SSC17-I-07

Planet's Open Water Imaging - Geo-Accuracy Assessment

Ricardo Rios-Olmo
Planet Labs, Inc.
Washington, DC; (787) 630-2347
ricky@planet.com

Martin Miller
Space and Naval Warfare Systems Center Pacific
San Diego, CA; (619) 553-1726
mfmiller@spawar.navy.mil

ABSTRACT

Planet, an aerospace company that designs, builds and operates a fleet of Earth imaging small satellites, is under contract with the Navy's Program Executive Office Space Systems to expand imaging collections over water and develop technology to make this data accessible through its web-based geospatial platform.

Planet has deployed a constellation of low-cost, state of the art small satellites that will effectively act like a line-scanner of the Earth's surface. Planet's current mission is to provide images of the entire Earth's landmass one time per day, every day. The work with the Navy seeks to expand this global monitoring capability from the land to the sea, starting with coastal regions and expanding into the oceans. Planet's innovative approach to space is also observed in its image pipeline and rectification processes which will be discussed in this paper. Rectification and interpolation approaches are evaluated over water collects to observe how these impact relative geo-accuracies out to 10km, 60km, and open water (>=100km). Analysis revealed relative geo-accuracies of 220m at 10 km, 221m at 60 km, and >~1.4km in open water.

INTRODUCTION

Planet designs, builds, and operates the largest constellation of imaging satellites available. Planet's mission is to image the entire Earth, every day and make global change visible, accessible, and actionable. Planet calls its small satellites: Doves.

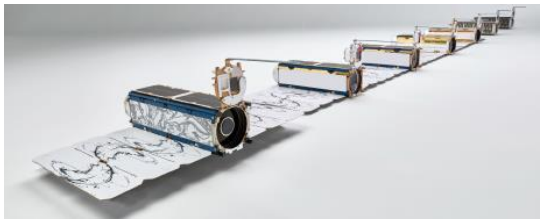

Figure 1: Image of Dove Satellite

To date, Planet has launched more than 200 Dove satellites, operates more than 100 Dove spacecraft, and collects and processes more than 150 million km² of satellite imagery per day. Toward the end of the second quarter of 2017, Planet's constellation of Doves will revisit every spot on the Earth daily which will include open water areas. Planet complements its imagery collection backbone with an internally developed, web-based, imagery processing platform that enables automated image processing and orthorectification as well as data discovery and delivery.

In an effort to understand the accuracy of Planet's products over water, Planet was under contract with the Navy's Program Executive Office Space Systems via the Rapid Innovation Fund program. The goal is to

measure the relative geo accuracy of the image data sets over littoral (10km), coastal (60km) and open water (>100km). The purpose is to provide an understanding and drive confidence on Planet's processing pipelines for the addition of maritime imaging to Planet's commercial product line.

Satellite Description

The Dove satellite design is based on the "3U" cubesat form factor. The Dove spacecraft has a full complement of subsystems including instrumentation (telescope/camera), attitude determination and control/guidance, navigation, communications, avionics/command and data handling, electrical power system, structure, and thermal control system. Each spacecraft is powered by solar panels and communicates with ground stations via multiple antennae.

PlanetScope Processing

Once the data is streamed to one of the ground stations, it is immediately ingested into Planet's cloud environment and goes through the processing pipeline. From there, the information provided by the (GPS) (spell out first ref) and positional instruments is processed leading up to the orthorectification processes for the imagery. These processing steps include:

- Darkfield / Offset Correction
- Flat Field Correction
- Camera Acquisition Parameter Correction
- Absolute Calibration
- Visual Product Processing
- Orthorectification

Geometric Positional Accuracy

The locational accuracy of all the imagery products depends on the quality of the reference data used: Ground Control Points (GCPs) and Digital Elevation Model (DEMs). Additionally, the roll angle of the spacecraft during the image acquisition and the number as well as the distribution of GCPs within the image will impact the final product accuracy.

Each Dove is equipped with instruments that allow Planet to determine the pointing accuracy. When the satellite is in "Imaging mode" Planet utilizes a star camera combined with a MEMS (spell out first ref; no second reference so no acronym needed) gyroscope. To determine location, Planet uses custom Two-Line Elements (TLEs) that are generated based on ranging the satellites from the ground stations. In addition, each Dove is equipped with a GPS sensor onboard for higher position and time accuracy. Processing of the GPS information is done on the ground and not on board the satellite. Using all the information provided, Planet's current pointing accuracy is on average calculated to be: 0.1 deg 2σ in roll/pitch/yaw.

PlanetScope Rectification

Planet utilizes a unique imagery rectification approach that minimizes processing steps to increase overall processing efficiency in preparation for the large amounts of imagery data that will be downloaded and rectified at Full Operational Capability. This approach reduces resampling steps through a proprietary parallel processing approach that enables moving from raw to orthorectified imagery without degradation of imagery quality.

To support the integration and compilation of multiple images over time, each pixel is adjusted for Bayer Masking, Telescope Geometry, Orbital Geometry, Satellite Pointing Accuracy, and Topography. All ortho tiles are orthorectified using GCPs and fine DEMs (30 m to 90 m posting) to less than 10 m root-mean-square error (RMSE) positional accuracy. Some 50,000 points are automatically generated for each satellite image and converted into a mathematical model to match relevant points to a database of some 5 million local ground control points derived from Landsat 8 and other sources. The Landsat 8 archive and OpenStreetMap database are automatically referenced to quickly provide robust, year-round, tie points.

IMPACT AND RELEVANCY

Planet's work under the Navy's PEO Space Systems contract demonstrates the feasibility and development of a new ocean observing capability. Nanosatellites

such as Planet's Doves provide resiliency and technological responsiveness not previously available.

Beyond the general advantages of nanosatellite platforms, Planet's Doves can deliver high temporal imagery. Using large constellations of spacecraft, in low earth orbit, allows repeat visits of the same point on the earth frequently. Using this imagery, there is the possibility to monitor changes in weather, natural disasters, and a variety of other uses. The importance of Planet's recent work is extending these capabilities out into littoral and ocean areas, as an additional source of information that Navy and Department of Defense systems can use as reference.

DOVE SATELLITE'S ACCURACY

Estimated Accuracy (Original Ground Coordinates)

Each Dove satellite is equipped with a GPS, gyroscopes and other instruments which allow Planet to accurately determine position and pointing direction. This information allows Planet to calculate and produce an image's (single frame) initial ground coordinates. When calculating these initial ground coordinates, three variables have a large impact on the accuracy of this location:

- Pointing Determination
- Location
- Timing

The correct values for each of these variables are recorded and brought down to the ground stations along with the image. Once the image enters Planet's processing chain, these values are used to produce the image's first ground coordinates. It is worth noting that these ground coordinates have not gone through any rectification process and are purely mathematical in origin. Every image downloaded from a satellite will contain its own set of ground coordinates independently calculated from the rest of the image strip. These are an image's first set of RPCs.

After these initial RPCs have been generated it then enters the rectification process in which the image is automatically rectified based on the availability of ground control points. Some cases like snow cover, extreme cloud cover or open water imaging produce no ground control points and hence its original RPCs are maintained.

For the purposes of this white paper, these original ground coordinates will be considered our "estimated" accuracy.

Interpolated RPCs

As mentioned before, an image's original RPCs are calculated independently from other images. However, in a Dove satellite's collect, an image is captured approximately every 0.5 seconds and a combination of these single frames (scenes) in one pass and from a single satellite forms an image strip. What this means is that the variables discussed in the previous section which affect the accuracy of the image's ground coordinates are consistent across the entire image strip.

Figure 2: Scene vs Scene Strip

If in the same image strip, at least one image has been properly rectified, meaning, one has been locked to the ground based on a number of GCPs, then we're able to interpolate a new set of RPCs for images without any GCPs. Being able to interpolate new RPCs improves the geo-accuracy for each of the images for which this is possible.

Because one or more images in the strip has been successfully rectified and because the same variables mentioned above equally affect all images in the same strip, mathematically we're able to correct the effect that two of the three variables have on the image's

accuracy. Location offsets and timing are neglected while the satellite's pointing determination still affects the image's accuracy. Based on average values for a build 13 Dove satellite, the average offset introduced is approximately 400m.

Figure 3 visually represents a case where the image strips intersects both land and water. Portions over land are able to be fully rectified using GCPs and so the accuracy over the portions over water are able to be corrected using interpolated RPCs.

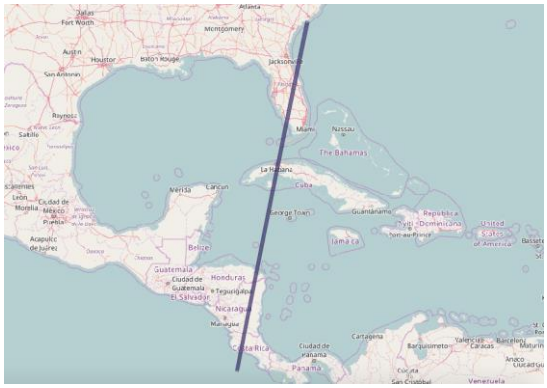

Figure 3: Planet Image Strip over Florida, Cuba and Honduras.

Interpolated RPCs can increase the accuracy of an image by an order of magnitude if not more.

ACCURACY ASSESSMENT STUDY

Littoral Areas (<=10km)

To examine Planet's image product accuracies up to 10km, several locations around the South China Sea were selected. For example, the Crescent group as shown in Figure 4.

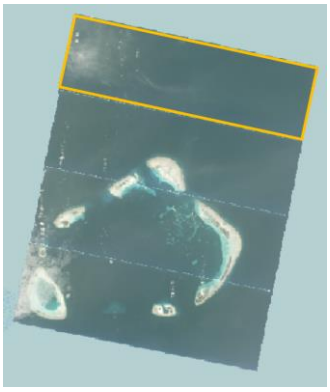

Figure 4: Plane Scenes over Crescent Group in South China Sea

Using RapidEye imagery as reference, Planet was able to calculate the accuracy (RMSE) of the PlanetScope imagery for images that contain land. The values obtained from this exercise can be seen in the table below.

Table 1: Measured RMSE for Crescent Group

Image ID	RMSE
20161022_021632_0e14	8.5 m
20161022_021631_0e14	10.7 m
20161022_021630_0e14	32.9 m
20161022_021628_0e14	**ESTIMATED**

In this example, the last image of the series (highlighted with a yellow box in Figure 4) is completely over water and so it is not possible to calculate its accuracy using the reference image. Instead, the Estimated and Interpolated accuracies were obtained as a reference. The table below shows the respective values for all the images in the series.

Table 2: Estimated vs Interpolated Errors for Crescent Group

Image ID	Estimated Error	Interpolated Error
20161022_021632_0e14	3306.4 m	161.2 m
20161022_021631_0e14	3515.2 m	120.1 m
20161022_021630_0e14	3578.9 m	385.6 m
20161022_021628_0e14	3562.1 m	527.5 m

The interpolated values shown in the table above represent the worst-case scenario for an image at 10km or less. These values we calculated over all locations selected for this study and the average interpolated error obtained was: **195.8m.**

Coastal Regions (<=60km)

At 60km, determining the accuracy of imagery over water becomes a challenge due to the lack of GCPs. As described in the previous section, the lack of GCPs presents a problem in being able to calculate an image's accuracy over a location in relation to a reference image with known accuracy. In an attempt to obtain some ground truth Planet was able to locate information containing the location of oil wells and platforms in the Gulf of Mexico area.

The information for oil platforms was obtained from the Bureau of Ocean Energy Management's (BOEM) website, which provides shapefiles containing locations of platforms in the Atlantic coast, Gulf of Mexico and the Pacific coast. The data set was then overlaid with an image strip that intersects with the data set. Doing so provided the ability of measuring the accuracy of Planet's data using the oil field locations as a reference.

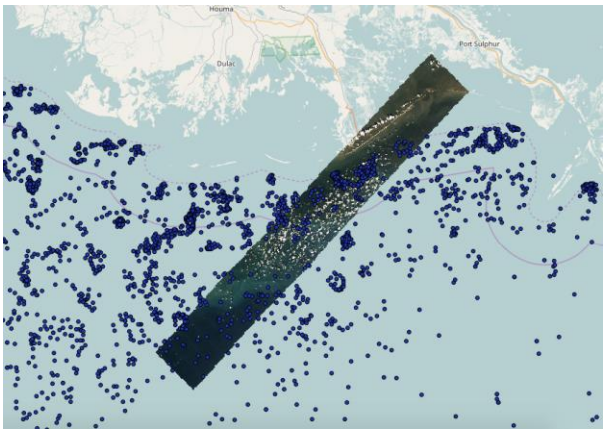

Figure 5: Planet Image Strip overlaid with BOEM Oil and Gas platform locations.

With both datasets properly imported in QGIS, Planet was able to measure the difference in location between where the imagery says the platform is vs. where the dataset obtained from BOEM says it is. Note that the accuracy of the BOEM oil platform locations is unknown.

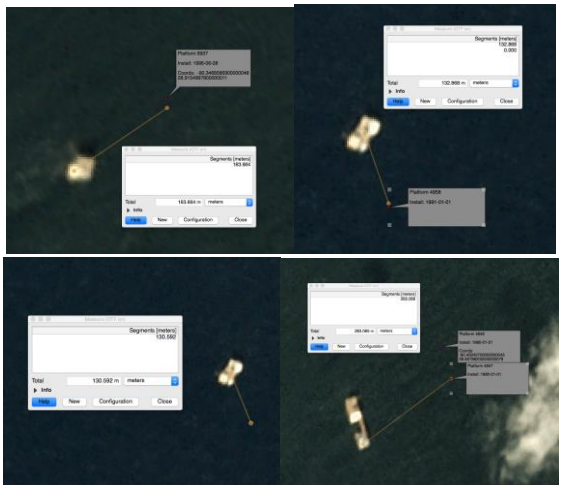

Figure 6: Screenshots of measurements from platform in Planet imagery to BOEM platform locations.

Choosing 30 different platform locations and using the measuring tool in QGIS, Planet visually measured the offset of the platforms which ranged from 25m to 654m at different distances from the coast.

The average measured interpolated error across all 30 data points can be seen in the table below.

Table 3: Measured Interpolated Errors for Oil and Gas Platforms in the Gulf of Mexico

	Interpolated Error
Mean	221.3 m
Median	191.8 m

Open Water (>= 100km)

To further examine and corroborate the accuracy of Planet's imaging capability over water, this time in areas 100km or more from the coast, Planet selected several image strips around the globe. See Figure below.

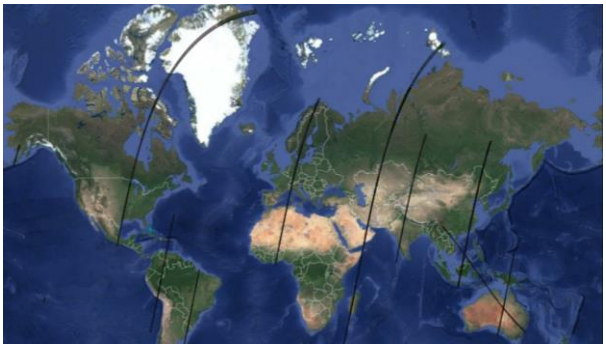

Figure 7: Planet Image strips around the globe.

The path of collection for these image strips provides insight to the accuracy and behavior of a Dove satellite's imaging capability over land and water.

As described in the previous sections, different sets of RPCs are generated for an image from its original ground coordinates to when the image is rectified using GCPs. A footprint can be generated for each one of these:

- Pointing Accuracy (Estimated)
- Interpolated RPCs
- Fully Rectified

Obtaining all three of these footprints enables calculation of the relative accuracy over regions with rectified footprints. From those, an estimated error and an interpolated error can be calculated. This has been done along the entirety of the strips pictured in Figure 7.

Table 4: Average Estimated and Interpolated Errors for Selected Image Strips

	Estimated Error	Interpolated Error
Mean	5116.5 m	1410.3m

To further evaluate accuracies at 100km or more from land and like in the previous section, Planet obtained publicly available information containing oil and gas platform locations. This time in five different areas around the Earth:

- North Sea
- Gulf of Mexico
- Suez Canal
- Sea of Okhotsk

Similarly, the oil and gas platform locations were overlaid with Planet image strips and the accuracy was visually measured using QGIS. As an example, North Sea platform locations and image strips can be seen in Figure 8.

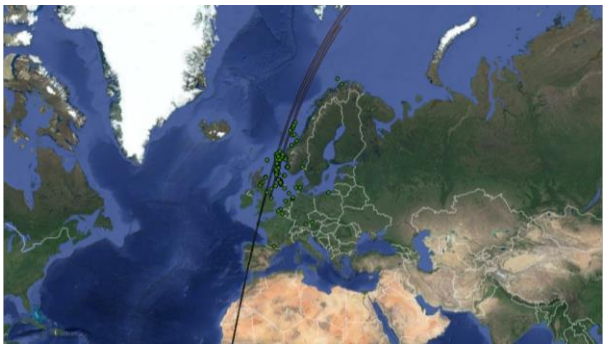

Figure 8: Planet Image strips overlaid with oil and gas data sets over the North Sea area.

As observed above, the image strips start in the Arctic and go over the oil and gas platforms before reaching land.

This time, Planet measured both Interpolated and Estimated errors when using the oil and gas platform locations as reference. For North Sea, Planet evaluated 11 oil and gas locations, the average measured error can be observed in the table below.

Table 5: Average Estimated and Interpolated Errors for Image Strips over the North Sea

	Estimated Error	Interpolated Error
Mean	1537.5 m	682.7m

Over all locations, Planet evaluated nine different image strips. The overall average results can be observed in the following table.

Table 6: Average Estimated and Interpolated Errors for Image Strips over all locations.

Total Unique Satellites Evaluated	9
Estimated Error	6904.5 m
Interpolated Error	1388.8 m

SUMMARY

Under contract with the Navy's Program Executive Office Space Systems, Planet determined its data relative accuracy over littoral, coastal and open water regions. Through each of the sections above, Planet demonstrated its technical approach and evaluates the relative geo accuracy for the images produced by the Dove space crafts. The goal was to drive confidence in Planet's capabilities to collect over water or in areas where GCPs are not available to provide accurate rectification for the imagery.

Throughout the assessment, Planet demonstrated the following accuracies:

Distance From Shore Evaluated	Average Accuracies (Interpolated)
<10km	195.8
<60km	221 m
>=100km	~1.4 km

Known relative geo-accuracies over water enables Planet to make collects beyond the Earth's landmass available to users like the Navy that can benefit from these for its day-to-day operations and mission sets by providing them with unprecedented coverage over water, significantly increasing maritime domain awareness. As a result of the work done through the Rapid Innovation Fund, Planet is in the process of releasing an Open Oceans commercial product. The technical preview for the Open Oceans program went live in June 2017 through which Planet has made several open ocean areas available via the platform.

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