DETECTING IMPERVIOUS COVER WITH ARTIFICIAL LIGHTING IN ASTRONAUT PHOTOGRAPHY FROM THE INTERNATIONAL SPACE STATION

by

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ABSTRACT

Impervious cover continues to pose a threat to flood-prone regions, especially the ones in dense urban areas. Mapping the location of impervious surface becomes vital to properly managing drainage and runoff in a city, along with the health of fluvial ecosystems. Kotarba and Aleksandrowicz, in 2016, tested the ability of nighttime astronaut imagery from the International Space Station (ISS) to detect impervious cover. The artificial lighting emitted from a city's nightscape is used as a proxy for imperviousness. This paper expands on their research by focusing on the nightscape in San Antonio, TX from December 2015, and by observing the effect the camera look angle has on impervious surface detection. Analysis was done by comparing the ISS light intensity imagery to 2016 National Land Cover Database (NLCD) Degree of Imperviousness ground reference data on the basis of low, medium, and high urban density. Difference images between reclassified ISS images and the NLCD reference data for low, medium, and high imperviousness were calculated with up to 49% kappa accuracy, a moderate agreement. ISS images' overall accuracy increased with the growth of the threshold for urban density although the kappa statistic was highest with the smallest threshold for imperviousness. ISS photographs classified dense urban areas correctly but failed to correctly classify poorly lit impervious surfaces such as rural roadways, residential neighborhoods, and airport runways. ISS imagery had a high producer's accuracy, particularly with lower thresholds for imperviousness, meaning that the likelihood is high that impervious cover detected by the ISS is actually impervious cover. Overall, ISS imagery detects impervious surfaces moderately well and may be more accurate due to the imperfect nature of the ground reference data.

Keywords: impervious cover, artificial lighting, astronaut photography, International Space Station, San Antonio, nighttime lights, National Land Cover Database

I. INTRODUCTION

A fifth of the world's population can no longer view the Milky Way Galaxy in the night sky, and a tenth of the world's population views the night sky with their daytime vision (Gaston et al. 2014). Moreover, a higher percentage of people are living in cities which causes urban areas to expand, bringing along a multitude of consequences. One of them comes in the form of the built environment of a city (streets, buildings, sidewalks, etc.) or its impervious cover, which includes materials such as concrete and asphalt that cannot be permeated by water. The large amounts of light that are being emitted into space are a result of the impervious cover of cities which are inevitably linked together with nighttime artificial lighting. Artificial lighting is the introduction of light into a time or place that would otherwise not have light resulting from one of the three natural light cycles: the day-night, seasonal, and lunar cycles. As time goes on, observed brightness from cities, as well as impervious surface area, is increasing in most developed regions (Gaston et al 2014). The high levels of impervious cover in a city can lead to massive rainwater runoff and cause "flashier" flooding, harming human life and structures. Increased infrastructure leads to the loss of vegetation and tree cover which increases the variability of water temperature in streams and decreases riverbank stabilization (Arnold and Gibbons 1996). Impervious cover also intensifies the amount of pollutants, such as pesticides, metals, and nutrients, running off into streams which lead to a decay in stream biota (Paul and Meyer 2001).

Nighttime imagery of cities that is collected by astronauts from the International Space Station (ISS) is being used more often to analyze geographic aspects of cities. Analyzing remote sensing data for a city during the day can be difficult due to the complex spatial make-up of a city; different land cover types (i.e. impervious surface, vegetation, agriculture, etc.) tend to visually blend together (Figure 1). A city's make-up and its impervious cover can be more easily viewed at night due to the insight directly gained about human activity from artificial lights from space (Levin and Duke 2012, Kyba et al. 2014). According to Kyba et al., "artificial light highlights human activity in a way that daytime scenes do not." This imagery is notable because of city lights' direct indication of artificial structures and human activities, or impervious cover (Kotarba and Aleksandrowicz 2016). The mapping of artificial lighting in a city simultaneously reveals the levels of impervious cover in an urban area which will lead to a more widespread knowledge of impervious cover levels through a more accessible medium, which is

Figure 1. ISS048-E-25405. This is a daytime astronaut image of San Antonio, TX from July 11, 2016 at 12:16 PM CST taken from the ISS. Image courtesy of the Earth Science and Remote Sensing Unit, NASA Johnson Space Center.

astronaut imagery.

Based on a review of the literature, only one study has analyzed impervious cover using artificial lighting from urban nightscapes in ISS photography, which was done using the aerial nighttime view of the layout of Berlin, Germany in April 2013 (Kotarba and Aleksandrowicz 2016). This paper performed a similar analysis in San Antonio, TX with ISS imagery from December 2015. The goal of this research paper is three-fold: 1) to show that astronaut imagery from the ISS is a viable data source for the analysis of urban nightscapes, 2) to explore and document the effects that the camera look angle has on the detection of impervious cover, and 3) to lay the foundation for combatting the problems of excessive impervious cover by verifying an additional source of impervious surface visualization. As urbanization processes continue to occur and impervious surfaces continue to grow, the negative effects of impervious cover need to be mitigated; mitigation starts with identifying the absolute locations on the Earth's surface that are causing these negative impacts. Accessibility to data sources that can easily provide and portray areas of high impervious cover is the first step in finding solutions to issues related to impervious cover, such as increased flooding and decreased stream biota. ISS astronaut imagery of nightscapes could be an additional high quality and accessible data source. This research project is dedicated to testing the accuracy of this imagery and allows for further insights on the levels of impervious cover in San Antonio and on the capability of astronaut imagery to detect impervious surfaces.

The following research question is answered in this paper: how accurately does artificial lighting in nighttime astronaut imagery of the Earth from the ISS detect impervious cover in San Antonio in 2015 compared to national land cover classifications? I hypothesize that ISS nightscapes will accurately detect impervious cover in each imperviousness category. There will be increasing accuracy with increasing imperviousness because the high imperviousness categories include surfaces that are certainly impervious. Furthermore, this paper will subsequently answer the following question: what effect does the obliqueness of an astronaut image from the ISS have on the ability of that image to accurately detect impervious surfaces? I hypothesize that the lowest oblique imagery will show impervious cover more accurately than the imagery with the highest look angle due to expected distortion with greater obliquity.

II. LITERATURE REVIEW

The purpose of urban artificial lighting is to expand the otherwise limited daily time range available for human activities and to allow for increased safety and security (Hale et al. 2013). Land use classes such as streets, commercial areas, manufacturing hubs, city centers, residential neighborhoods, and airfields all emit light from various lamps and light poles. Although some lights are blocked by other objects such as buildings or trees and cannot be seen from space, direct and scattered light is emitted into and can be seen from space from most light sources (Kuechly et al. 2012). These lights can begin to be seen from space when they are clustered together. Small towns are seen as light specks, and metropolitan areas of tens of thousands of inhabitants boast a more extensive nightscape. This study draws on and contributes to two main bodies of literature: nighttime satellite image sources and artificial lighting in urban nightscapes. One commonality among the analyses of urban nightscapes is the necessity of an image source capable of capturing high-quality images in the dark. The three main image sources that are used in studies related to artificial lighting, the DMSP-OLS, Aerial Surveys, and ISS imagery, are each reviewed in the proceeding subsections to gain a wider understanding of the different data and methods used while studying artificial lighting.

Image Sources: DMSP-OLS

Most artificial lighting-related research papers have been performed using images from the Defense Meteorological Satellite Program Operational Linescan System (DMSP-OLS), which has been operational since 1977 (Kyba 2014). There have been a total 132 publications that have used the DMSP-OLS satellite images in a study up to

2013, with the amount of publications growing steadily every year since 1992, the year the imagery switched from being recorded on film strips to a digital archive which greatly increased its application and accessibility. Analyses using DMSP-OLS imagery often are related to urban land dynamics, socioeconomic variables, and demographic characteristics (Huang et al. 2014). One such analysis measured how urban land use affected U.S. soil resources and caused certain unique soil types to "disappear" underneath urban growth (Imhoff et al. 1997). Another study calibrated digital numbers indicating brightness across Europe to observe differences in lighting over a fifteen-year time interval. It identified an overall increase in brightness across Europe while identifying reasons for decreasing brightness in former Soviet satellite nations, Slovakia, and Belgium (Bennie et al 2014). These two studies illustrate how DMSP-OLS imagery is sufficient in measuring phenomena at a continental scale and could be replicated across the globe. However, in the last decade the DMSP-OLS has become obsolete due to its coarse spatial resolution, which ranged anywhere from 1-2.7 km per pixel, and has become insufficient for a city-sized study area or smaller.

Image Sources: Aerial Survey

Researchers can also utilize an aerial survey, which often corresponds to a much higher spatial resolution, in studies related to artificial lighting. To get this kind of resolution, one must utilize a camera on the nadir part (directly below the spacecraft) of an aircraft as Kuechly et al. did in their spatial examination of light pollution in Berlin, Germany. Doing so is not easy, however, as the authors mosaiced 2646 images from their aerial survey together into one image. They found that areas categorized as streets account for 31.6%, the most of any land use class, of zenith-directed light in Berlin even though they only account for 13.6% of the area of the study region (Kuechly et al. 2012). Hale et al. also performed an aerial survey and gathered light data for the city of Birmingham, United Kingdom in their spatial analysis of light pollution. Their resultant data included a raster showing reflected light and a point layer showing the location of 117,599 light sources. Using this data, Hale et al. gathered that there is a direct relationship between indicators of artificial light and built density in a city (Hale et al. 2013). Furthermore, it should be noted that small unmanned aerial systems (drones) are being used more routinely in recent years to capture high-quality aerial imagery similar to what is captured by aircraft but in much smaller study areas (Harvey et al. 2016, Tang and Shao 2015). These aerial surveys can be viewed as a bridge linking ground-based surveys that provide infallible measurements and satellite data. However, the process necessary to perform an aerial survey is tedious, can be expensive, and should only be done if one must have the highest possible spatial resolution in their imagery; satellite data and astronaut photography are much more prolific and accessible.

Image Sources: ISS

Aside from traditional remote sensing satellite imagery, an alternative data source for capturing nighttime images has emerged in the last ten years: astronaut photography of Earth from the ISS. The ISS is a space station which orbits Earth about 250 miles above the surface and is inhabited by astronauts and cosmonauts to perform experiments and collect scientific data in the context of microgravity. The National Aeronautics and Space Administration (NASA), along with the contributions of space agencies in Russia, Japan, Europe, and Canada, first started to construct the ISS in space in 1998 and plan to continue to utilize it until 2030. Astronauts enjoy taking images with hand-held cameras

(Levin and Duke 2012) onboard the ISS, in addition to their regular work schedule, as they are moving approximately 17,500 miles an hour through Earth's orbit. Astronauts have been taking nighttime images from space since the beginning of human spaceflight. They take pictures of features and landscapes on the Earth's surface that they feel so inclined to, and they also occasionally have assigned geographic events to capture (i.e. a hurricane or wildfire). During the sixth mission to the ISS in 2003, astronauts began taking images of urban nightscapes (Levin and Duke 2012), however, the nightlights of the cities made images of cities blurred due to the high speed of the ISS. In 2012, the NightPod motorized tripod was installed onboard the ISS by the European Space Agency; it greatly enhances the quality of nighttime imagery by tracking a target point on Earth's surface, neutralizing the effects of the station's speed (Sabbatini and Esposito 2014, Kyba 2014). Imagery taken from the ISS has a high spatial resolution and allows researchers to observe differences in night lights within cities. About thirty percent of ISS images are taken at night and are freely available through 'The Gateway to Astronaut Photography of Earth' website, https://eol.jsc.nasa.gov/ (Kuffer et al. 2017). This website is provided and managed by the Earth Science and Remote Sensing Unit at NASA's Johnson Space Center.

Researchers have begun to use ISS imagery for artificial lighting-related projects. A case study was done by Kotarba and Aleksandrowicz to find the extent of impervious surface area in Berlin, Germany and compare the accuracy of the study completed with ISS photography against the same study completed with DMSP-OLS imagery. The researchers used pixel brightness values to determine the land use of each pixel. Once they found the land use for each pixel, they assigned a degree of imperviousness to that land use class and then compiled the data to find a percentage of the study area that was covered by impervious surfaces. The study found ISS photography to have a low pixel-to-pixel accuracy but a high comprehensive accuracy, both of which were found to be a significant upgrade from DMSP-OLS imagery. ISS photography is the most accurate data source for measuring impervious surfaces and was most accurate when estimating low degrees of imperviousness (Kotarba and Aleksandrowicz 2016). ISS nighttime photography has rarely been used in the analysis of impervious surface detection as this article is one of the few studies that has done so. Much more research could be done in the utilization of ISS photography to measure impervious surfaces around the globe. My research is modeled after this impervious cover study using ISS astronaut photography while accounting for the limitations of the ISS photographs outlined by the researchers. My research will incorporate imagery that is two to three years more recent than this study, which will correspond to a higher level of quality in the images, and a new study area, moving from a single image of Berlin, Germany to multiple images of San Antonio, TX.

Another geographic study that utilized ISS nighttime astronaut photography of Earth was done by Kyba et al. (2014) to analyze differences in lighting norms between cities by comparing two sets of photographs of urban nightscapes from the ISS, one set comprising images of six different European cities from the same night and one set comprising nine images of Madrid at different times throughout the night. Doing so allowed for lighting norms between cities and within cities at different times of day to be compared empirically. For instance, the images of Madrid revealed a drastic decrease in the use of nightlights as the night progressed. Furthermore, the longtime division of

Berlin could still be seen in the nighttime imagery since the West and the East were overseen by different nations and introduced different lighting norms that have lasted through the unification of Berlin (Kyba et al. 2014). This research could be improved upon by comparing similar sets of images in other regions of the world to detect emerging intercontinental patterns. The methods of Kyba et al. (2014) will inform this paper in empirically analyzing the geometry of San Antonio's urban nightscape.

ISS imagery has several distinctive characteristics. A unique benefit of ISS imagery is its ability to easily capture a variety of oblique images at different scales since astronauts have the freedom to point their cameras in whichever direction while continuously adjusting the camera's focal length. ISS nighttime astronaut photography does have limitations. While astronaut photographs of cities have a decent spatial resolution, typically somewhere between 5 and 50 meters per pixel, they do not have the capacity to differentiate between specific sources of light on the surface (i.e. street lamp vs residential house light). In this case, a much higher spatial resolution of around 1 meter or finer is needed; to achieve this kind of resolution one must perform an aerial survey. Moreover, there is no regular pattern to the photographs that astronauts decide to take. The orbit of the spacecraft also restricts the imagery taken in some respects as it does not pass over every point on Earth every day, giving it a low temporal resolution. Instead the ISS takes an irregular path, which is beneficial for taking photographs of a variety of features but is not for attaining a normalized dataset.

Reviewing the preceding literature has helped the conceptual research design of this paper by outlining the appropriate spatial extents that could be sufficiently studied while using ISS astronaut photography as an imagery source. The astronaut photographs have a much higher spatial resolution than the DMSP-OLS imagery does and is significantly more accessible than imagery from an aerial survey, both of which are partial reasons for my choosing of ISS astronaut photography for my research paper. For instance, if one's study area was at a national scale (as previously discussed with DMSP-OLS imagery) it would not be fully taking advantage of the spatial resolution of astronaut photographs. Moreover, one would be reaching beyond the capacity of the astronaut photographs if they were to analyze individual light sources within a city (as previously discussed with aerial surveys) since the spatial resolution of astronaut photography is not that high. A proper spatial extent would be a city-sized study area along with a comprehensive approach, meaning to not concentrate on individual sources of light but to examine clusters of them within the city. Many continental or global studies have been done on nighttime light emitted from urban areas, most of which were done using DMSP-OLS imagery. Local, city-specific analyses requiring high spatial resolution data have seldom been performed due to recent technological improvements allowing for such investigations. This study will contribute to the bodies of literature of nighttime satellite image sources and artificial lighting within urban nightscapes by further confirming the correlation between impervious cover and artificial lighting brightness and the value of imagery from the ISS in detecting impervious surface.

III. METHODOLOGY

Study Area

The city which will be the focus in my research, San Antonio, is a large city in south central Texas that displays a large urban nightscape (Figure 2). San Antonio has a population of 1,511,946 (U.S. Census Bureau 2017) and ranks seventh in total population in the United States (City Mayors Statistics 2012). It covers an area of 460.93 square miles (U.S. Census Bureau 2017) and is in Bexar County. San Antonio is known for holding twelve joint Air Force bases (City of San Antonio 2019) as it is colloquially referred to as the “Military City.” Furthermore, it’s a popular destination for tourists to

Figure 2. ISS045-E-155786. This is a nighttime astronaut image of San Antonio, TX from December 3, 2015 at 4:17 AM CST taken from the ISS. It is oriented with the southeast direction pointing upward. Image courtesy of the Earth Science and Remote Sensing Unit, NASA Johnson Space Center.

take a stroll on the River Walk or to visit the 18th-century Spanish fortress known as the Alamo. Most of the artificial lighting from San Antonio's nightscape emits from the major transportation arterials of the city, such as Interstate Highways 35, 410 and 10, United States Highways 87, 90 and 281, SW Military Dr and Wurzbach Pkwy, and the areas immediately adjacent to them filled with commercial and/or industrial facilities. Another major contributor of the city's nighttime brightness is the city center of San Antonio. Downtown and the highway network are both highly impervious, measured at 80% impervious or greater. Residential neighborhoods emit a significant amount of light as well, although their light is less intense. Notable areas of little to no artificial lighting

Figure 3. San Antonio Area Map. This custom map displays major highways, neighborhoods, and streams of San Antonio which offer an understanding of the layout of the city.

include the creek corridors of Salado and Leon Creek, San Antonio International Airport, the Lackland Air Force Airport, and the less urbanized part of town south of IH Loop 410. The features mentioned above can be seen in Figure 3.

Data

ISS Imagery Light Intensity

Collecting imagery of Earth from space is a difficult task that has fortunately been undertaken by astronauts from the ISS for nearly twenty years. All researchers need to do is search through the freely available imagery online at "The Gateway to Astronaut Photography of Earth." Table 1 displays three selected astronaut images: ISS045-E-155770, ISS045-E-155795, and ISS045-E-163632. Each image was taken with a Nikon D4 electronic still camera with a focal length of 400mm. Multiple images of the same area were selected to test the effect that look angles or obliqueness, the angle between the satellite and the zenith of the images' centerpoints, have on the detection of impervious cover. The images were taken within 72 hours of each other, and at a similar time of night, to control the effects of urban change over time. Out of all the nighttime ISS images of San Antonio within the last five years that were of a sufficient scale, approximately 8-meter spatial resolution and centered on the city center, and quality (without blur), the images with the highest, lowest, and near average oblique were selected. These three nightscapes determine my study area, which is the common intersection of all three images, as seen below in Figure 4.

Astronaut images are not taken systematically around the globe and have no

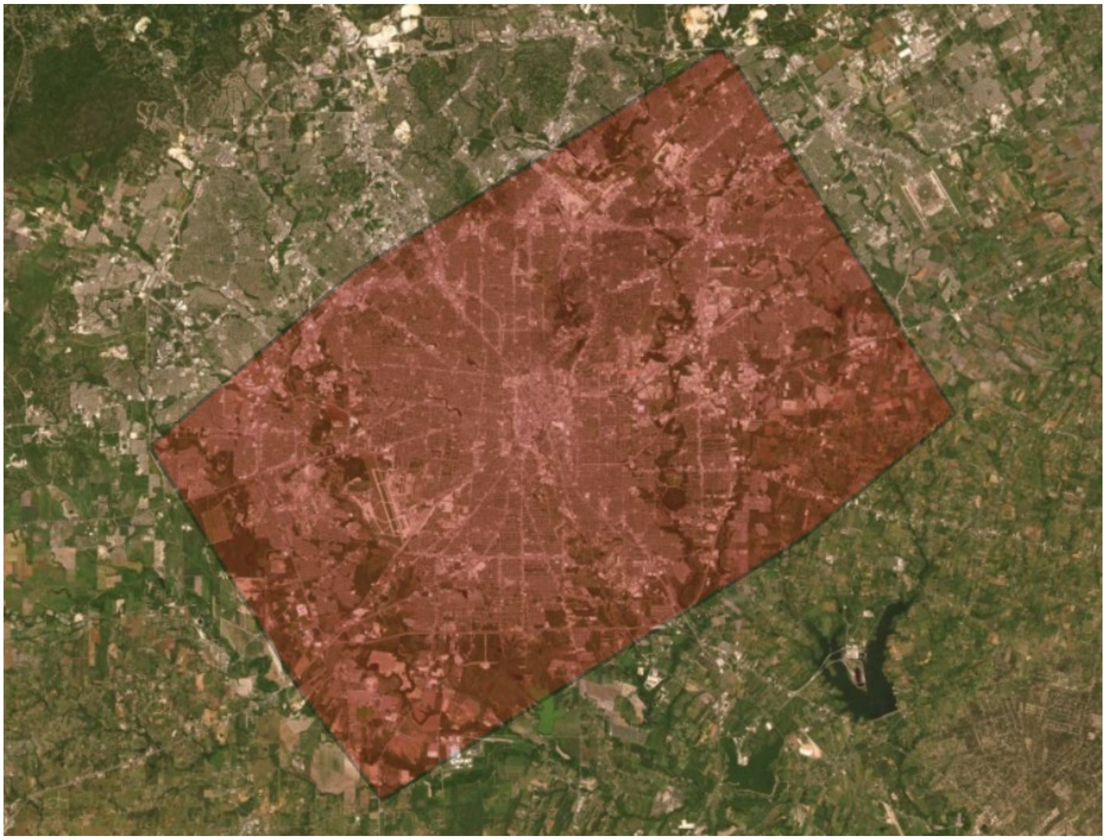
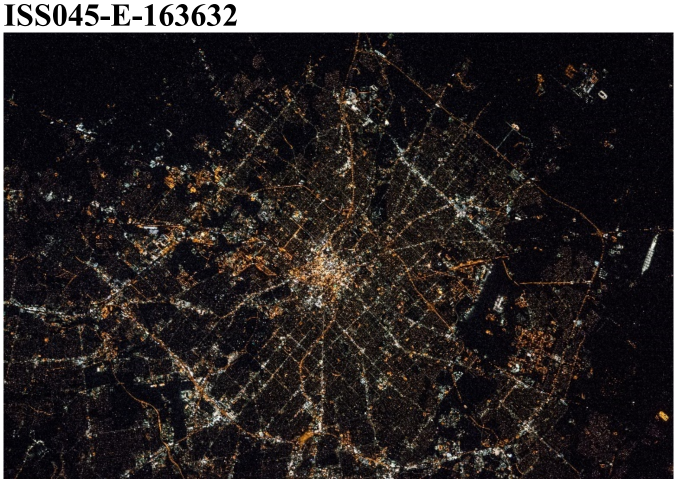


Figure 4. Study Area. Shown above is the study area, stretching approximately 907 km^2, that image analysis will be performed within. This study area was calculated by intersecting the three selected images. The length of the study area stretches from Southwest to Northeast San Antonio and fully encapsulates Interstate Highway Loop 410. World Imagery Basemap courtesy of ESRI, DigitalGlobe, GeoEye, Earthstar Geographic, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

coordinates attached to them, unlike most satellite imagery. The San Antonio nightscapes were georeferenced, or assigned a spatial reference, in ESRI's ArcGIS suite. Control points were produced from a San Antonio streets shapefile in the NAD 1983 State Plane Texas South Central projected coordinate system to anchor the image. Perfect overlaying of an image over its control points was difficult and required much refining. For further details regarding georeferencing, reference Table 1. After being georeferenced, the selected ISS images were each converted into "light intensity" images by averaging the

Table 1. Imagery Selected for Analysis	
Image	**Metadata**
ISS045-E-155770 	Time: December 3, 2015 3:17:19 AM CST Look Angle: 9° Area: 37.8 km x 25 km Georeferencing: - 66 control points - Root Mean Square Error (RMSE): 21.391 m - 3rd order polynomial transformation
ISS045-E-155795 	Time: December 3, 2015 3:17:36 AM CST Look Angle: 24° Area: 40.2 km x 27.4 km Georeferencing: - 71 control points - RMSE: 23.252 m - 3rd order polynomial transformation
ISS045-E-163632 	Time: December 6, 2015 2:16:00 AM CST Look Angle: 19° Area: 41.5 km x 25.9 km Georeferencing: - 73 control points - RMSE: 20.774 m - 3rd order polynomial transformation

digital number brightness values of the red, green, and blue color bands into a panchromatic image. Each pixel, therefore, has a single brightness value ranging from 0-255, representing the aggregate degree of artificial light being emitted from the surface area the pixel covers on the ground. The light intensity data allows for comparable measurements against the single-band ground reference degree of imperviousness layer, which is described in the next section.

NLCD Reference Data

The Multi-Resolution Land Characteristics (MRLC) Consortium, which is made up of six federal agencies including the United States Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA), maintain the National Land Cover Database (NLCD) and release new datasets every five years that show land cover in the Contiguous United States (CONUS). These datasets are derived from Landsat imagery by using regression tree software (Parece and Campbell 2014) and can be found at https://www.mrlc.gov/. The NLCD 2016 Percent Developed Imperviousness CONUS dataset is used as the reference dataset in this study to compare the ISS imagery against and is also used as input for training. It was chosen as it shows a single percent imperviousness datum aggregated to the pixel level and because of its temporal proximity to the selected ISS imagery, December 2015. Clipped to the study area, this dataset represents land cover that is impermeable by assigning a value of 0 – 100% of imperviousness to each 30-meter pixel. Higher values represent more impervious cover in that pixel. The ISS imagery was resampled from approximately 10-meter spatial resolution up to the NLCD 30-meter resolution to make the datasets more comparable.

This loss of precision and lack of an equally fine resolution reference dataset is a limitation of this project and is further discussed in the conclusion section.

SARA Land Use Data

A land use dataset was acquired from the San Antonio River Authority (SARA) for 2017, which is temporally similar to the ISS and NLCD data. This dataset is vector-based and outlines parcels in Bexar County as a certain land use, such as residential, commercial, industrial, open space, etc. It is freely available online at the following link: http://exploresara-sara-tx.opendata.arcgis.com/datasets/bexar-current-land-use-2017. This layer is used as the zonal boundaries to analyze the accuracy of the ISS imagery to detect impervious cover by land use class and to discover which land use classes tend to cause higher or lower agreement between the ISS and NLCD datasets.

Methods

This research project employed quantitative and geographic methods, such as GIS and remote sensing, to address the issue of availability of accessible imagery that displays impervious surface in cities. In order to combat issues related to extensive impervious cover such as flooding and light pollution, there first must be plentiful data that portrays impervious cover. This research project is designed to test if ISS astronaut photography can be this reliable data source. Once again this research project focused on the following question: how accurately does artificial lighting in nighttime astronaut imagery of the Earth from the ISS detect impervious cover in San Antonio in 2015 compared to land cover classifications? I hypothesize that ISS nightscapes will accurately detect impervious surfaces with increasing accuracy as the imperviousness increases. The secondary research question asks: what effect does the look angle of an astronaut image have on impervious cover detection? I hypothesize that the imagery with the lowest look angle will show impervious surfaces more accurately than the imagery with the highest. In order to test these hypotheses, this research paper utilized the following methodological techniques, as outlined in Figure 5.

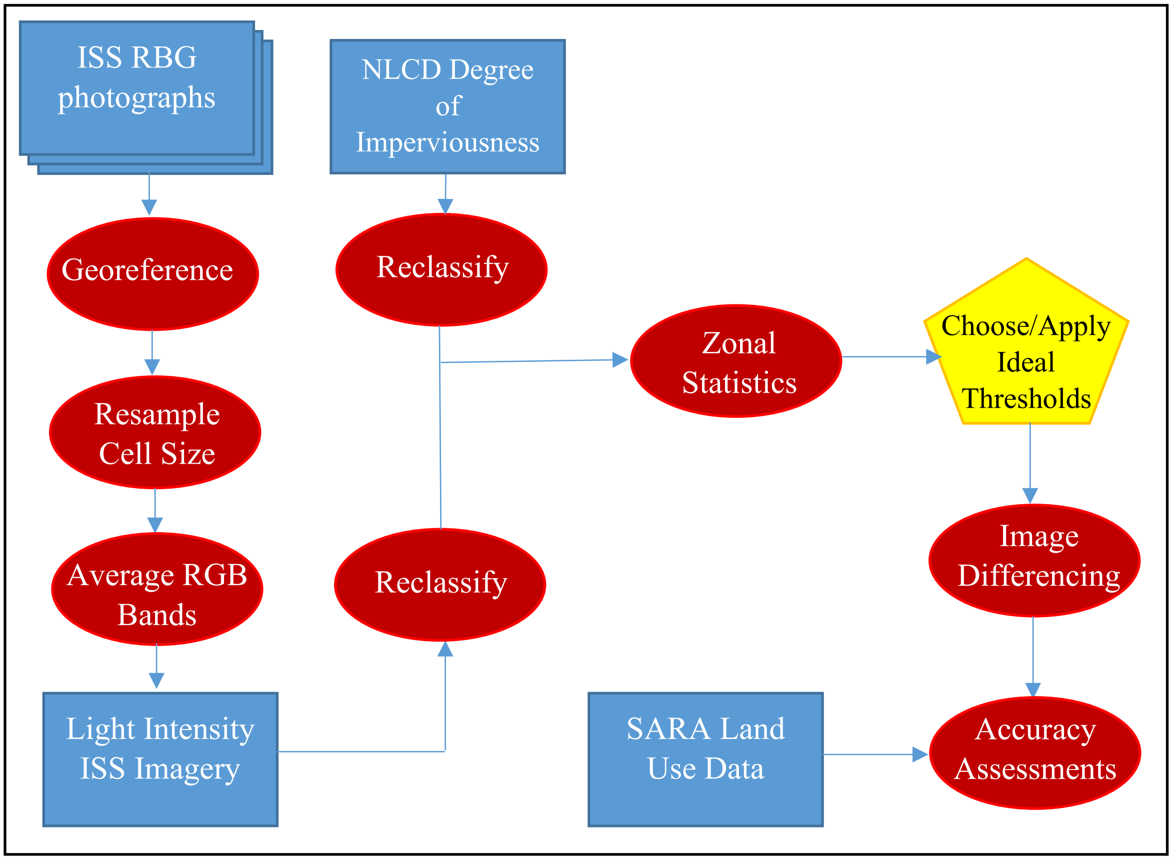


Figure 5. Methodology Flowchart. This workflow concisely illustrates the steps taken in the methodology to answer the research questions.

Data Processing

In order to compare the ISS and NLCD datasets, their values need to be comparable and on matching scales. The NLCD degree of imperviousness layer displays percentages, ranging from 0-100%, and the astronaut light intensity image layer displays unit-less digital numbers, ranging from 0-255. Therefore, a value of 20% imperviousness may not necessarily be equal to a digital number of 20. Since the datasets have differing scales, an ideal threshold in the light intensity images that best matches the imperviousness percentage must be discovered. To discover the ideal thresholds and resolve this inequality, a training process that resembles machine learning must be implemented.

First, three imperviousness values were chosen: 20%, 50%, and 80%, which are standard limits used by the MRLC for low, medium, and high intensity of imperviousness; they also resemble traditional impervious cover limits derived by Arnold and Gibbons (Arnold and Gibbons 1996). These three values were used to form three categories: 1) 20% and greater, 2) 50% and greater, and 3) 80% and greater; all impervious percentages greater than or equal to the chosen value were used for that category. Next, a training zone point layer with half-mile radial buffers was created to begin the training process. Two of the training zones can be seen in Figure 6. Sixteen total training zones were placed across the prescribed study area in a stratified systematic fashion, half of them in urban areas with relatively high amounts of impervious cover while the other half in rural ones with relatively low amounts of impervious cover. The urban-rural balance is to assure one group does not outweigh the other. To further balance out the urban areas, a majority filter was passed over the final derived ISS images to assist in cleaning out the inevitable salt-and-pepper effect in rural areas. The NLCD degree of imperviousness layer was displayed within the training zone boundaries. Then the NLCD layer needed to be reclassified, using the ArcGIS Reclassify tool, for low (20%), medium (50%), and high (80%) degree of imperviousness categories. So, in each of these three reclassification categories, the range from the specified value to 100 was reclassified to represent a singular value of impervious cover. The data became binary, showing either pervious or impervious cover; pervious area (i.e. 0-19%) is displayed as a value of 0 and impervious area (i.e. 20-100%) is displayed as a value of 1. Next, all the impervious pixels in each of the training zones was summed up using the ArcGIS Zonal Statistics as Table tool. After adding up sixteen training zone sums, there is a single value for each of the three thresholds.

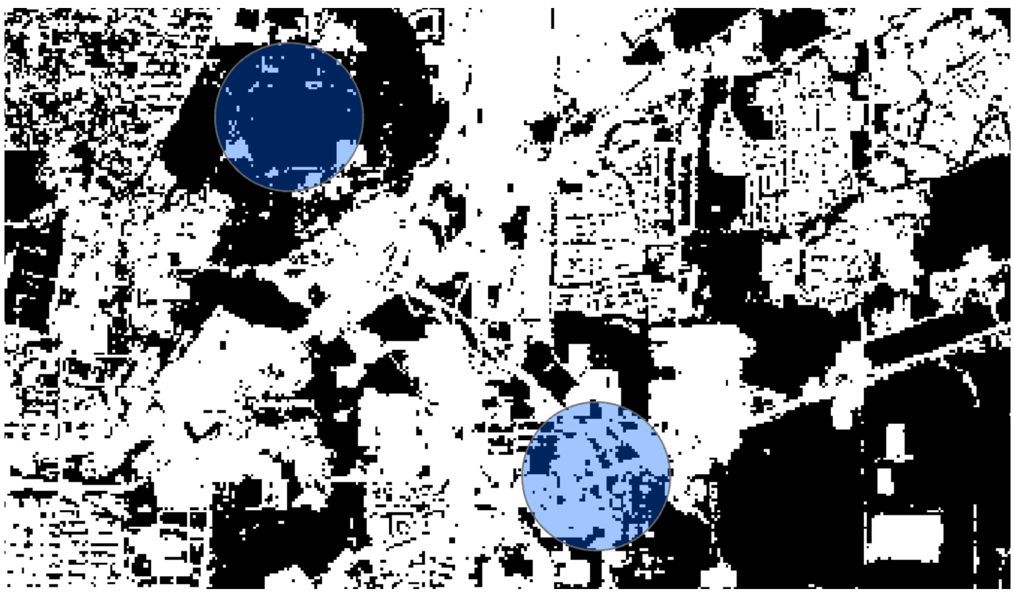


Figure 6. Training Zones. Shown above are two examples of the total sixteen training zones used throughout the study area. Each zone has a 0.5 mile radius and occupies a total area of 0.78 mi^2. Reclassified ISS image was derived by the authors from the original ISS image courtesy of the Earth Science and Remote Sensing Unit, NASA Johnson Space Center.

In addition to the NLCD dataset, the same process was carried out with the astronaut imagery. The ISS imagery thresholds were examined to decide which one best matches the corresponding NLCD degree of imperviousness values. The authors created a python script to loop through reclassifying ISS nightscapes using every possible threshold from 0 to 255 by multiples of 5. After the script reclassifies a nightscape, it sums impervious pixels in the training zones for that reclassification, just like the NLCD dataset. The impervious pixel sums are calculated in a loop nested inside the reclassification loop. The now comparable sums indicate which threshold in ISS imagery best matches each degree of imperviousness in the NLCD. In other words, the reclassification layer that represented the final thresholds can now be used for analysis. The final thresholds are displayed below in Table 2.

Table 2. Final Digital Number Thresholds for Low, Medium, and High Imperviousness Groupings in Each ISS Image

Look Angle		DN - 20% Impervious	DN - 50% Impervious	DN - 80% Impervious
9	ISS045-E-155770	17	29	73
19	ISS045-E-163632	20	36	84
24	ISS045-E-155795	15	25	57

Image Differencing

To determine astronaut imagery's ability to detect impervious cover, nine image differences were calculated between each of the reclassified ISS images and their corresponding NLCD reference images. One differenced image was generated for each of the three thresholds in all three ISS images. The ISS and NLCD images are binary images, consisting of pixels with the values of 0 and 1. Each NLCD image was differenced from its corresponding ISS image in the raster calculator by first multiplying the NLCD image by 2, causing it to have pixel values of 0 and 2. The differencing process, when conducted in this manner, results in four derived categories that allow for differentiation between matching categories (both impervious or both pervious). The process is illustrated in Figure 7. Image differencing reclassifies the ISS imagery into four categories on a pixel-by-pixel basis as follows: 1) ISS & NLCD classified as impervious, 2) ISS & NLCD classified as pervious, 3) ISS classified as impervious but NLCD classified as pervious (ISS misclassification), and 4) ISS classified as pervious but NLCD classified as impervious (ISS omission). Category 3 corresponds to a Type I error, and category 4 to a Type II error. The ability of the astronaut imagery to detect

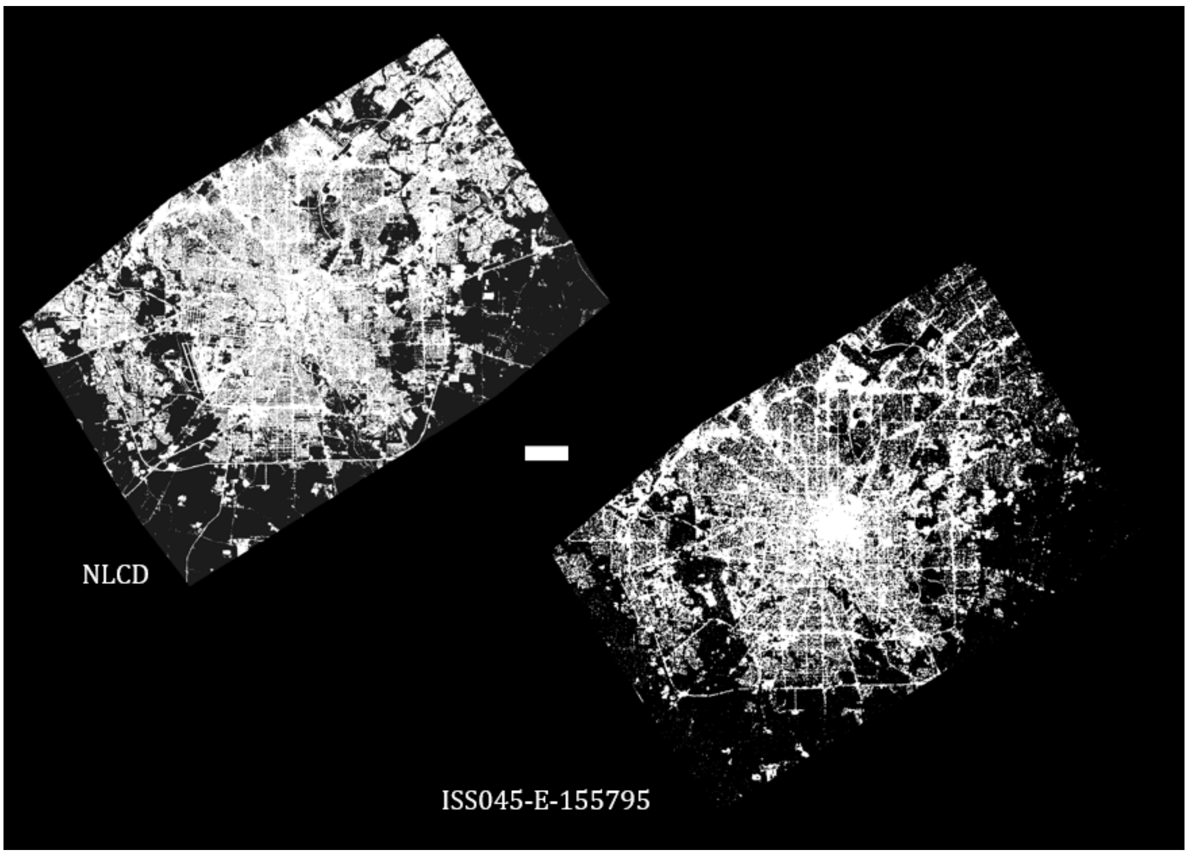


Figure 7. Image Differencing Process. Each ISS classification was subtracted from its corresponding NLCD image on a pixel-by-pixel basis as illustrated above. NLCD data courtesy of the MRLC Consortium. Reclassified ISS light intensity was derived by the authors from the original ISS image courtesy of the Earth Science and Remote Sensing Unit, NASA Johnson Space Center.

impervious cover can be judged based off of the amount of pixels that fall into these four categories which will be summarized in error matrices using standard accuracy assessment measures; these measures include overall accuracy, kappa accuracy, which deducts accuracy due to chance, and user's and producer's accuracies, which correspond to the commission and omission error, respectively. Additional accuracy assessments will be performed using 2017 land use data for Bexar County acquired from SARA by calculating zonal statistics for each of the four categories previously discussed. These additional accuracy assessments will help discern which particular land uses ISS imagery struggles to accurately detect impervious cover within.

Limitations to this methodology include potential dissimilarities between images, although taken within seconds of each other, which have slight differences in spatial resolution, clarity, and obliquity. The imagery may also have discrepancies in their georeferencing, which is difficult to perfect and is prone to human error. Although the ISS imagery and the NLCD dataset are temporally analogous, there may be minor variations in the physical layout of the city, causing misleading comparisons between datasets. Other inaccuracies may be a product of the inherent resolution of the imagery and land cover data.

IV. RESULTS & DISCUSSION

Figure 8 displays each of the three image differences for ISS045-E-155795. These image differences were calculated for the other two ISS images as well and are not pictured. Table 3 displays the ISS imagery's overall accuracies and kappa values, which omit the accuracy due to chance. An assumption of kappa values is random distribution of error (Olofsson et al. 2014), which is not the case for this study. The error, as seen in Figure 9, is concentrated in certain areas depending on that area's land use patterns. One should consider the failure of this study's error to fulfill the kappa assumption and examine the kappa values cautiously. Furthermore, Olofsson et al. (2014) discouraged reporting both overall and kappa accuracies because the values are typically highly correlated (Olofsson et al. 2014). However, overall and kappa accuracies were both reported for this study due to the values being indirectly related. The 20% impervious or greater category has the highest kappa accuracies for each image with the highest being near 50%, indicating a moderate correlation of 50% better than random chance. As the impervious threshold rises, the kappa accuracies begin to decrease among each image, dropping as low as 34% which still indicates a moderate agreement. It is worth noting

Table 3. Overall Accuracies & Kappa Accuracies for Low, Medium, & High Imperviousness Groupings in Each ISS Image

Look Angle		20% Impervious		50% Impervious		80% Impervious	
		Overall	Kappa	Overall	Kappa	Overall	Kappa
9	ISS045-E-155770	74.7%	49.4%	77.2%	40.1%	88.5%	34.0%
19	ISS045-E-163632	72.8%	45.6%	79.0%	41.7%	90.1%	34.2%
24	ISS045-E-155795	74.1%	48.1%	77.4%	40.8%	89.1%	37.6%

that the lower kappa values correspond to high overall accuracies of around 90% while the higher kappa values correspond to a lower overall accuracy of around 74%. In the images with a high impervious threshold, the vast majority of the image is pervious cover, so the ISS imagery was able to detect the pervious area with high accuracy, but as the kappa values indicate, some of that accuracy was due to chance.

There were several types of land cover that the ISS imagery failed to classify correctly as impervious cover. The ISS imagery had trouble classifying the runways at San Antonio International Airport and Lackland Air Force Base as impervious, shown in Figure 9C. The runways are typically made of an impervious material; however they are not well lit enough to be detected from space, so the ISS imagery incorrectly classified them as pervious. Rural roadways, as seen in Figure 9D, were features that were commonly missed by the astronaut imagery. Although these roadways are undoubtedly impervious, they do not have much lighting once outside of the city, and specifically outside of IH-410 on the south side of San Antonio. The astronaut photography also did not do well classifying residential areas appropriately, as shown in Figure 9A. The ISS imagery detected parts of the residential areas as impervious while the NLCD more

Table 4. User's Accuracies for Low, Medium, and High Imperviousness Groupings in Each ISS Image

Look Angle		User's - 20% Impervious	User's - 50% Impervious	User's - 80% Impervious
9	ISS045-E-155770	81.1%	59.5%	44.1%
19	ISS045-E-163632	81.5%	66.8%	54.7%
24	ISS045-E-155795	79.9%	59.9%	47.5%

completely classified the neighborhoods, leaving large areas of impervious area missed by the astronaut imagery particularly in the northeast corner of the study area. On the other hand, the ISS imagery did well at classifying features that resided within a dense urban network, areas with industrial or commercial land uses, and urban highways. Since these areas have abundant lighting due to the high density of people and structures, the ISS photographs were able to detect them with a high accuracy.

All three ISS images in the 20% impervious or greater category had high user's accuracy, meaning the likelihood is high that a pixel is impervious if the ISS photography classified that pixel as impervious. Therefore, the user can have a high confidence that the ISS impervious classifications are actually impervious. However, the confidence that the classification included all the real impervious cover is low. In the low impervious threshold category, as displayed in Table 4, each image had a high user's accuracy. A leading cause for the difference between the ISS and NLCD classifications is due to the image acquisition date, shown in Figure 9E. The ISS image acquisition dates are December 3 and December 6, 2015 while the NLCD data acquisition took place in April 28, 2016. During this short period of time, there were some minor changes in the land cover within the study area. In December of 2015, the image acquisition date of the ISS imagery, Southwest Legacy High School and the neighboring Resnik Middle School were going through construction. These schools finished construction and opened in the fall of 2017. During the construction process, the buildings had been erected but the parking lots were still gravel. Therefore, the lot was partially impervious but had no artificial lighting since the school had not yet opened. This explains why the ISS image did not detect the school while the later-acquired NLCD data classified the whole

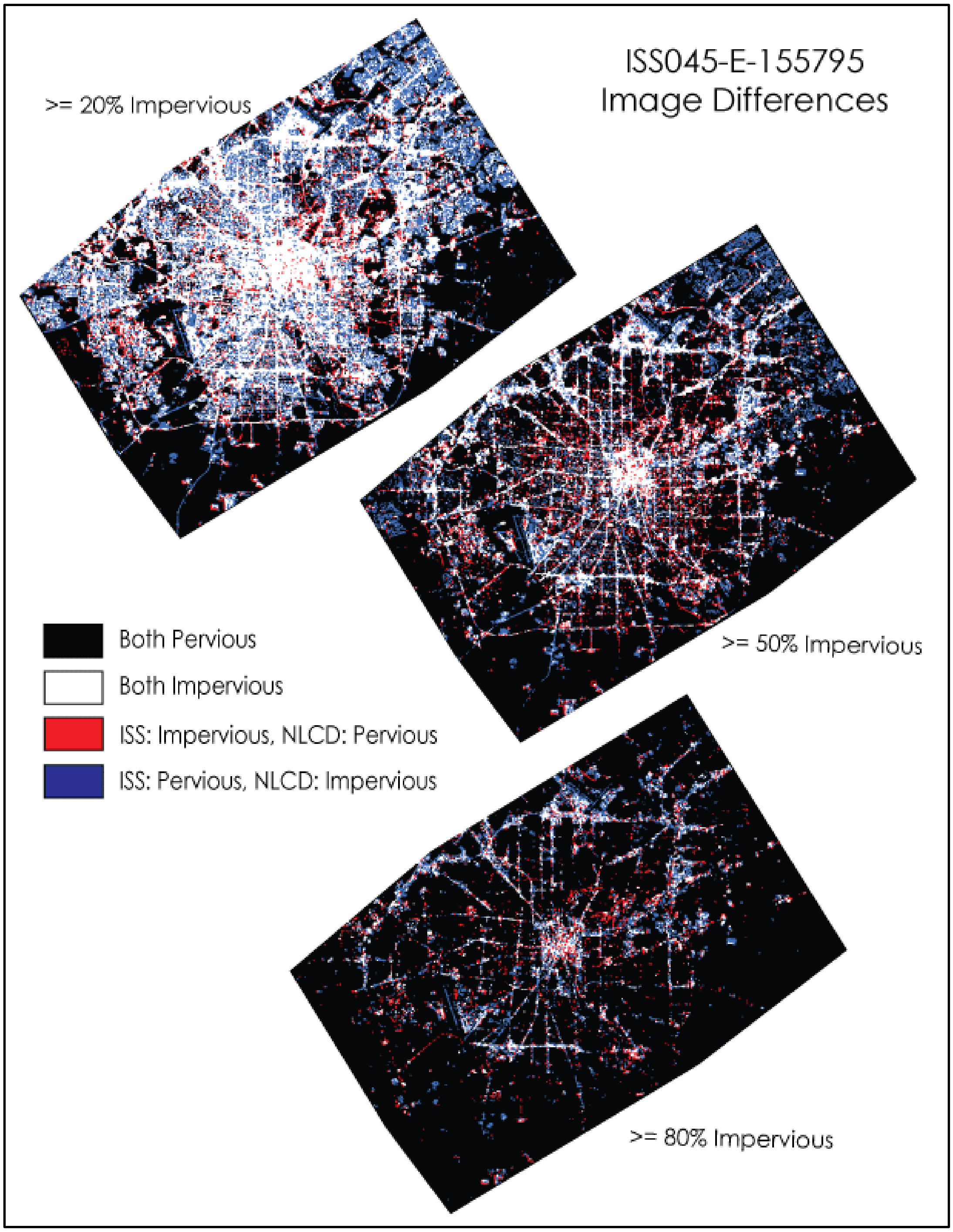


Figure 8. Image Differences for ISS045-E-155795. Shown above are the three image differences for ISS045-E-155795 for each imperviousness category. Each image has four classes: both pervious, both impervious, impervious cover misclassified by the ISS, and impervious cover omitted by the ISS. Images were derived by the authors from the original ISS images courtesy of the Earth Science and Remote Sensing Unit, NASA Johnson Space Center.

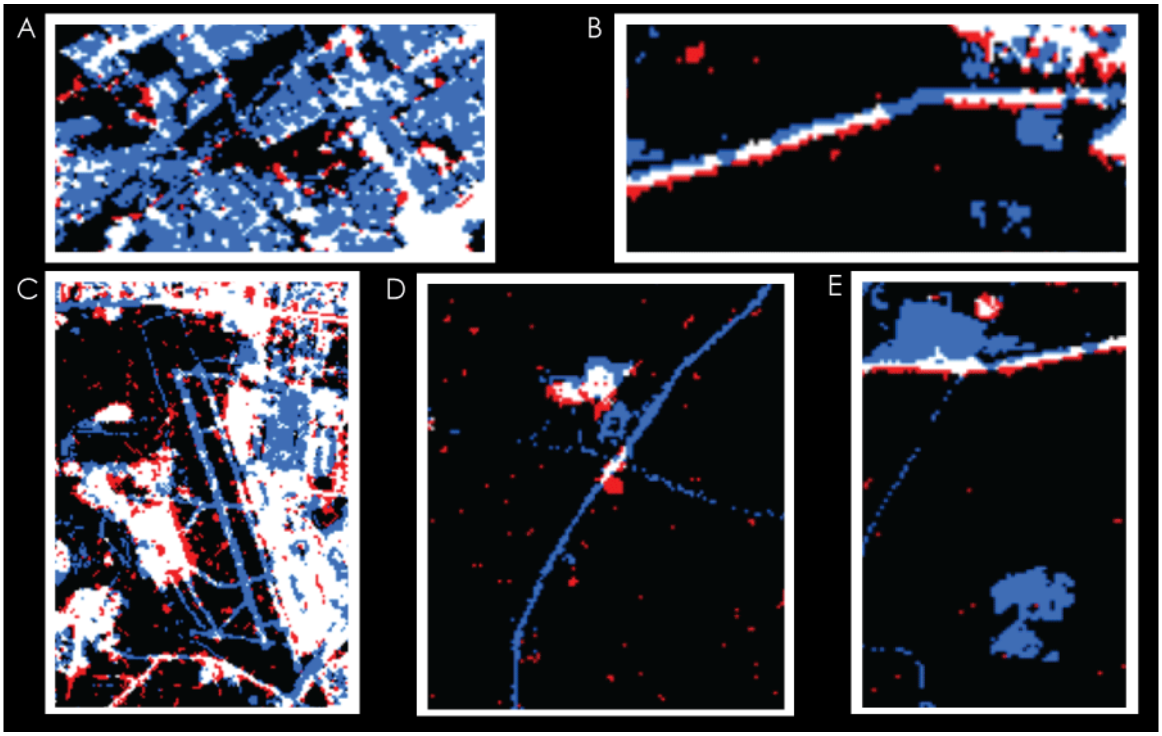


Figure 9. Examples of Error in Image Differences. These examples depict the leading causes for error in the image classifications between the ISS and NLCD by showing ISS misclassification (blue) and omission (red). A) The ISS struggles at classifying impervious cover in residential areas. B) Georeferencing errors are present especially in the outer edges of the study area due to image distortion and can be identified where omission and misclassification are on either side of an impervious feature. The ISS failed at classifying areas as impervious that are impervious yet poorly lit, such as C) airport runways and D) rural roads. E) Some error is also due to the five-month discrepancy in image acquisition dates of the ISS and NLCD in which features were constructed; the southern omitted cluster is Southwest Legacy High School and the northern omitted cluster is a truck salvage yard. Images were derived by the authors from the original ISS images courtesy of the Earth Science and Remote Sensing Unit, NASA Johnson Space Center.

property as impervious. There are several other examples of this same phenomenon across the study area such as the San Antonio Truck and Equipment salvage yard, and the San Antonio staging/lodging lot along the Salado Creek Greenway near IH-35 and Binz-Engleman Road. Human error within the georeferencing process, shown in Figure 9B, is also responsible for minor errors between the datasets, particularly on the outer edges of the study area. Spatial inaccuracies can easily be noticed on roadways outside of the city center where one side of the road is designated as an ISS error and the other side is designated as an ISS omission.

The look angle of the ISS imagery did not have a substantial effect on its ability to detect impervious cover although some minor patterns did arise (see Table 3). The least oblique image, ISS045-E-155770, which had a look angle of 9˚, had the highest overall accuracy and kappa accuracy for the least impervious category, 20% impervious or greater. ISS045-E-163632, which had the median look angle of 19˚, had the highest overall and kappa accuracy for the intermediate category of imperviousness, 50% impervious or greater. Finally, the image with the highest look angle of 24˚, ISS045-E-155795, had the highest kappa accuracy for the 80% impervious or greater category. The images with the highest accuracy are so by slim margins, which could be due to chance and/or a small sample of three images. However, there may be a direct relationship between the obliquity of an image and the magnitude of the imperviousness category for which it detects impervious surface most accurately.

Table 5. Land Use Overall Accuracies

	Undeveloped Meadow	Undeveloped Brush	Residential Dispersed	Residential Low Density	Residential Med Density	Residential High Density
Overall Accuracy	88.3%	93.4%	86.2%	85.6%	66.6%	52.4%
	Commercial	Open Space Urban	Open Space Cultivated	Residential Multi-Family	Industrial	Transportation
Overall Accuracy	76.5%	72.8%	97.6%	77.7%	72%	67.2%

Due to the uneven distribution of error across the study area, additional accuracy assessments were performed per land use in San Antonio using 2017 land use data from SARA. These accuracy assessments were made using the 20% impervious threshold with

ISS045-E-155770, and their overall accuracies can be observed in Table 5 above which range from 52.4% to 93.4%. Residential high density has the lowest overall accuracy by a large margin out of all the land use classes. This class corresponds to Figure 9A and represents single family homes on small lots that take up approximately a quarter acre of area. This class also makes up the majority of the ISS omission error. It has poor accuracy potentially because of a combination of NLCD overestimation of how much impervious cover is really in these areas and poor lighting during late nighttime hours, 2-3 AM, at these residential homes in which some families are bound turn off their lights or only leave one or two on. Similarly, medium density residential areas make up the second lowest land use accuracy, 66.6%. This class also contributes to the omission error found in residential areas. In the single family residential land uses, accuracy increases with decreasing density. The land use with the next lowest accuracy is transportation, with an accuracy of 67.2%, which can be explained by a combination of poorly lit rural roads (Figure 9D) and georeferencing error (Figure 9B). The poor accuracies in medium and high density residential areas and transportation reflect the uneven distribution of error as previously discussed in this section and emphasizes the reliability of the ISS imagery to detect impervious surfaces except in these select land use classes.

The precision of the ISS imagery was partially lost in this project due to the resampling of the native images to a coarser spatial resolution to match the 30-meter pixel size of the NLCD reference dataset. The ISS imagery has a native spatial resolution of approximately 8 meters, so each pixel has the potential to cover 836 m^2 less than it did in this study. Ideally, a ground reference dataset for impervious cover percentage by pixel would be available at the astronaut imagery's native spatial resolution, in order to take advantage of the additional detail. The NLCD imperviousness data is the only dataset to my knowledge that supplies impervious cover percentage on a per-pixel basis in this study region, so the necessary adjustments were made to be able to properly compare the datasets. Perhaps, the ISS imagery can detect real impervious surface better than discovered by the methodology outlined in this paper if there was an available high-resolution ground reference dataset ready for comparison. Furthermore, the NLCD data is not fully accurate, prompting the question how much more accurate could the ISS nighttime imagery be with a reference dataset that is more true to what is actually on the Earth's surface? One study found the NLCD Degree of Imperviousness dataset to have "an overall accuracy of around 70% for most thresholds" with overall accuracies ranging from 53.5% - 72.8% across different impervious thresholds; they also calculated poor kappa values ranging from 0.21 – 0.43 (Parece and Campbell 2014). Another study reported an overall accuracy 79% for the 2001 NLCD land cover and 78% for the 2006 NLCD land cover (Wickham et al. 2013). Others found a 2001 NLCD land cover accuracy for the conterminous U.S. to range from 59.7% - 89.5% (Yang et al. 2001). Therefore, the ISS classifications are likely more accurate than they appear to be in the measures outlined in this paper in relation to the actual land cover due to using an imperfect reference dataset.

V. CONCLUSION

In conclusion, metropolitan areas across the globe are suffering from the impacts of high volumes of impervious cover: increased flooding, riverbank destabilization, increased pollution to streams, and decreased wildlife. Datasets that portray impervious surface are hard to come by and difficult to interpret. There needs to be more accessible displays of impervious surface to begin to confront the issues discussed. This paper contributed to addressing these issues by answering the following questions: how well does artificial lighting in nighttime astronaut imagery of the Earth from the ISS detect land uses that employ impervious cover in San Antonio from 2015 and how does the look angle of astronaut imagery effect its ability to detect impervious surface? Reference Table 3 for an overview of overall and kappa accuracies. Overall accuracies ranged from 72.8% to 90.1%. The overall accuracies were highest in the most impervious category, with all accuracies over 88%. The opposite was true of kappa accuracies, where they were the greatest in the least impervious category. This indicates that some of the overall accuracy was due to the chance of assigning a pixel the correct value. Kappa accuracies ranged from 34.0% to 49.4%. Kappa values over 40% indicate a moderate agreement and an agreement 40% more accurate than a random pixel assignment. There was a range in overall accuracy across the ISS images of 16.3% and 15.2% in kappa accuracy. The highest kappa values were found in the least impervious category, so this category should be most utilized. The obliquity of the ISS imagery did not lend itself to a clear explanation, so the lowest look angle did not necessarily correlate with the highest accuracy. Instead, obliquity seemed to correlate with the amount of imperviousness in a category. For instance, the 80% impervious or greater category was most accurately detected with the imagery with the highest oblique, and the 20% impervious or greater category was most accurately detected with the imagery with the lowest oblique. Finally, the ISS imagery has potential to be more accurate than explained above due to the lost precision of the ISS imagery to match the resolution of the NLCD data and the fallible nature of the NLCD ground reference data as mentioned in several accuracy assessments; the imagery is more reliable at detecting imperviousness than these measures indicate except for in particular land use classes such as medium and high density residential areas and transportation.

This study contributed to bodies of literature related to satellite imagery and artificial lighting and to impervious surface issues by advocating for the proliferation of using artificial lighting in astronaut photography as a projection of land uses that have impervious cover. The result of answering the research questions will increase the body of knowledge surrounding using nighttime astronaut imagery as a source for impervious surface data and will offer considerations of how to best use it. Finally, this project suggests repeating this methodology with a variation in study area in order to solidify results amongst separate research papers. Also, research could be taken a step farther by empirically analyzing impervious surface areas in a city, finding the densest areas of impervious surface, and comparing the results against population and socioeconomic data in the same areas. Research that attempts to tackle these items could also make suggestions to the city focused on what steps can be taken to mitigate the effects of excessive impervious cover. Finally, further research could begin to investigate the correlation between artificial lighting in nighttime imagery and light pollution, laying the groundwork for more efficient urban lighting.

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