated for the GSFC AERONET site. Data points from the 5x5 and 10x10 pixel average plots are combined. Lower AOD values are from 3/22/2017 and higher AOD values are from 7/14/2018. Plots are separated by (a) blue band; (b) green band; (c) red band; (d) NIR band. PlanetScope values are in color and MODIS values are in grey. The image in (e) shows a screenshot of the AERONET site location in Google Earth.
Figure C3 Data points from Figure 6 isolated for the MD_Science_Center AERONET site. Data points from the 5x5 and 10x10 pixel average plots are combined. Lower AOD values are from 3/22/2017 and higher AOD values are from 7/14/2018. Plots are separated by (a) blue band; (b) green band; (c) red band; (d) NIR band. No AERONET data was available for the 500nm band on 3/22/2017 (b), so only values from 7/14/2018 are plotted for the green band. PlanetScope values are in color and MODIS values are in grey. The image in (e) shows a screenshot of the AERONET site location in Google Earth.
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