ON-ORBIT RADIOMETRIC CALIBRATION OF THE PLANET SATELLITE FLEET

DOVES AND SKYSATS

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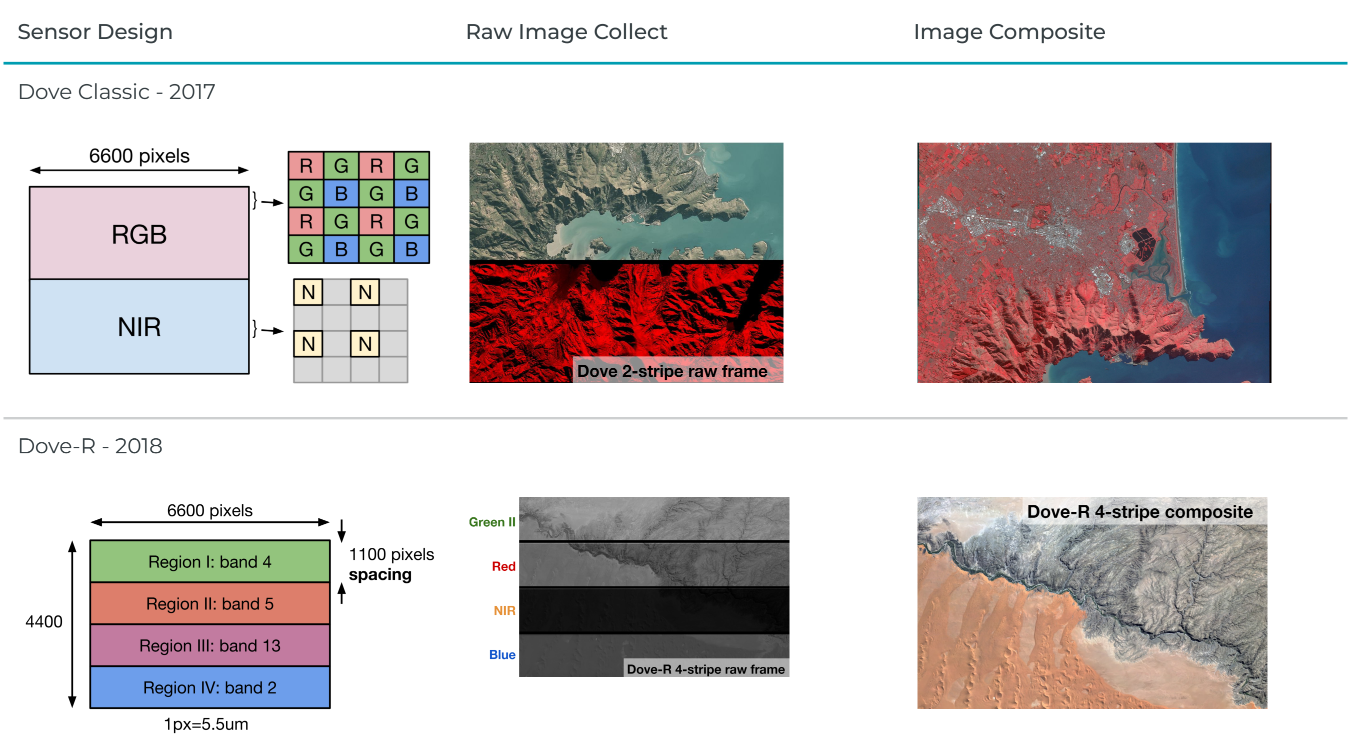
TABLE OF CONTENTS

INTRODUCTION

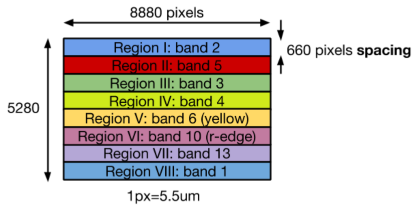
As of October 2021, Planet operates a fleet of over 200 satellites whose dual purpose is to "image the world" on a daily basis and to acquire important time sensitive imagery on demand and at high spatial resolution. The first objective is supported by Planet's fleet of Dove satellites which passively collect images over the Earth's land mass on a continuous basis, providing near daily monitoring of any location. The Doves are medium resolution cubesats with a ground sampling distance (GSD) of ~4 meters, have a swath width of 25-32.5 km, and image in nadir pointing mode for nominal image collection. The second objective is supported by Planet's fleet of SkySat high resolution (< 1 meter GSD) satellites. SkySats are larger, maneuverable and can be tasked to image any location on the planet at any view angle.

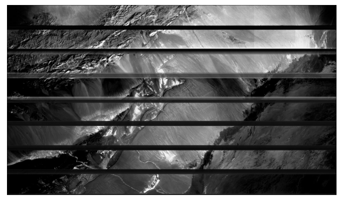
As an agile aerospace company, Planet works continuously to optimize spacecraft architecture and has iterated upon the Dove design several times. To date, three major generations of Dove satellites are in orbit collecting images (Figure 1). These medium resolution satellites have been launched over an extended period of time in groups referred to as “flocks.” Given the Dove’s small swath width and large number of individual satellites combined with the inclusion of high resolution SkySat imagery, consistent image processing and scaled radiometric calibration are a key requirement for producing a usable dataset across space and time.

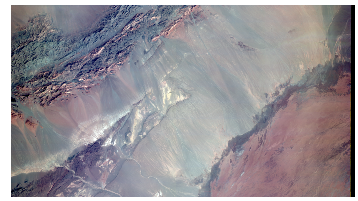
Figure 1: Planet Payloads over the years and associated global image coverage in km^2. Labels indicate when each group of Dove satellites, referred to as a Flock, was launched into orbit.



SuperDove - 2019







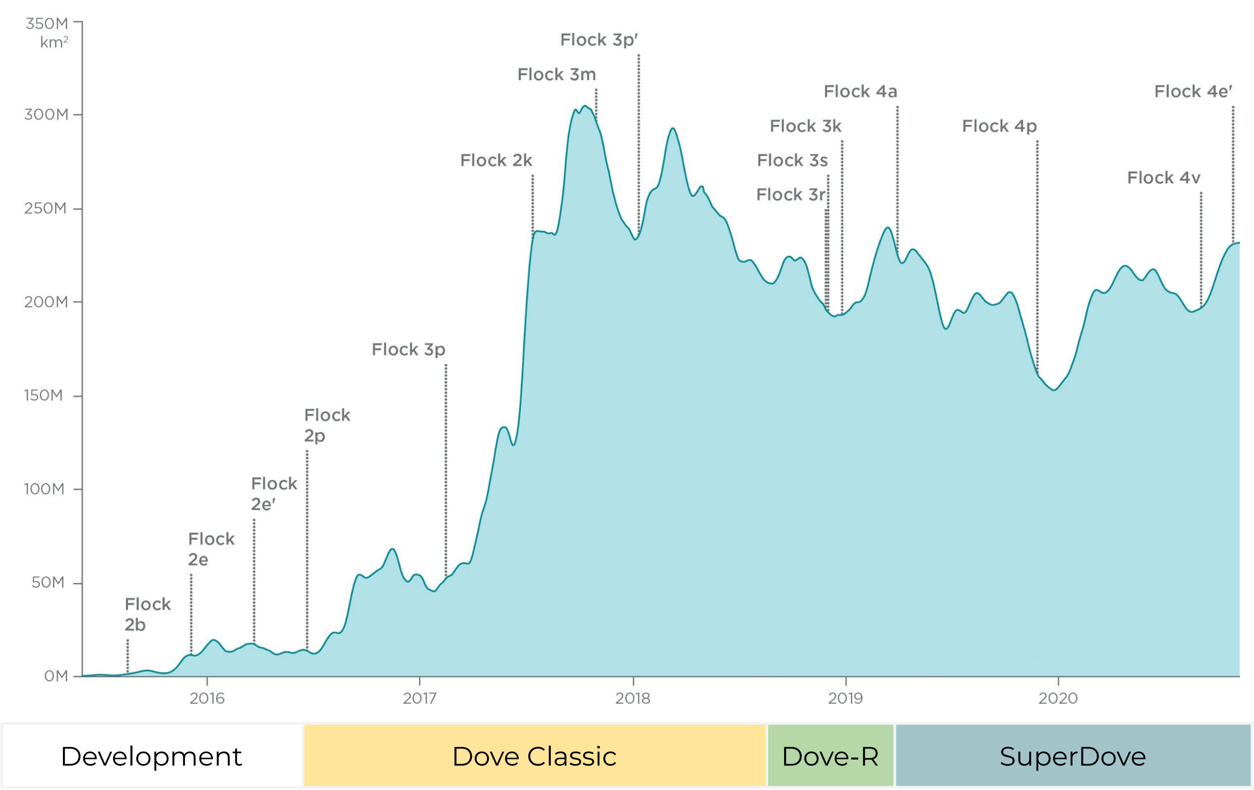
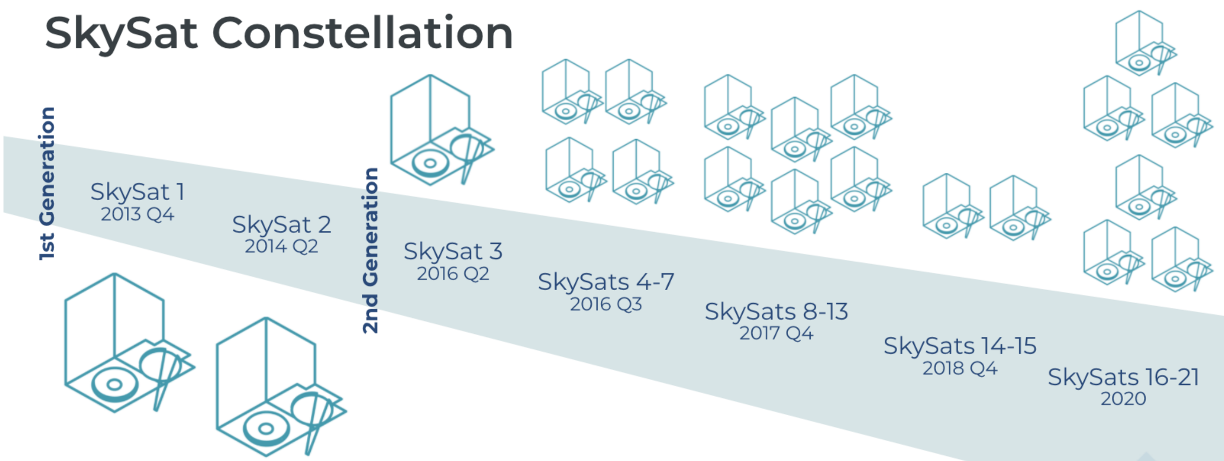


Figure 1: SkySat generations and launches over the years. In generation C, SkySats were grouped into “blocks”. The last block, block 3, was launched in 2020.



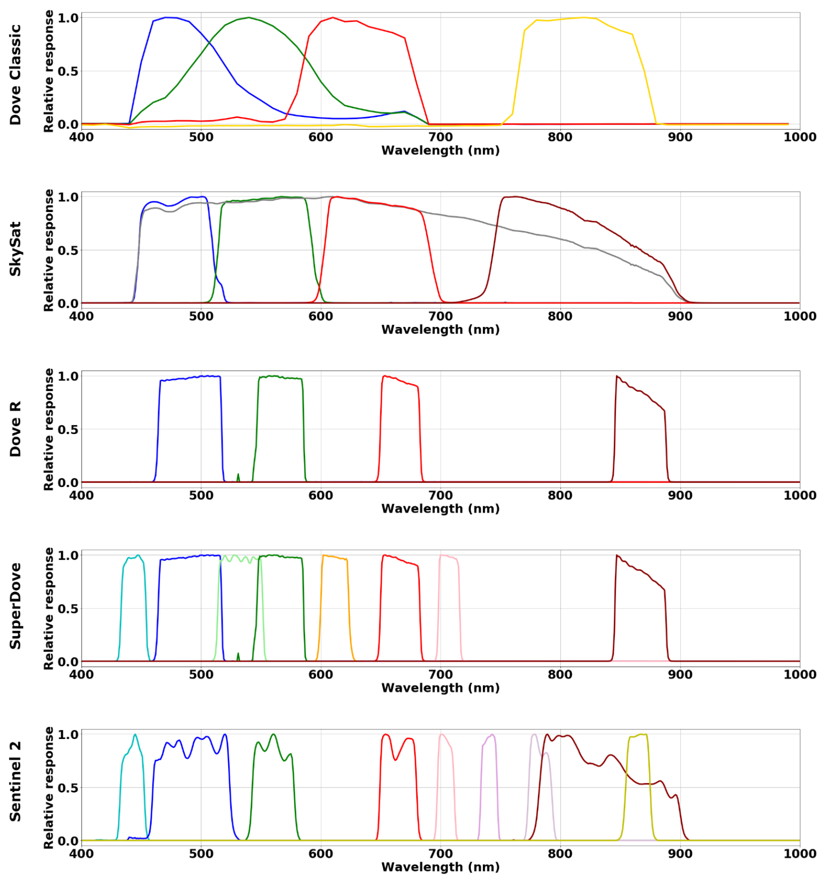
<table>
<tr><td colspan="5">Generation</td></tr>
<tr><td rowspan="2">A</td><td rowspan="2">B</td><td colspan="3">C</td></tr>
<tr><td>Block 1/SkySats 4-9</td><td>Block 2/SkySats 10-15</td><td>Block 3/SkySats 16-21</td></tr>
</table>

In this white paper we describe the process by which Planet Dove and SkySat satellite sensors are calibrated while in orbit. We start by detailing some of the challenges presented by a large, rapidly evolving fleet of satellites. We then describe in detail the method of updating the satellite calibrations once in orbit, including considerations for choosing calibration references as well as application of small adjustments to improve intra-flock consistency. Validation of the resulting updated calibrations is then described along with representative results from a recent calibration update.

CALIBRATION CHALLENGES

A well calibrated satellite requires detailed characterization of its sensor. For Planet's Dove satellites, each generation has a different sensor design with each Dove having its own unique relative spectral response, though all sensors within the same generation are very similar. The original Dove design, the Dove Classic, has a sensor with four wide overlapping bands in blue, green, red and near infrared. The next generation Dove-R satellites also have 4 spectral bands, but they are narrow, non-overlapping and chosen to closely match the corresponding ones from Sentinel 2. The most recent Planet payload, the SuperDove, has eight narrow, well defined spectral bands, four of which match the VNIR bands of Dove-R. Overall, 6 of the SuperDove bands are shared with Sentinel 2. SkySat has three separate sensors, each with wide bands in blue, green, red and near infrared. These are similar to the Dove Classic design, however with very little overlap between bands. SkySats also have a panchromatic band, though the calibration of the pan band will not be discussed here. Representative examples of the relative spectral response (RSR) curves for each of the Planet Dove generations and for SkySats are shown in Figure 2 along with the RSR for Sentinel 2[1] for comparison.

Figure 2: Relative spectral response curves of Planet's payloads



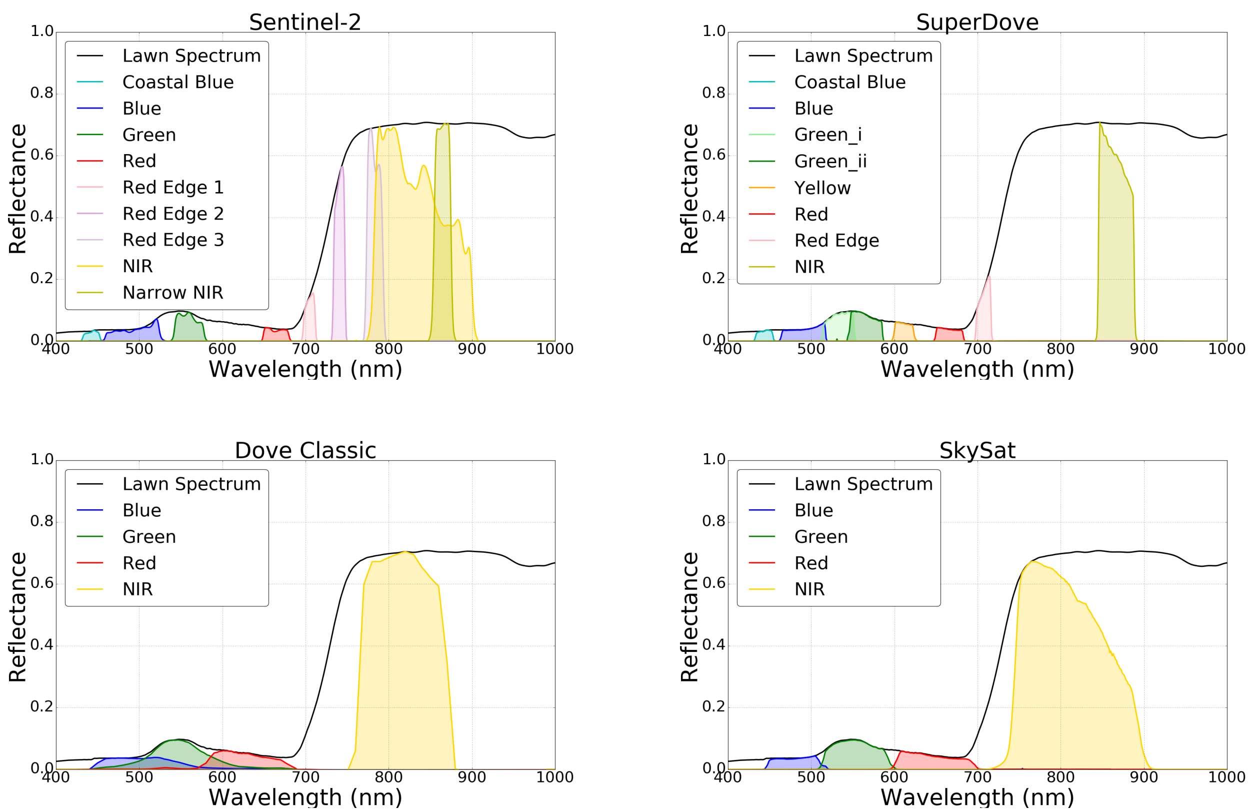
The similarity of spectral bands between Dove-R, SuperDove and Sentinel 2 is a calculated design choice to allow Sentinel 2 to be leveraged as a reference for on-orbit calibration utilizing simultaneous, intersecting crossovers. As the relative spectral responses (RSRs) between Sentinel 2 and Dove-R/SuperDove are very similar, we can collect crossover scenes from anywhere in the world to perform the on-orbit calibration and are not just limited to well characterized calibration sites where a spectral band adjustment factor (SBAF[2]) can be calculated.

SkySat and Dove Classic sensors, however, each have quite different relative spectral responses when compared to Sentinel 2 and therefore, even if well calibrated, will produce different measured radiance values since they are sensitive to different parts of the observed spectrum. For example, in

[1] https://sentinel.esa.int/web/sentinel/missions/sentinel-2
[2] G. Chander et al., "Applications of spectral band adjustment factors (SBAF) for cross-calibration," Geoscience and Remote Sensing, IEEE Transactions on, vol. 51, no. 3, pp. 1267–1281, 2013.

the scenario shown in Figure 3 where we show the sensors' response to a surface comprised of lawn grass, comparing a SkySat or Dove Classic scene to a Sentinel 2 scene without performing an SBAF correction would result in the signals in the blue, green and red bands differing by 10-20%. It is therefore necessary to normalize for the different response of each sensor for these satellites.

Figure 3: A lawn grass spectrum from a spectral library for (A.) Sentinel 2A (B.) SuperDove (C.) Dove Classic and (D.) SkySat



Beyond the differences in the sensor designs between the various Dove generations and between the Doves and SkySats, the large number of Planet satellites alone poses a significant challenge for on orbit calibrations. With single image collects of less than 660 sq km and individually only covering a small fraction of the Earth's surface each day, each satellite has limited opportunities for collecting usable images over calibration sites that provide reference data directly or over well characterized sites simultaneously with a reference satellite such as Sentinel-2. Operationally, calibrating Planet's fleet of satellites requires a high level of automation and scalability to produce accurate calibrations for every satellite.

CALIBRATION REFERENCE

Images from all of Planet's active satellites contribute scenes to the final products that our customers rely on. Therefore interoperability and consistency between all of Planet's satellites is essential. To achieve this consistency, all calibrations across Planet's fleets are based on gathering a dataset of near simultaneous crossovers with Sentinel 2 as the reference satellite, with a < 5% radiometric accuracy.[3] Sentinel 2 is a multi spectral instrument that images in 13 spectral bands that range from the visible to the short wave infrared. The spatial resolution of the spectral bands ranges from 10 to 60 m. Absolute radiometric calibration for Sentinel is performed every month using a diffuser fitted inside the calibration and shutter mechanism. Sentinel 2 uses several methods to validate radiometric calibration, including measurements over Pseudo Invariant Calibration (PIC) sites.

Because of the shared spectral bands with Sentinel 2, Planet's Dove-Rs and SuperDoves crossover comparisons avoid the need for RSR adjustments and therefore can be collected anywhere in the world. This allows for collection of sufficient simultaneous crossovers to allow rapid on-orbit calibration for commissioning after launch. It also allows for longer term monitoring and calibration adjustments while providing data spanning the full dynamic range of the satellite sensor.

Previously simultaneous crossovers with Landsat 8 and RapidEye were used for Dove Classic calibration. However, RapidEye satellites were decommissioned in 2020, removing them as a calibration reference going forward. In addition, Landsat provides a very limited number of per-satellite crossover opportunities. Because significant RSR differences between Dove CLassic satellites and Sentinel 2 are present, SBAF corrections are still necessary to directly compare TOA reflectance values. This restricts the usable simultaneous crossovers to well-characterized calibration sites. Because these sites are limited in number and are mostly composed of bright, pseudo invariant desert regions, this not only limits both the number of usable crossovers that can be collected in a short period of time, but also largely limits the measurements to high TOA reflectance values.

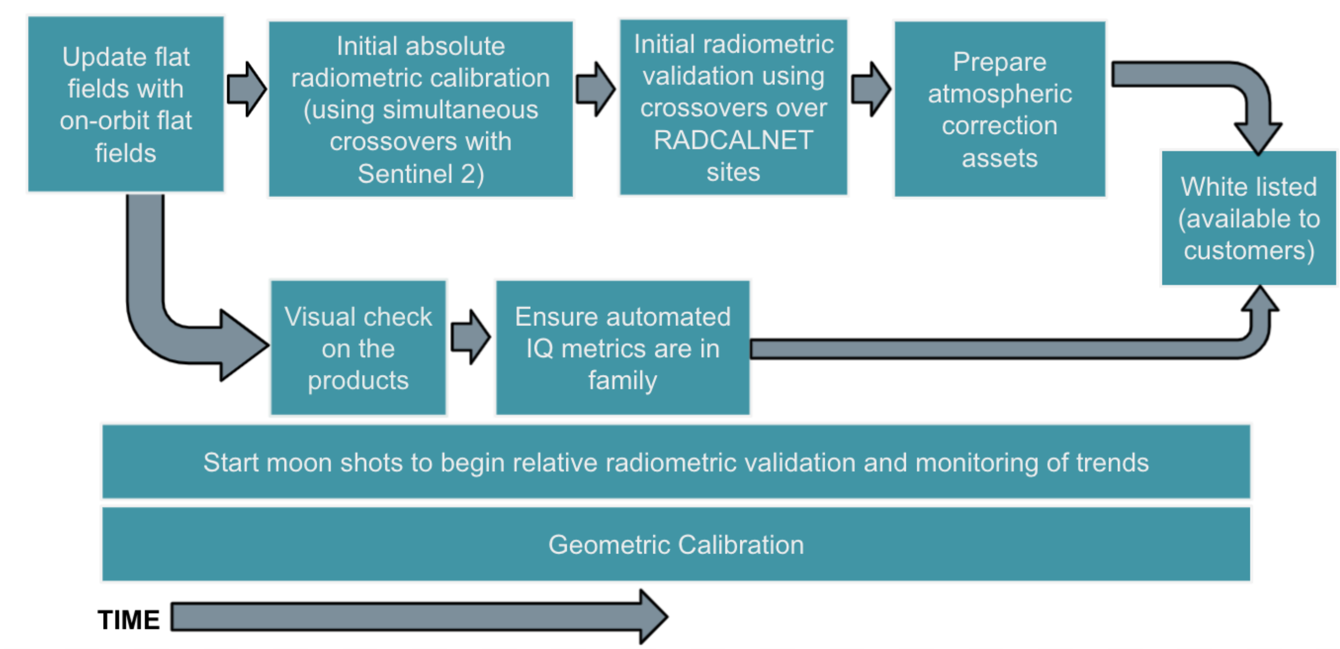
Before switching to using Sentinel 2 as the reference source across all satellites, calibration of SkySats used a vicarious approach with four RadCalNet sites as its target reference[4]. RadCalNet sites provide ground truth measurements of surface reflectance on a semi-daily basis when not affected by poor atmospheric conditions. Combined with measurements of atmospheric components (aerosols, water vapor, etc), this allows calculation of top of atmosphere (TOA) radiance values that satellite observations can be compared to. However, there are only a small handful of RadCalNet sites globally providing limited opportunity to both calibrate and validate over a wide range of surface conditions. Therefore, for greater radiometric consistency across Planet's entire fleet of high and medium resolution satellites, and for a larger number of reference comparisons to calibrate against, the SkySat calibration process has also been updated to use Sentinel-2 as a reference.

[3] https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-2-msi/resolutions/radiometric
[4] https://www.radcalnet.org

SATELLITE COMMISSIONING

Planet Dove satellites are manufactured and launched in groups, referred to as flocks, and go through a commissioning process once in orbit (see Figure 4). Commissioning tests that the satellites are properly functioning and prepares them to start downloading imagery for customer consumption. As part of the commissioning process, an initial on-orbit calibration is performed to account for any changes to the satellite imaging performance in its new environment.

Figure 4: General Planetscope calibration procedure.



For Dove Classic, Dove-R and SuperDove satellites, the initial calibration is the same as for all subsequent ones, with the exception of a shorter time frame needed to allow each satellite to provide high quality imagery for customer use as quickly as possible. Since each satellite goes through a rigorous calibration process on the ground before launch, generally only small adjustments are necessary after first light, allowing for a quick turnaround using less data. Subsequent calibration updates are performed every six months based on imagery collected over the entire previous six month period, or possibly a shorter time period for satellites that do not image over the entire six month timeframe.

The entire SkySat constellation has been launched and there are no plans to launch more. Block 3 SkySats were initially launched with the average radiometric coefficients of currently operating SkySats as their preliminary coefficients. After launch, the SkySats were tasked to image RadCalNet and PIC sites daily to collect calibration and validation data. As of December 2021, Block 3 satellites have preliminary coefficients applied while they collect sufficient calibration data.

DOVE CLASSIC AND SKYSAT CALIBRATION

CALIBRATION SITES

Because of band RSR differences, Dove Classic and SkySat simultaneous crossovers with Sentinel 2 must be collected over well characterized sites for calibration purposes. There are 29 sites globally distributed which are used for this purpose, listed in Table 1, most of which were used previously by the RapidEye team for temporal radiometric calibration. Stable, homogenous regions within these sites were hand selected to be used for Planet calibration. In addition, internationally recognized calibration sites known as Pseudo Invariant Calibration sites (PICS) are also used. All of these sites have very low to no vegetation cover and are seasonally stable.

Table 1: Calibration site descriptions

CALIBRATION SITES

Site Name	Lat, Long	Description
Pseudo Invariant Calibration Sites		
AlgodonesDunes	32.88, -115.02	Desert (Sonoran), dunes at multiple scales and homogenous with little vegetation
Libya1	24.56, 13.45	Desert (Sahara), flat, dry, large, dunes at multiple scales, but overall homogeneous, no vegetation.
Niger1	20.27, 9.60	Desert (Sahara), flat, dry, large, dunes at multiple scales, but overall homogeneous, no vegetation.
Niger2	21.28, 10.75	Desert (Sahara), flat, dry, large, dunes at multiple scales, but overall homogeneous, no vegetation.
Sudan1	21.67, 28.22	Desert, flat, dry, large, homogeneous, no vegetation.
RapidEye Calibration Sites		
SaudiArabiA	23.44, 51.15	Desert, flat, dry, dune patterns at several scales, but homogeneous when averaged over larger areas, no vegetation.
SaudiArabiB	27.56, 44.23	Desert, flat, dry, dune patterns at several scales, but homogeneous when averaged over larger areas, no vegetation.
Taklamakan	39.03, 80.09	Desert, flat, dry, large, dunes at multiples scales, but overall homogenous
SNR2	32.84, -114.56	Desert (Sonoran), flat, dry, dunes, homogenous
ChinaA	43.94, 109.95	Desert (Gobi), partly steppe, dry, large, less vegetation, mountainous
ChinaB	40.31, 103.71	Desert (Gobi), dry, large, some sand dunes, mountainous, no vegetation

Bolivia	-20.33, -66.97	Salt Desert, flat, dry, homogeneous and very bright, no vegetation.
Thar	28.18, 71.81	Arid desert (Thar), small dunes, but largely homogenous. Mostly vegetation-free.
SudanC	16.60, 27.24	Desert, flat, dry, large, homogeneous, no vegetation.
AustraliaC	-25.08, 138.15	Flat, dry, somewhat homogeneous, almost no vegetation.
RRV	38.49, -115.76	Dry-lake playa, flat, small, but spatially uniform.
Libya4	28.51, 23.58	Desert (Sahara), flat, dry, large, dunes at multiple scales, but overall homogeneous, no vegetation.
EgyptC	23.00, 28.64	Desert, flat, dry, large, homogeneous, no vegetation.
EgyptB	25.81, 29.16	Desert, flat, dry, large, homogeneous, no vegetation.
Libya	26.51, 12.94	Desert (Sahara), flat, dry, large, dunes at multiple scales, but overall homogeneous, no vegetation.
Dunhuang	39.87, 94.19	Desert (Gobi), flat, dry, overall homogeneous, no vegetation. Possibly affected by atmospheric aerosol due to sandstorms and dust.
NorthernMal	21.05, -4.50	Desert (Sahara), flat, dry, large, dunes at multiple scales, but overall homogeneous, no vegetation.
Mexico	32.91, 114.39	Desert (Sonoran), flat, dry, dunes, homogenous, NW corner agricultural areas
MauritaniaA	20.93, -11.97	Desert (Sahara), flat, dry, large, dunes at detailed scales, but overall reasonably homogeneous areas, large dunes at northern part.
NamibiaA	-24.55, 15.40	Coastal Desert, flat, dry, large, somewhat homogeneous, no vegetation.
NamibiaB	-17.03, 12.19	Coastal Desert, flat, dry, large, somewhat homogeneous, no vegetation.
Kandahar	30.57, 65.25	Desert, flat, dry, large, homogeneous, no vegetation.
NigerA	19.54, 9.00	Desert (Sahara), flat, dry, large, dunes at multiple scales, but overall homogeneous, no vegetation.
NigerB	18.66, 11.29	Desert (Sahara), flat, dry, large, dunes at multiple scales, but overall homogeneous, no vegetation.

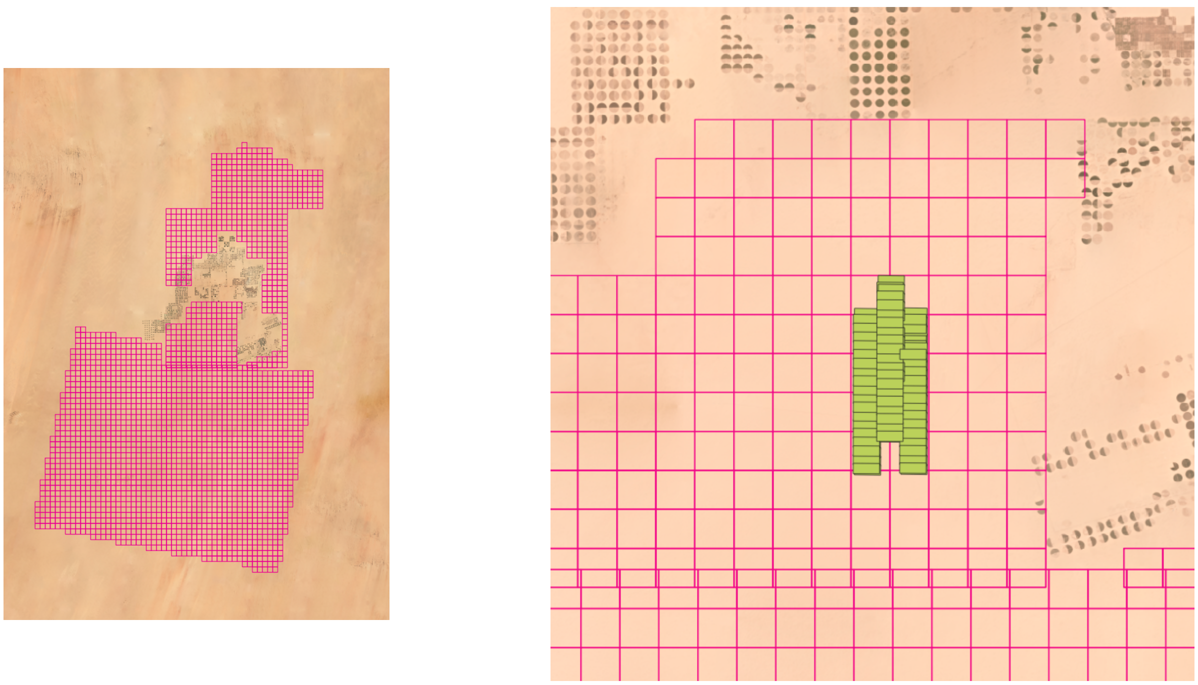
Each calibration site is characterized using Hyperion hyperspectral data. The Hyperion instrument onboard the Earth Observing One (EO-1)[5] satellite was launched in 2000 and active until 2017. Hyperion collected 220 spectral channels at a 10-nm resolution between 0.357 and 2.576 micrometers at a spatial resolution of 30m. Site spectra were created by averaging 12 overlapping Hyperion scenes of a sample area of the calibration site, one from each month of the year to capture seasonality effects. This average image is then sampled at a resolution of about 3.5 x 3.5 km across

5 https://www.usgs.gov/centers/eros/science/usgs-eros-archive-earth-observing-one-eo-1-hyperion?qt-science_center_objects=0#qt-science_center_objects

the areas of the site used for crossover sampling, aggregated to per-band sample averages, and radiance spectra over the full spectral range of Hyperion. Figure 5(a) shows an example of a calibration site in Egypt with the Hyperion sample grid overlain, while Figure 5(b) shows a zoomed in view of this site and the individual scenes from a SkySat collect overlain to provide context. Each SkySat is tasked to image a targeted region within each of the Rapid Eye calibration sites daily.

Figure 5: (a) Rapid Eye Egypt C site (North) and PIC Sudan1 site (South) with hyperion sample grid overlain. (b) Zoomed in view of the Rapid Eye Calibration site Egypt C with the hyperion data sample grid overlain. The green boxes represent a tasked SkySat collection. Each SkySat is tasked to image each Rapid Eye site daily.

(a) (b)



ON-ORBIT CALIBRATION PROCEDURE

Simultaneous crossover events over calibration sites are defined as 2 satellites imaging a region of the Earth at approximately the same time. For Dove Classic, the maximum time difference between two crossover images allowed for calibration purposes is two hours. Crossover times outside of this time boundary are rejected. For the SkySat, in order to increase the number of crossovers available for calibration, the time limit is 3 hours. Collecting crossovers within these boundaries is particularly difficult for the block 3 SkySats (14-21) as they are not in sun synchronous orbit (SSO). The 53° orbital inclination of the block 3 satellites allow for a high intra-day revisit time, but as they do not make consistent daily crossing times, their crossovers are not always within the allowable time frame.

In order to be considered for calibration purposes, the crossover must also occur within one of the calibration sites shown in Table 1. In addition, the maximum view angle of both the reference and test satellite must be less than 10 degrees. As Doves are always nadir pointing this is not an issue, but many SkySat scenes are filtered out as SkySats routinely take images over this limit. Scenes are further filtered out if they have greater than ~10% cloud cover for Doves and ~20% for SkySats. The SkySat cloud cover limits are more relaxed as the SkySat calibration dataset is more data limited than the Doves'.

Products for simultaneous crossovers found within the calibration sites are processed to top of atmosphere reflectance. SkySat and Dove Classic collections are resampled to 20 m. The overlapping region between two pairs is then found and chunked into samples using the predefined sampling grid (Figure 5). For SkySat, the on-orbit calibration procedure is performed individually for each camera.

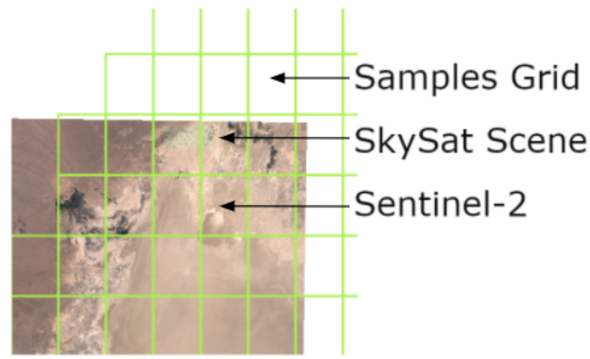
SBAFs for each sample are calculated using the following equation, where ***A*** and ***B*** represent the reference (Sentinel 2) and test (Planet) satellites, respectively, and ρ_λ is the Hyperion TOA reflectance at a given wavelength λ:

$$SBAF_{B \to A} = \frac{\bar{\rho}_{\lambda(A)}}{\bar{\rho}_{\lambda(B)}} = \frac{\left(\dfrac{\int \rho_\lambda RSR_{\lambda(A)} d\lambda}{\int RSR_{\lambda(A)} d\lambda}\right)}{\left(\dfrac{\int \rho_\lambda RSR_{\lambda(B)} d\lambda}{\int RSR_{\lambda(B)} d\lambda}\right)}$$

For each sample, summary statistics (mean, median, mode, etc) are calculated and recorded. For each scene pair, all sample points within the overlapping region are gathered and the mean reflectance value of each band for each sample is used to calculate the joint mode of the mean reflectance values in each band for the collection of both Planet satellite samples and reference samples. The joint mode is a pair of values, one for each spectral band, that represents the strongest sample-value-to-sample-value relationship present in the crossover pair, and it is the mode of the distribution of corresponding sample values from the pair, which is a two-dimensional distribution. Because SkySat scenes are so small, there is often not enough data available to calculate a joint mode. In those cases, the median reflectance value is used instead. Figures 6 and 7 depict crossover events for both SkySat and Dove Classic with Sentinel 2.

Figure 6: Crossover event of SkySat and Sentinel 2. Two sample areas are intersected in the example. As the region is homogeneous, the sample points are clustered together. In this example, there is not enough data to calculate the joint mode and instead the median value of each scene is used.

(a)



(b)

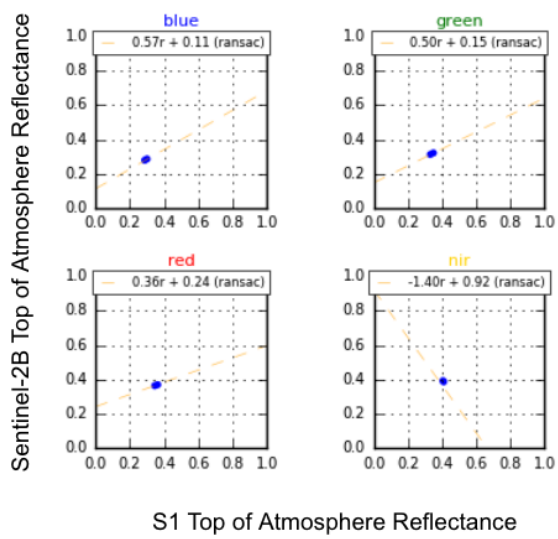
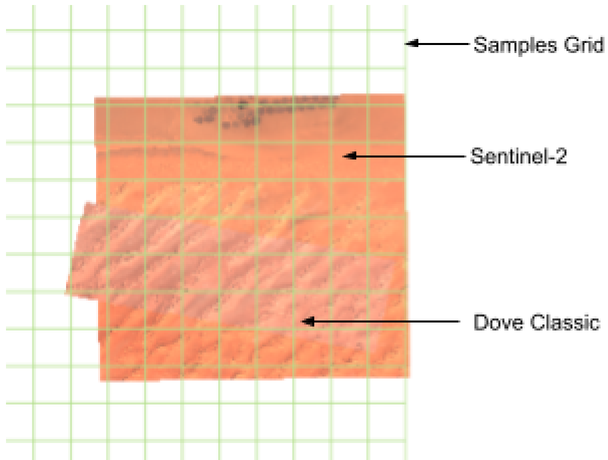
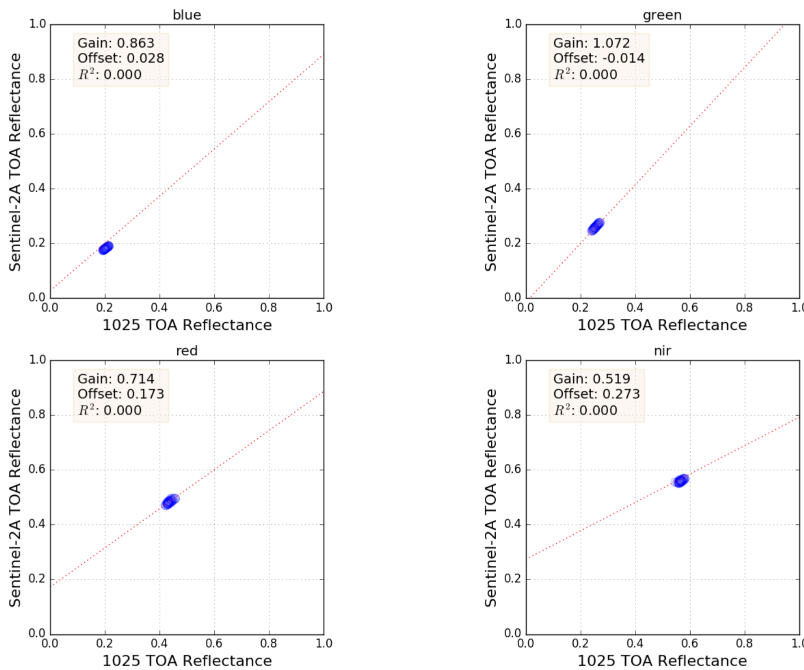


Figure 7: A single crossover event between Dove Classic and Sentinel 2. Over 30 common sample areas are intersected but both satellites in this example (a). Since the region is approximately homogeneous, the sample data points all cluster tightly together (b). The joint mode is then calculated from these points.

(a)



(b)



The joint modes (or mean values in the case of SkySat crossovers) of all the individual scene pairs are then collected and a RANSAC fit is used to calculate the gain and offset for each band. For SkySats, the RANSAC fit is forced through the origin. The Dove Classic example has many more data points in the final regression than the SkySat example due to the fact that Doves constantly monitor whereas SkySats are tasked satellites.

DOVE-R AND SUPERDOVE CALIBRATION

ON-ORBIT CALIBRATION PROCEDURE

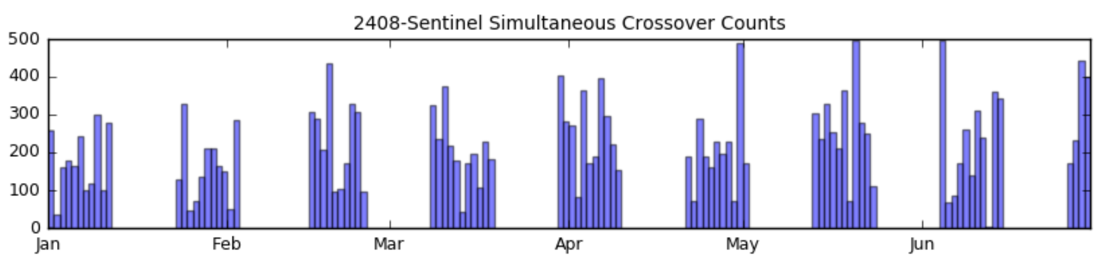
As noted previously, the four bands of Dove-R and 6 of the 8 bands of SuperDove are very similar to corresponding bands of Sentinel-2, allowing them to be compared directly to one another. For the two SuperDove bands which do not correspond directly to any Sentinel-2 bands, we have found that averaging the TOA reflectances of the two closest Sentinel 2 bands (Sentinel's B3 and B4 bands for SuperDove's yellow band, and Sentinel's B2 and B3 bands for SuperDove's green_i band) provides an effective substitute. With these mappings and the bands that are directly comparable, calibration of Dove-R and SuperDove does not need to be limited to only calibration sites, allowing for collection of sufficient numbers of crossovers for each individual satellite, even given their small footprints.

For the time period being covered, a global search is conducted for all intersecting crossovers between Dove and Sentinel collects that occur within 2 hours of each other. To ensure a variety of ground cover conditions and a full range of reflectance values, all land masses are divided into a regular grid (Figure 8(a)), with each grid element having an equal probability of being searched. In addition, the time period covered by the update is divided into one week intervals and weeks are selected randomly, ensuring that there's no systematic bias based on what time period the imagery was collected during (Figure 8(b)). Scenes are filtered out if they have greater than ~10% cloud cover. The total number of Sentinel crossovers collected for each satellite is limited to 20,000, which is then randomly divided into two groups: one for the calibration update and one for subsequent validation. The calibration update is additionally validated using crossovers of RadCalNet sites and compared to ground truth data that those sites provide.

Figure 8: (a) Gridding used for global crossovers search. The colored grid elements indicate locations where the SuperDove satellite 2408 had at least one near-simultaneous crossover with Sentinel-2 during the first half of 2021 where the search was performed only until 20,000 likely crossovers were found. The spatial distribution reflects the random selection of tiles from the global grid. (b) Time distribution of the simultaneous crossovers shown in the grid. Gaps appear where 2408 and Sentinel-2 are out of phase with each other.

(a)

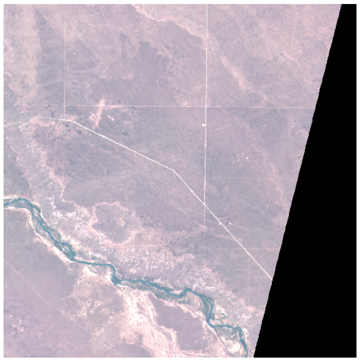
(b)

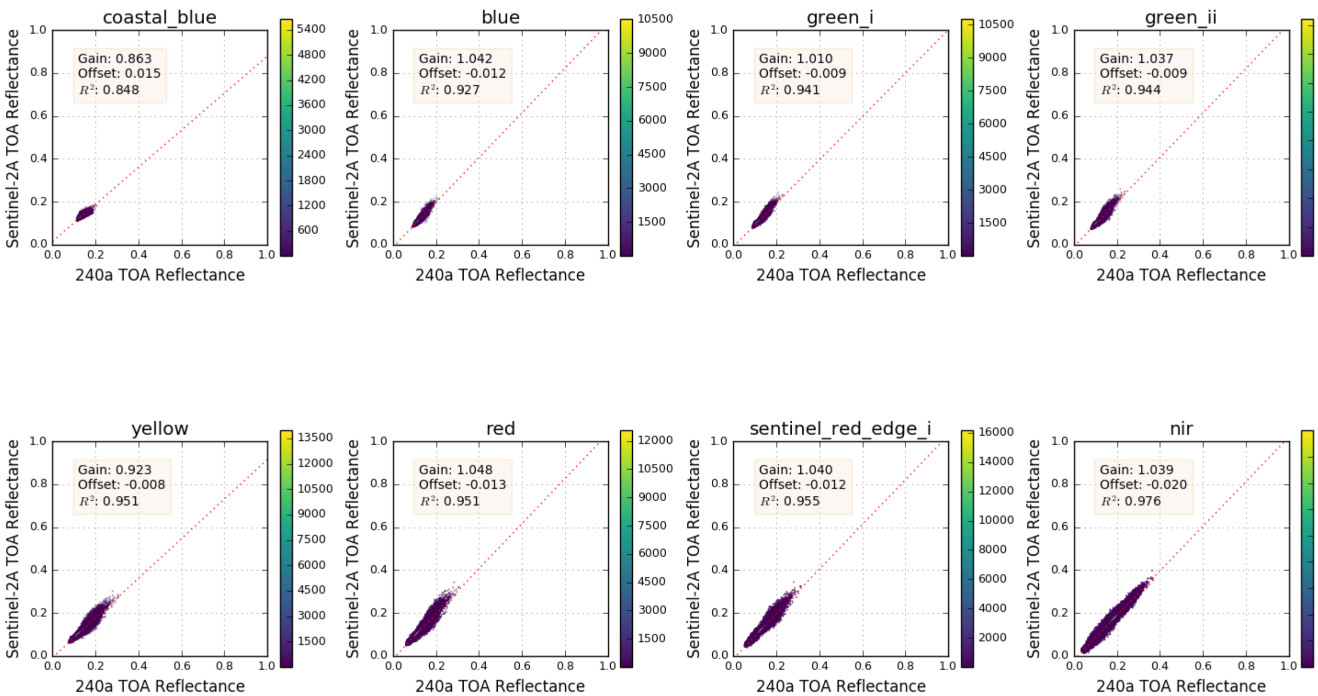


For each crossover pair between a Dove and Sentinel satellite, TOA reflectance tile products are generated at 20 m GSD and corresponding image pixels are analyzed and compared between the two images. Summary statistics (mean, median, mode, etc) are calculated and recorded. To determine a correction to apply for a calibration update, a linear fit to the scatter plot of the joint modes of all crossover pairs (Dove vs Sentinel) is derived for each Dove satellite. The reason for using the mode here rather than, say, the mean or median of the distribution, is because it is less sensitive to outliers caused by, for example, undetected clouds or cloud shadows that have moved between the times the Dove and Sentinel images were collected. Figure 9 shows an example of a single crossover's scatter plots showing SuperDove satellite 240a compared to Sentinel-2.

Figure 9: A single tile for a SuperDove crossover with Sentinel 2a. The SuperDove green_i and yellow bands are analyzed using an average of the nearest two surrounding Sentinel 2 band reflectances.

SuperDove 240a | **Sentinel-2A**





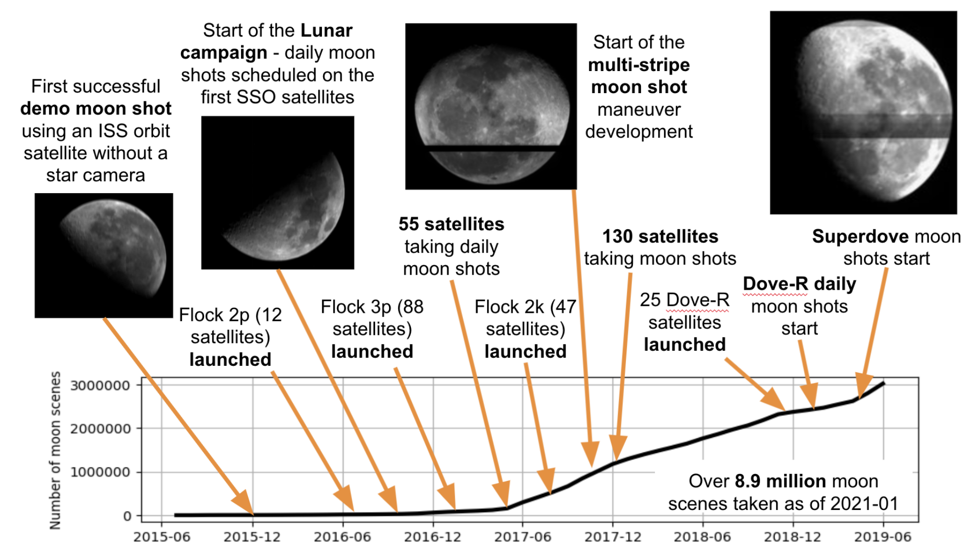
LUNAR MONITORING AND ADJUSTMENTS

ROLO MODEL

With a large fleet of Doves it is important that each satellite measures radiances that are consistent with all other satellites within the fleet, otherwise the usefulness of measured values that reflect, for example, crop health and allow monitoring change over time would be limited. To supplement direct calibration against Sentinel-2, Planet has conducted a separate campaign of collecting daily moon images for satellites in its Dove fleet. These images are compared to the ROLO model of the moon[6], which provides ~10% absolute and < 1% relative accuracy in radiance. The model is built from over 1000 moon images, each in 32 wavelengths, taken at a variety of selenographic longitude, latitude and phase angles. ROLO models the moon's full disk brightness using 328 coefficients, which along with the positions of the earth, moon and a satellite yields an expected reflectance value. That combined with the solar spectrum and the Dove's RSR yields a radiance which can be compared to the satellite's measured radiance.

Given its high relative accuracy, the ROLO model provides an effective way to improve consistency between the satellites within the Dove fleet. Since late 2016, Planet has been conducting a campaign of daily moon collects, with over 130 Dove Classics taking moon shots by late 2017 (Figure 10). Dove-R and SuperDove satellites were each added to the campaign soon after their respective launches. As of January 2021, over 8.9 million moon scenes have been collected.

Figure 10: Planet's lunar monitoring campaign



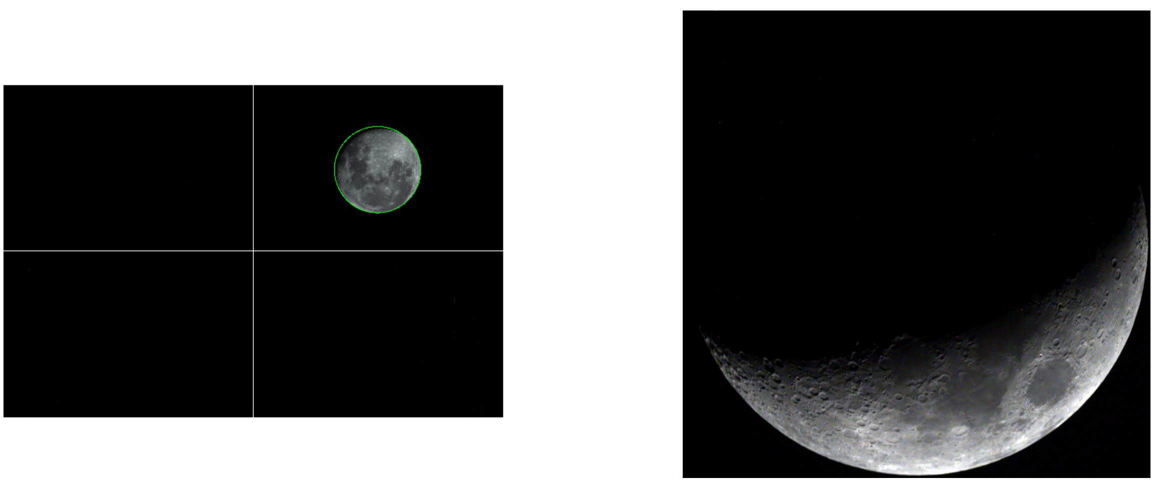
[6] H. H. Kieffer and T. C. Stone, "The spectral irradiance of the Moon," The Astronomical Journal, vol. 129, no. 6, p. 2887, 2005

Dove satellites begin collecting moon images shortly after launch as part of the commissioning process. During this time, each satellite is maneuvered to point towards the Moon through the full range of the lunar cycle, allowing for studies of varying response ranges. A full cycle of moon images are taken during the first available lunar cycle after launch to confirm normative operation. Subsequent monitoring maneuvers are executed at low, medium and high moon phases for the life of the satellite. This provides an effective exposure to a "constant" illumination source with no atmospheric interference that is useful for calibration, validation and general checks on the health of each satellite.

ANALYSIS AND ADJUSTMENTS

The detailed procedure for collection and analysis of moon images is dependent on the sensor design, and therefore differs somewhat for each Planet Dove satellite generation. Dove Classic sensors have a two-stripe, 4-tap design that allows each tap to contain a complete image of the moon. Each stripe has a bayer mask design, with RGB on the upper stripe and NIR on the bottom. When collecting moon images, a specific maneuver was designed to focus the moon at the center of each tap, with multiple images captured for each maneuver. Figure 11 illustrates an example of one such moon collect. Each image provides complete data for either the three RGB spectral bands or the single NIR band.

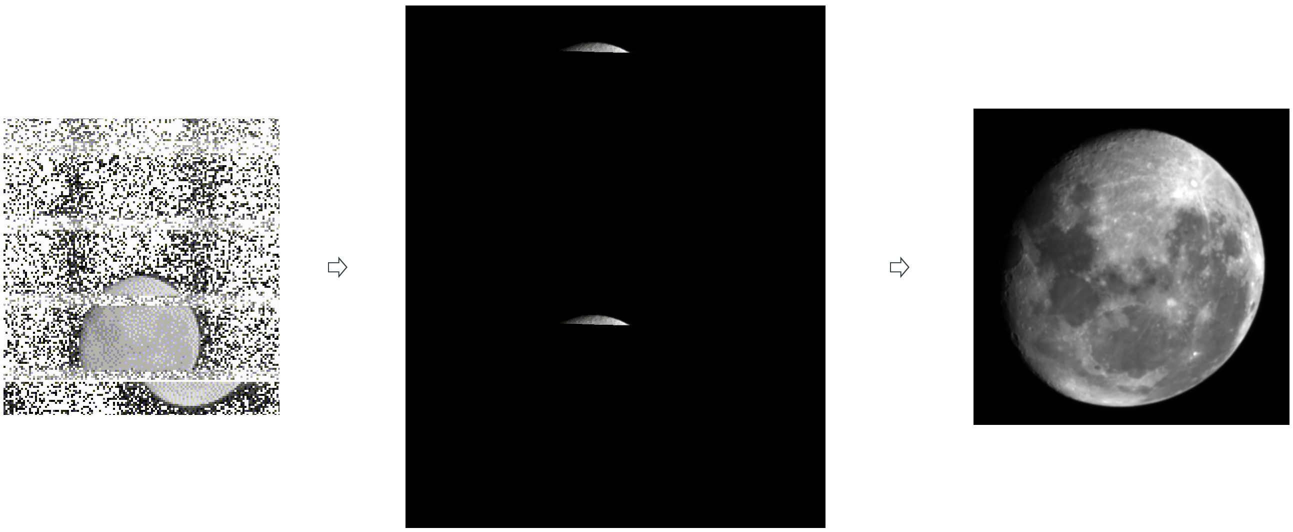
Figure 11: (a) Illustration of a single moon collect maneuver for a Dove Classic. (b) A complete set of moon images covering all phases during a month.



(a) (b)

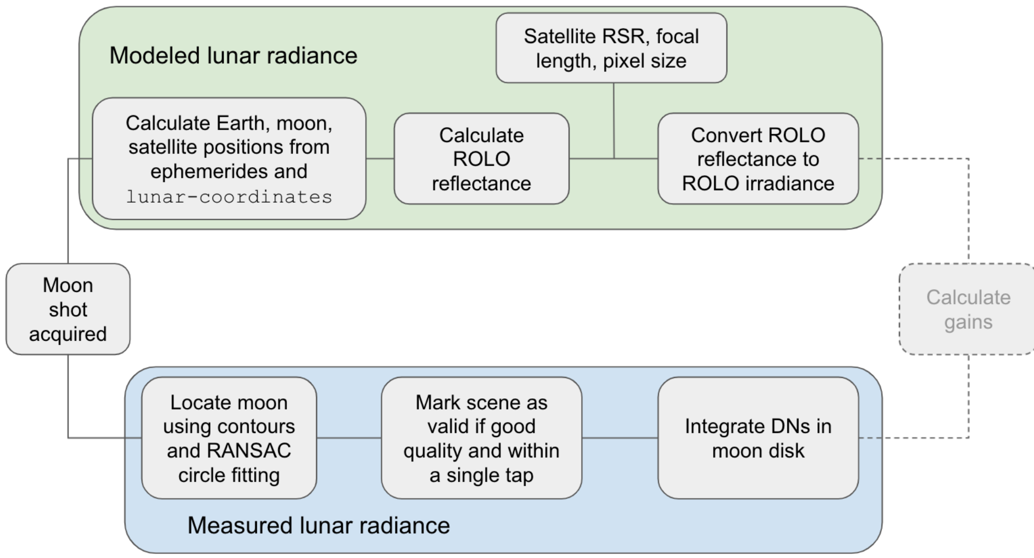
The sensor stripes for Dove-R (4-stripe) and SuperDove (8-stripe) are too narrow to allow a full moon image to be contained within a single stripe, requiring a different procedure than that for Dove Classics. For these sensors, lunar images are collected in a single pass, registered and then portions combined to create a full moon disk for each sensor band, which can then be used to compare to the ROLO model (Figure 12).

Figure 12: Illustration of the process by which Dove-R and SuperDove satellite moon images are reconstructed.



Once lunar images are collected, reconstructed, stored and analyzed for determining the measured lunar radiance, the ROLO model radiance is calculated based on the relative geometry of the Earth, moon and satellite at the time images were collected (Figure 13).

Figure 13: Flowchart illustrating the general process of analyzing collected moon images.



Given the measured radiances for each moon image collected and the expected radiances calculated from the ROLO model, deviations from the model are used for both monitoring the health of Planet's satellites and for measuring small differences in the responses of each satellite compared to all the others within the same generation. The former is used when making decisions on when to end-of-life older satellites, while the latter is used to improve consistency within the fleet of Planet Doves by applying small relative adjustments as part of the calibration process.

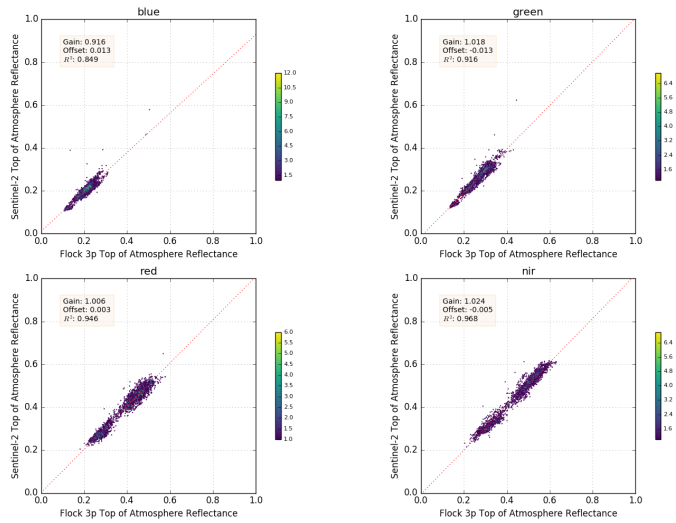
EXAMPLE CALIBRATION RESULTS

DOVE CLASSIC

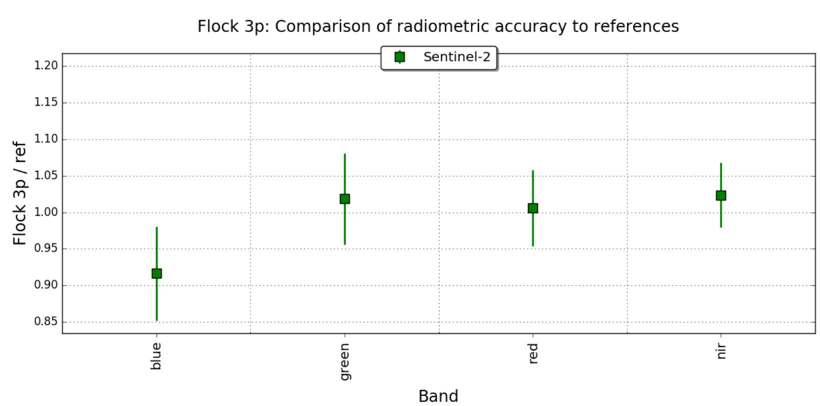
A calibration update was performed for Dove Classic satellites using data collected from January 1 to June 30 of 2021. Calibration is performed per satellite Flock to ensure consistency within a build when compared to Sentinel 2. For Planet's Flock 3p satellites, the last Dove Classics to be launched, there were approximately 3500 simultaneous crossovers over the calibration sites within a two hour crossover window of Sentinel 2 for this time period that also met specified quality constraints. The scatter plot comparisons to Sentinel 2 for each band are shown in Figure 14 for this dataset along with summary statistics.

Figure 14: Flock 3p Doves compared to Sentinel 2 over a 6 month period for simultaneous crossover scenes over calibration sites. (a) Scatter plots of the modes from crossover samples, along with the (b) per-band accuracies and (c) sample statistics.

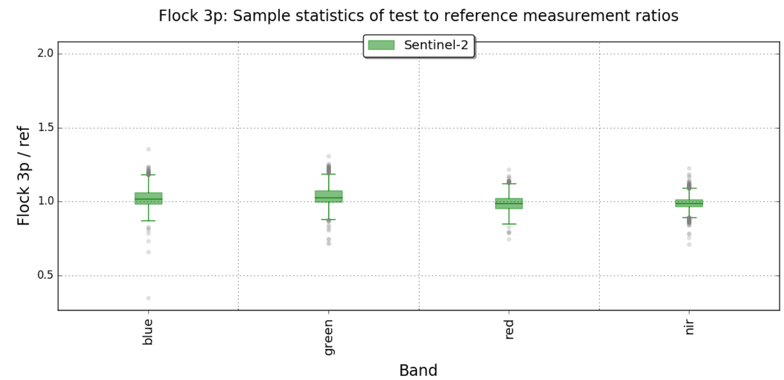
(a)



(b)

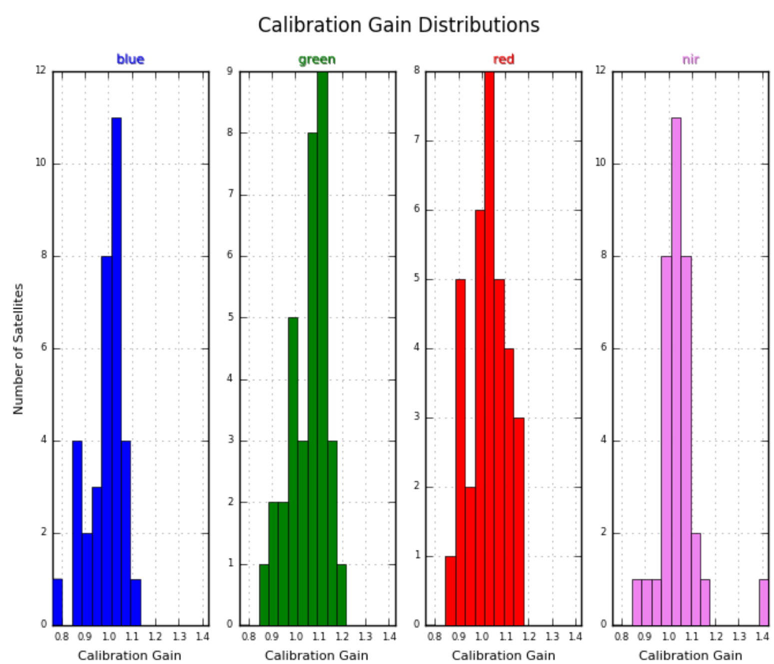


(c)



These crossover results were combined with lunar trending data for each satellite to derive the per-satellite corrections. Not all Flock 3p satellites had sufficient quality data to derive a lunar adjustment factor. For those that didn't, the baseline flock wide correction was used. Figure 15 shows the distribution of gain correction factors that were applied to Flock 3p satellites. These new calibrations became effective at the end of Q3 of 2021.

Figure 15: Distribution of calibration gain adjustments applied to Flock 3p satellites. Calibration offsets are fixed to the values determined during commissioning.

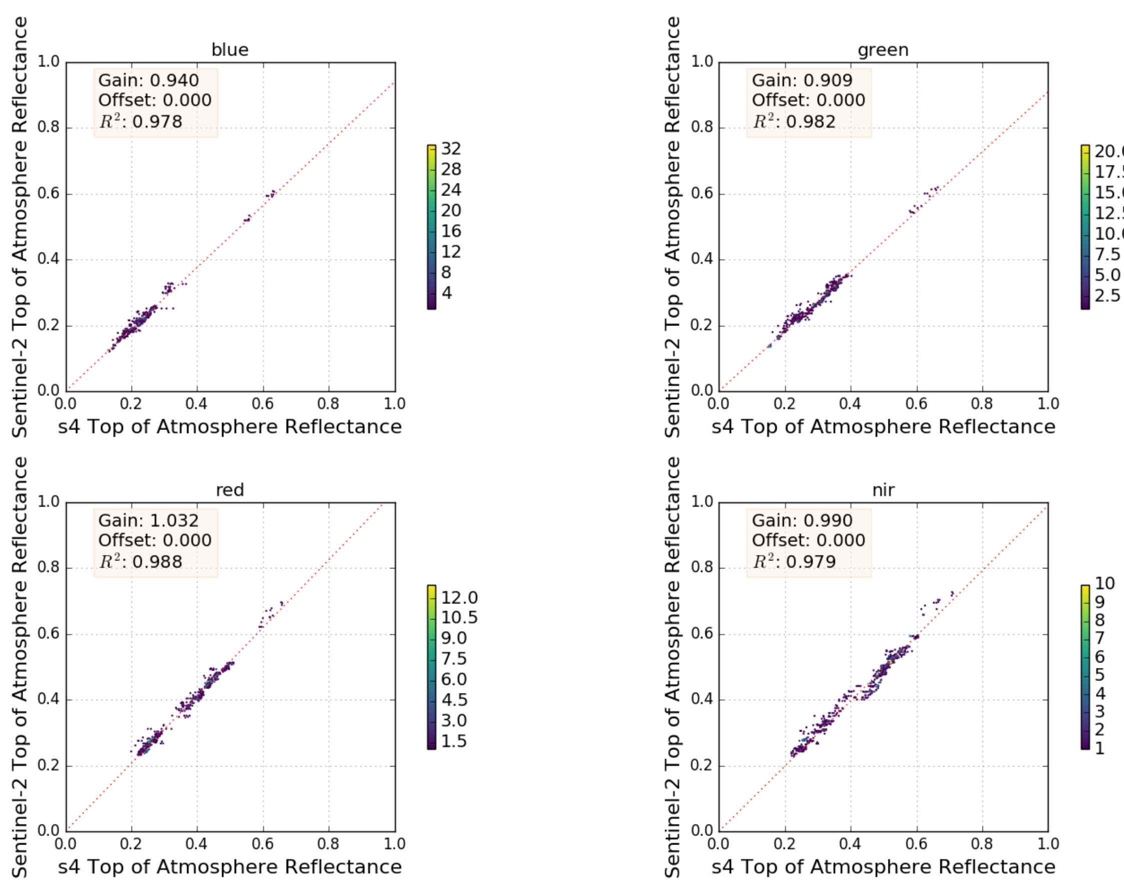


SKYSAT

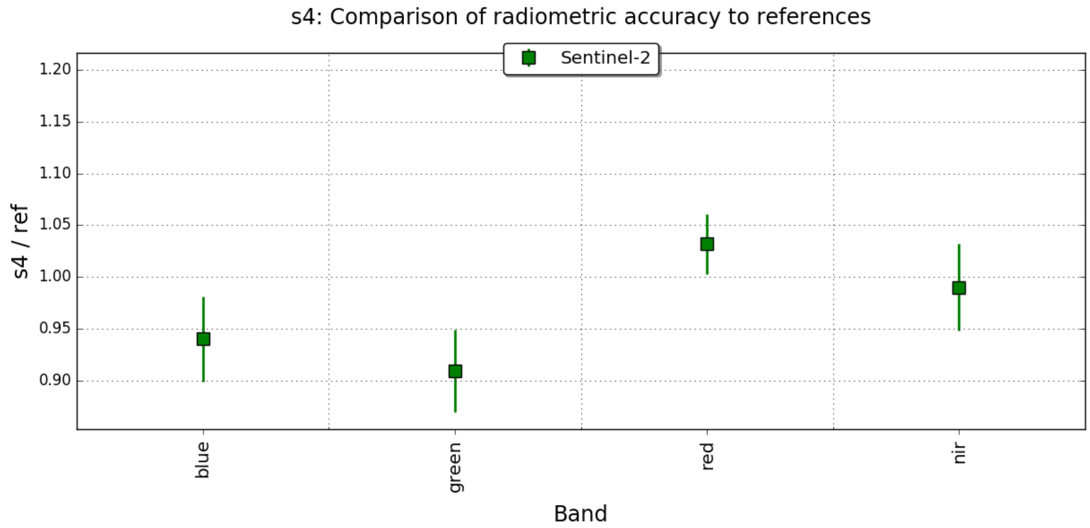
Updated SkySat calibration coefficients for block 1 and 2 SkySats were calculated using data collected from September 15th 2020 until December 1st 2021. September 15th 2020 was chosen as it marked the last time the SkySat coefficients had been updated using the vicarious calibration method. Figures 16 and 17 show the scatter plot comparisons to Sentinel 2 for the block 1 SkySat s4 sensor 2 and the block 2 SkySat s111 sensor 2. There were approximately 1000 simultaneous crossover SkySat 4 sensor 2 scenes that met quality constraints over the calibration sites within a three hour crossover window of Sentinel 2 for this time period and s111 had approximately 800 crossover scenes.

Figure 16: Collection of all joint modes and median values of simultaneous crossover scenes SkySat s4 sensor 2 and Sentinel 2 over calibration site for the time period of September 2020 - September 2021. (a) Scatter plots, (b) per band accuracies and (c) sample statistics.

(a)



(b)



(c)

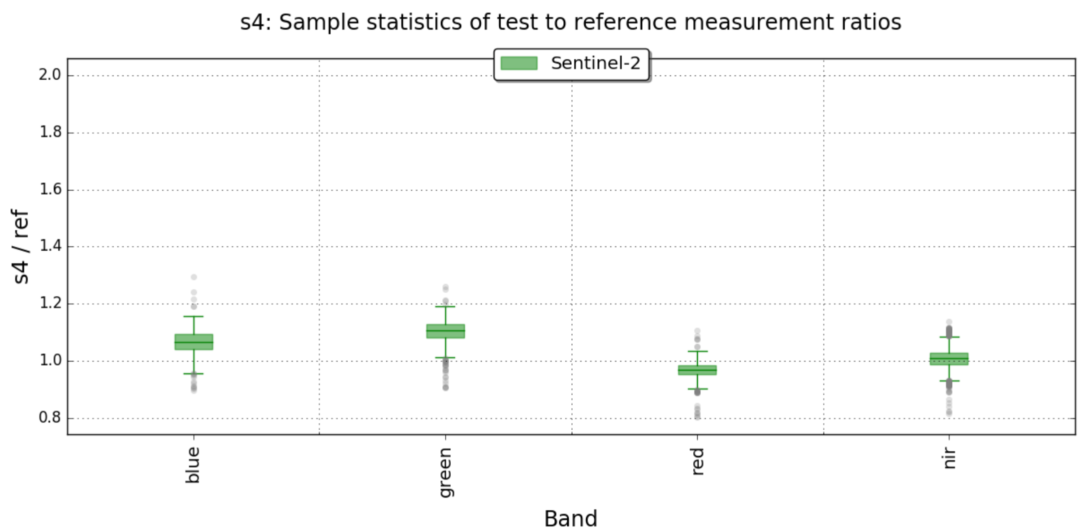
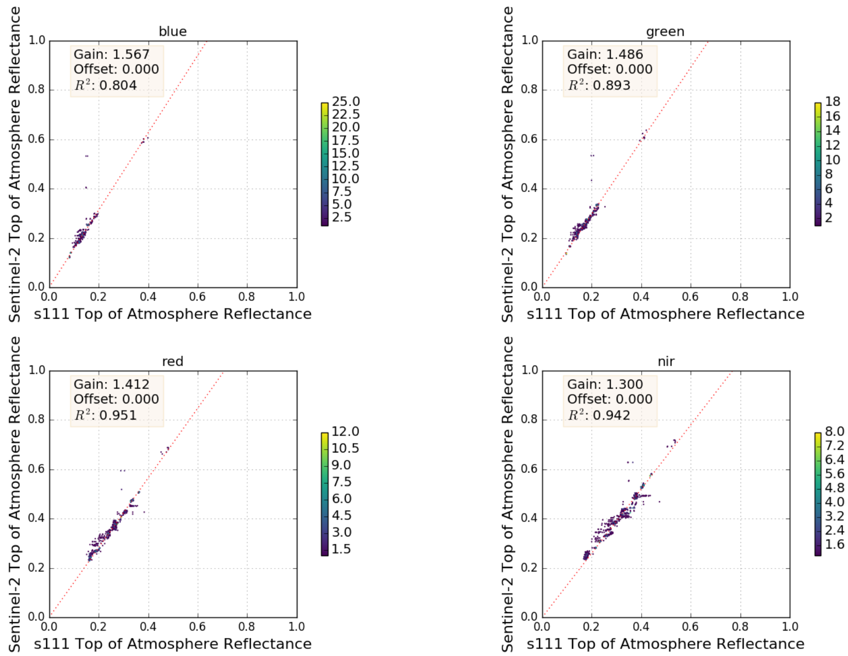
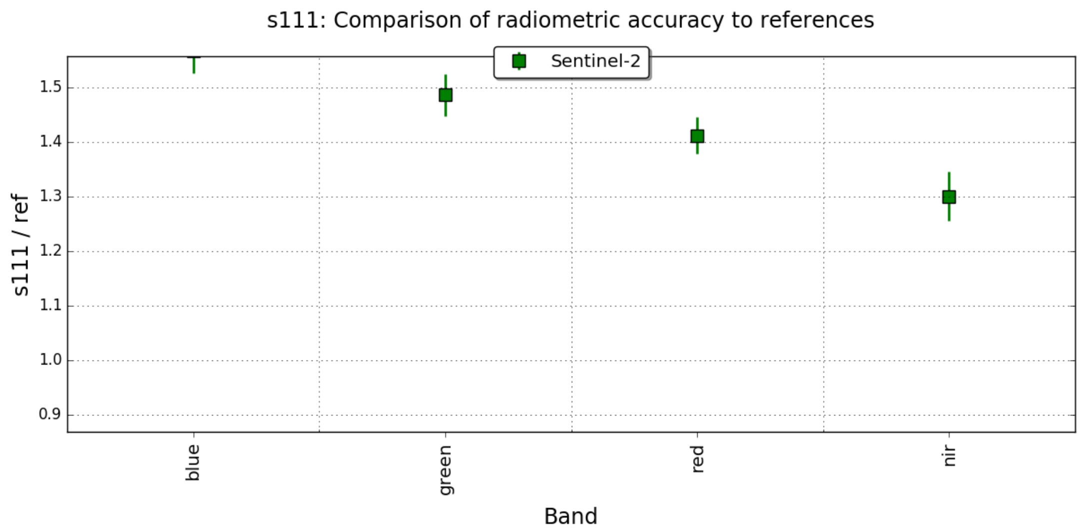


Figure 17: Collection of all joint modes and median values for the time period of September 2020 - September 2021 for simultaneous crossover scenes SkySat s111 sensor 2 and Sentinel 2 over calibration sites. (a) Scatter plots, (b) per band accuracies and (c) sample statistics

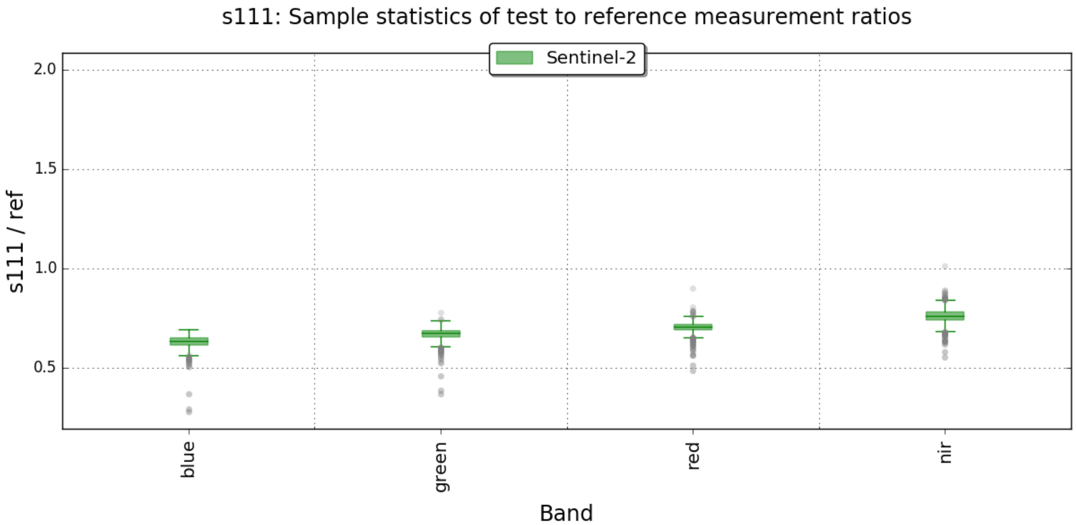
(a)


blue
Gain: 1.567
Offset: 0.000
R^2: 0.804
green
Gain: 1.486
Offset: 0.000
R^2: 0.893
red
Gain: 1.412
Offset: 0.000
R^2: 0.951
nir
Gain: 1.300
Offset: 0.000
R^2: 0.942
Sentinel-2 Top of Atmosphere Reflectance
s111 Top of Atmosphere Reflectance

(b)


s111: Comparison of radiometric accuracy to references
Sentinel-2
s111 / ref
blue
green
red
nir
Band

(c)

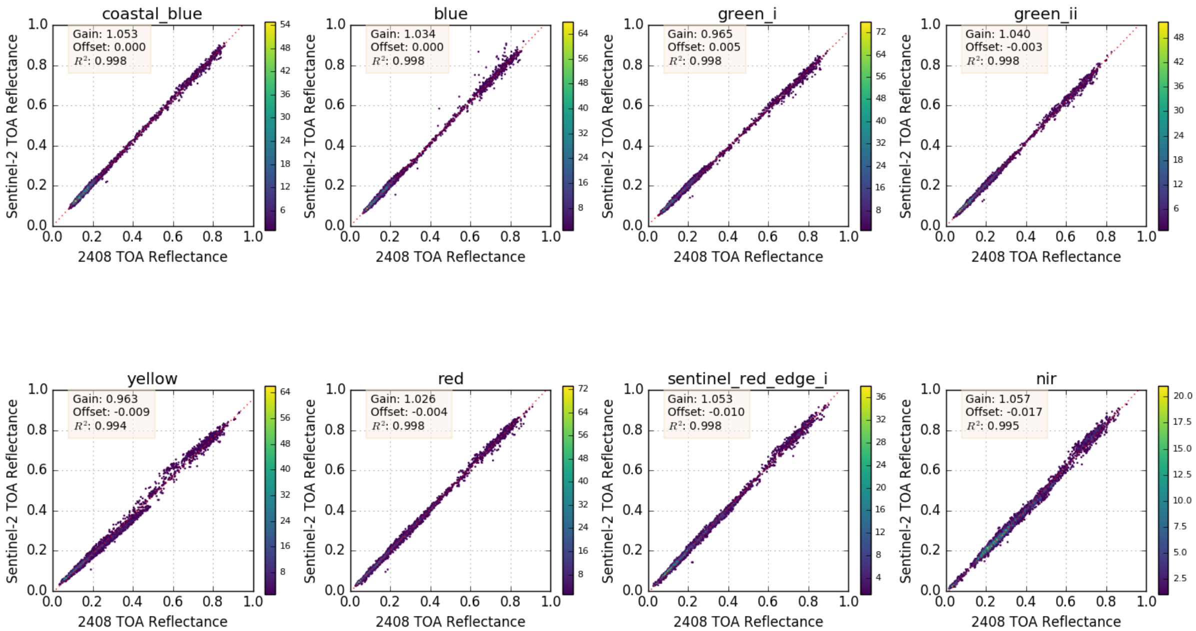


SUPERDOVE

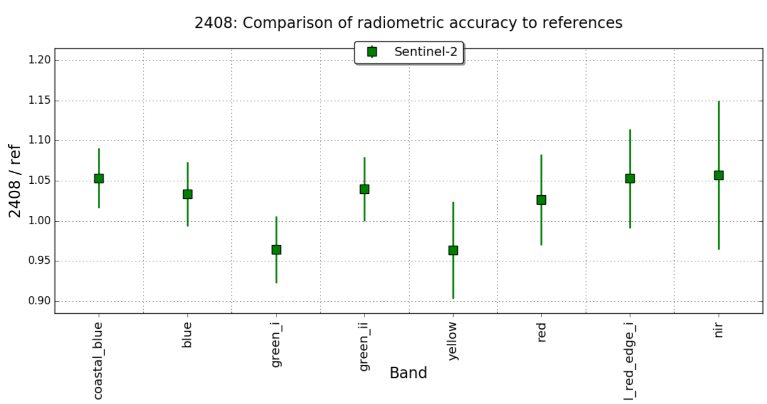
A calibration update was performed for SuperDove satellites using data collected from January 1 to June 30 of 2021. Simultaneous crossovers with Sentinel-2 were searched for within predefined tiles covering all Earth's land masses. One week time periods and individual tiles were selected randomly until either all SuperDove satellites active during that period had at least 20,000 total crossovers with Sentinel-2 or there were no more tiles to search. In all, 76 SuperDove satellites are represented in the calibrations covering ~1.5 million SuperDove-Sentinel 2 crossovers pairs. The scatter plot comparisons to Sentinel 2 for each band after excluding all poor quality crossovers, such as those with extensive cloud cover, are shown in Figure 18 for this dataset along with summary statistics.

Figure 18: SuperDove satellite 2408 compared to Sentinel 2 over a 6 month period for global simultaneous crossover scenes. (a) Scatter plots of the modes from crossover samples, along with the (b) per-band accuracies and (c) sample statistics.

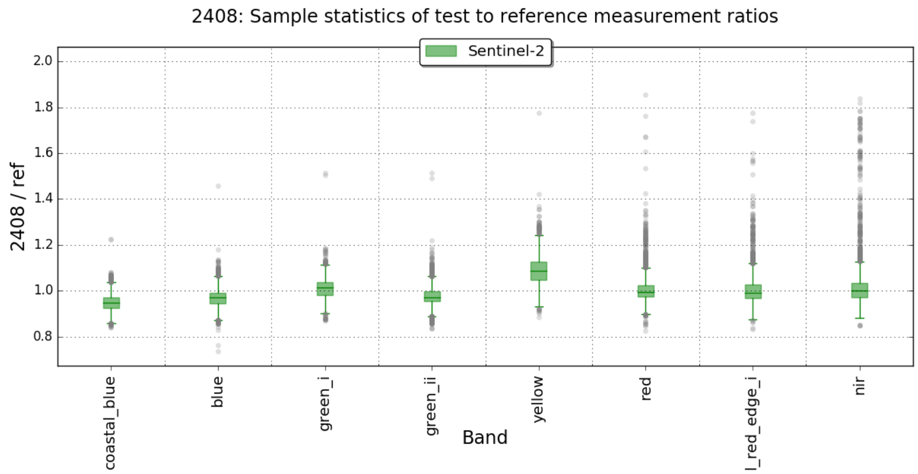
(a)


coastal_blue
Gain: 1.053
Offset: 0.000
R^2: 0.998
blue
Gain: 1.034
Offset: 0.000
R^2: 0.998
green_i
Gain: 0.965
Offset: 0.005
R^2: 0.998
green_ii
Gain: 1.040
Offset: -0.003
R^2: 0.998
yellow
Gain: 0.963
Offset: -0.009
R^2: 0.994
red
Gain: 1.026
Offset: -0.004
R^2: 0.998
sentinel_red_edge_i
Gain: 1.053
Offset: -0.010
R^2: 0.998
nir
Gain: 1.057
Offset: -0.017
R^2: 0.995
Sentinel-2 TOA Reflectance
2408 TOA Reflectance

(b)

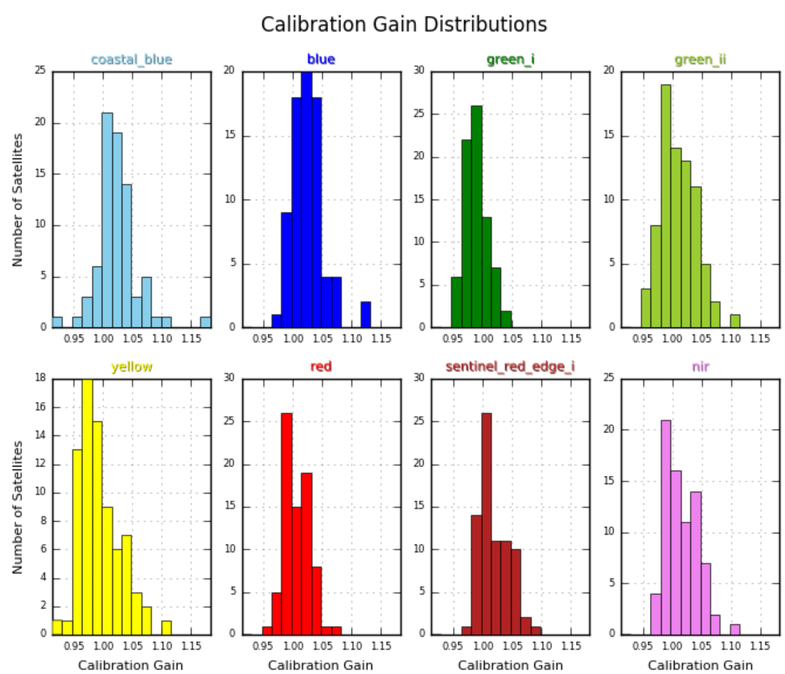

2408: Comparison of radiometric accuracy to references
Sentinel-2
2408 / ref
Band
coastal_blue
blue
green_i
green_ii
yellow
red
l_red_edge_i
nir

(c)



The calibration gains derived from these comparisons to Sentinel-2 were used to generate corrections to the calibrations that became effective at the end of Q3 of 2021. Figure 19 shows the distribution of calibration gain updates for all the SuperDove satellites within this update.

Figure 19: Distribution of calibration gain adjustments applied to SuperDove satellites. Calibration offsets are fixed to 0.



CALIBRATION VALIDATION

RADCALNET

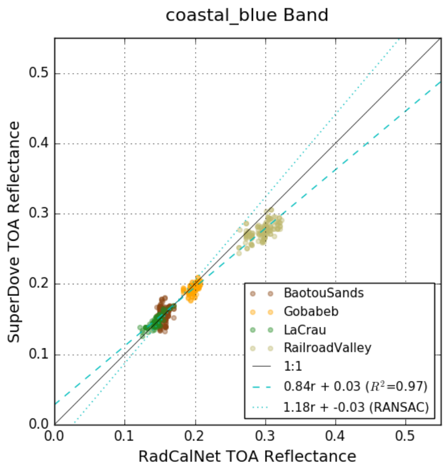
Using independent validation datasets from the RadCalNet[7] automated calibration sites, a vicarious approach is utilized to assess the radiometric accuracy for satellites after they received calibration updates. RadCalNet provides SI-traceable Top-of-Atmosphere (TOA) spectrally-resolved reflectances and captures spectral data at 30 minute intervals during daylight hours each day. Images are processed to TOA reflectance for comparison to the RadCalNet references. The RadCalNet data provides TOA reflectance at 10 nm spectral resolution and is processed to extract the equivalent Planetscope and SkySat reflectances by convolving the sensor RSR with the spectrally resolved reflectances. This process is applied to both Dove and SkySat satellites from generated products using the calibration updates applied.

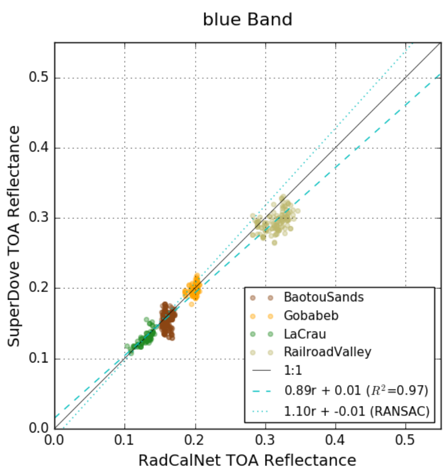
For each of the Planet Dove generations and for SkySats as a group, products are generated for crossovers of the RadCalNet sites for cloud free conditions at each site for the time period of the calibration update. TOA reflectance products are generated using updated calibrations and then compared to the RadCalNet data for each site's defined sampling area and for the closest in time recorded same day measurement. Figure 20 shows SuperDove scatter plot comparisons for the January - September 2021 time period illustrating the comparison being made for the blue, green, red and nir sensor bands.

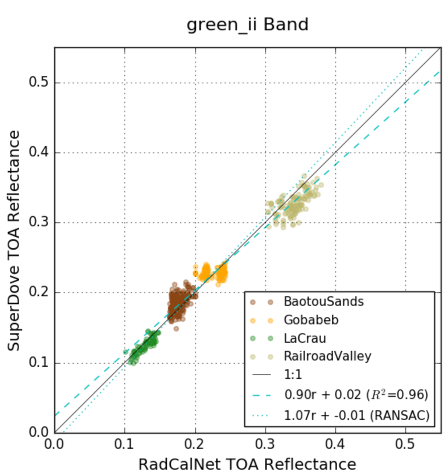
Figure 20: Example validation: SuperDove TOA reflectance compared to RadCalNet calibration site data for the Sentinel-2 spectral bands. The corresponding results for Sentinel-2 TOA reflectance, collected over the same time period, are shown on the right for comparison.

[7] https://www.radcalnet.org/#!/

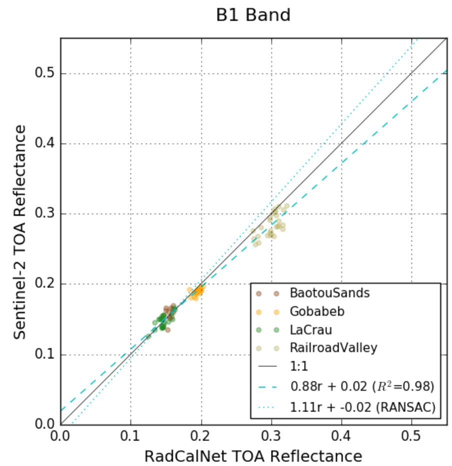
Planet

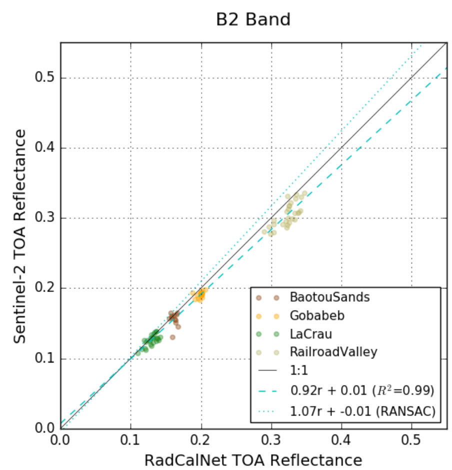


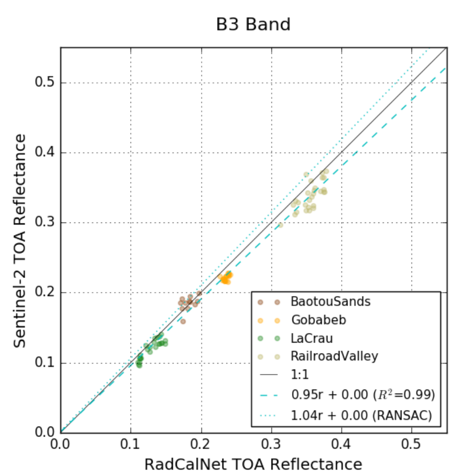




Sentinel-2







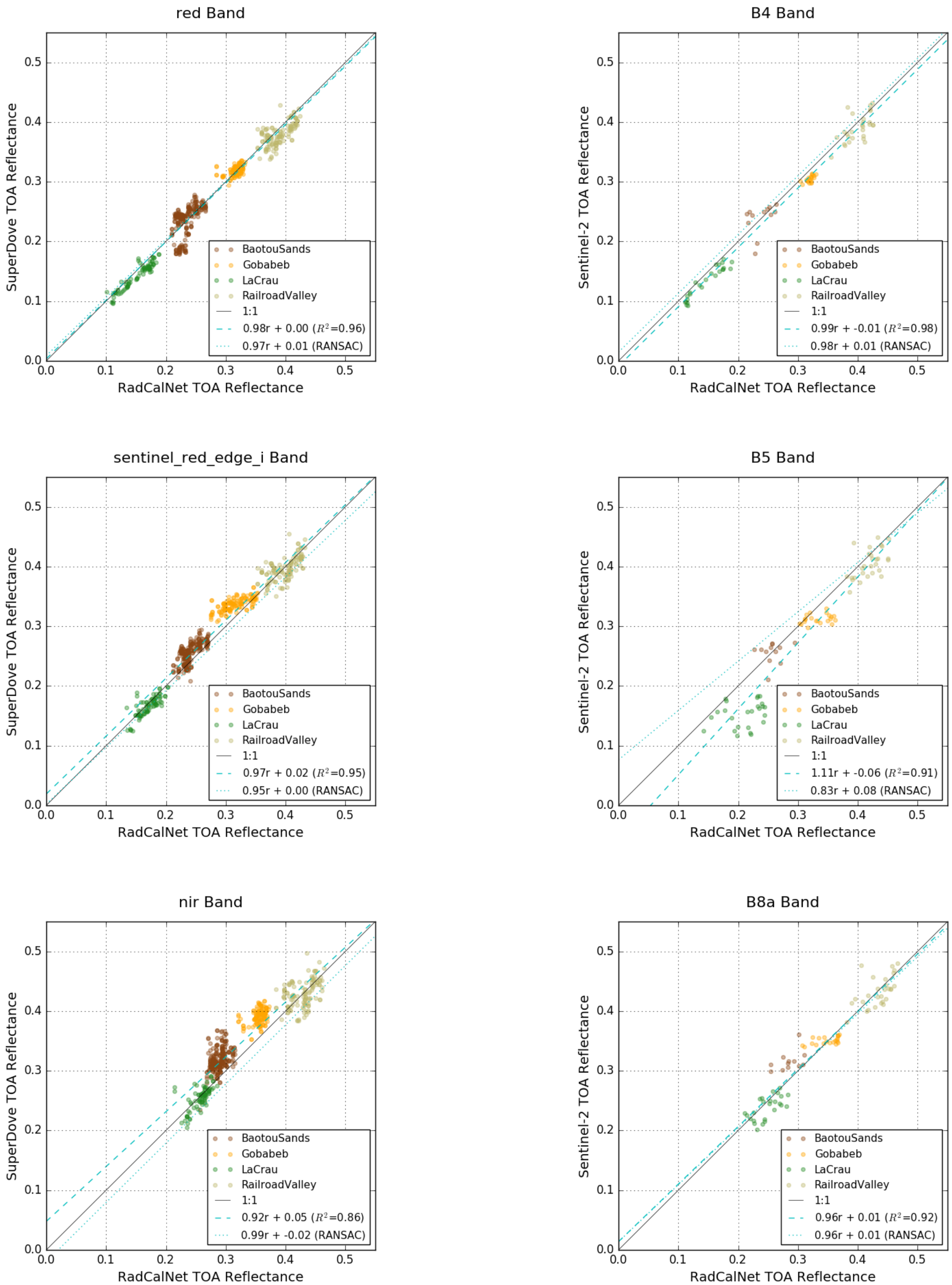
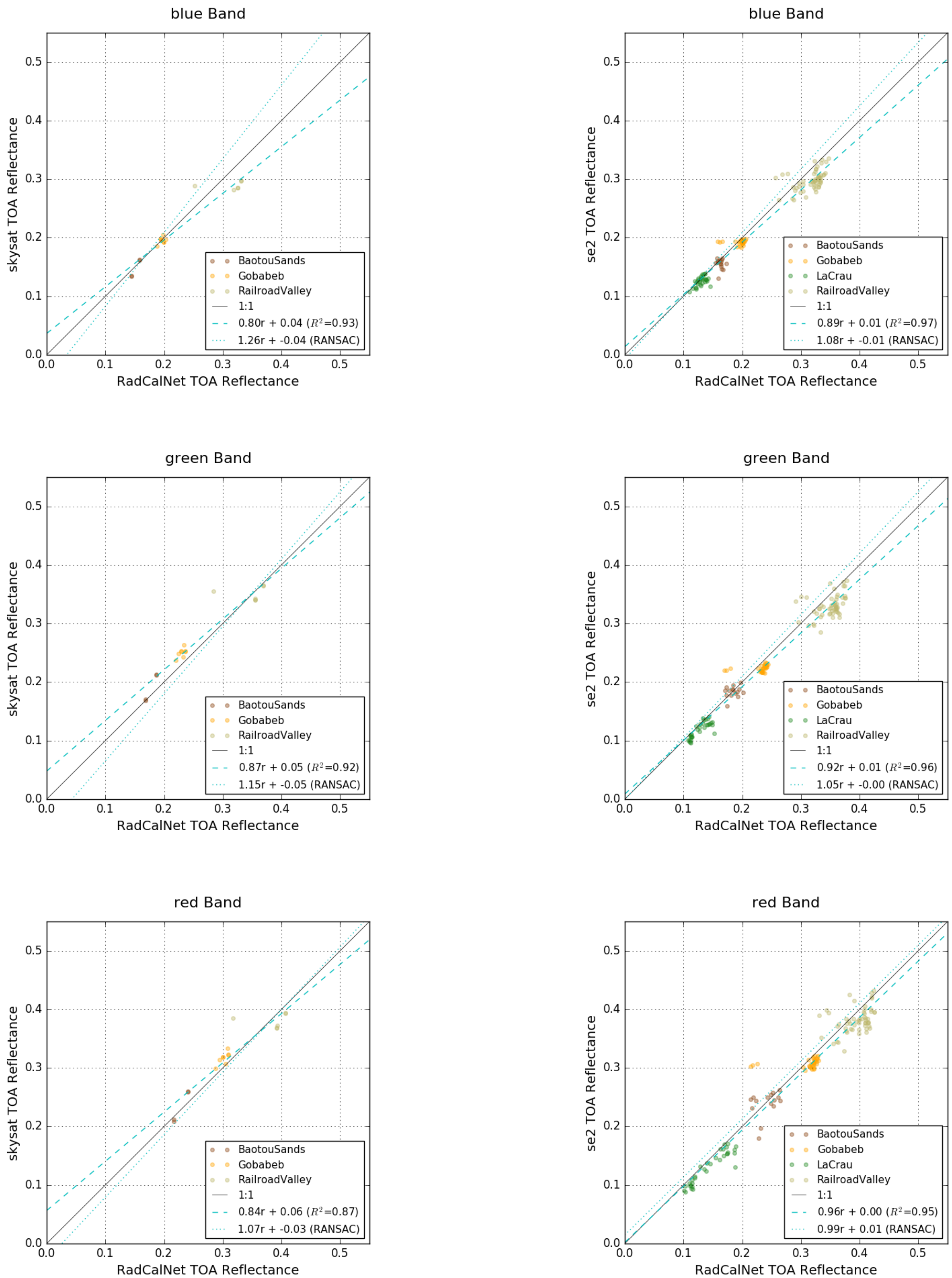
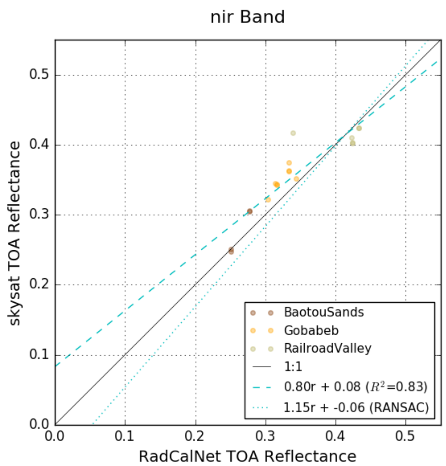

red Band
SuperDove TOA Reflectance
RadCalNet TOA Reflectance
BaotouSands
Gobabeb
LaCrau
RailroadValley
1:1
0.98r + 0.00 (R^2=0.96)
0.97r + 0.01 (RANSAC)
B4 Band
Sentinel-2 TOA Reflectance
RadCalNet TOA Reflectance
BaotouSands
Gobabeb
LaCrau
RailroadValley
1:1
0.99r + -0.01 (R^2=0.98)
0.98r + 0.01 (RANSAC)
sentinel_red_edge_i Band
SuperDove TOA Reflectance
RadCalNet TOA Reflectance
BaotouSands
Gobabeb
LaCrau
RailroadValley
1:1
0.97r + 0.02 (R^2=0.95)
0.95r + 0.00 (RANSAC)
B5 Band
Sentinel-2 TOA Reflectance
RadCalNet TOA Reflectance
BaotouSands
Gobabeb
LaCrau
RailroadValley
1:1
1.11r + -0.06 (R^2=0.91)
0.83r + 0.08 (RANSAC)
nir Band
SuperDove TOA Reflectance
RadCalNet TOA Reflectance
BaotouSands
Gobabeb
LaCrau
RailroadValley
1:1
0.92r + 0.05 (R^2=0.86)
0.99r + -0.02 (RANSAC)
B8a Band
Sentinel-2 TOA Reflectance
RadCalNet TOA Reflectance
BaotouSands
Gobabeb
LaCrau
RailroadValley
1:1
0.96r + 0.01 (R^2=0.92)
0.96r + 0.01 (RANSAC)

Figure 21: Example validation: SkySat s4 sensor 2 TOA reflectance compared to RadCalNet calibration site data for the Sentinel-2 spectral bands. The corresponding results for Sentinel-2 TOA reflectance, collected over the same time period, are shown on the right for comparison.


blue Band
skysat TOA Reflectance
RadCalNet TOA Reflectance
BaotouSands
Gobabeb
RailroadValley
1:1
0.80r + 0.04 (R^2=0.93)
1.26r + -0.04 (RANSAC)
blue Band
se2 TOA Reflectance
RadCalNet TOA Reflectance
BaotouSands
Gobabeb
LaCrau
RailroadValley
1:1
0.89r + 0.01 (R^2=0.97)
1.08r + -0.01 (RANSAC)
green Band
skysat TOA Reflectance
RadCalNet TOA Reflectance
BaotouSands
Gobabeb
RailroadValley
1:1
0.87r + 0.05 (R^2=0.92)
1.15r + -0.05 (RANSAC)
green Band
se2 TOA Reflectance
RadCalNet TOA Reflectance
BaotouSands
Gobabeb
LaCrau
RailroadValley
1:1
0.92r + 0.01 (R^2=0.96)
1.05r + -0.00 (RANSAC)
red Band
skysat TOA Reflectance
RadCalNet TOA Reflectance
BaotouSands
Gobabeb
RailroadValley
1:1
0.84r + 0.06 (R^2=0.87)
1.07r + -0.03 (RANSAC)
red Band
se2 TOA Reflectance
RadCalNet TOA Reflectance
BaotouSands
Gobabeb
LaCrau
RailroadValley
1:1
0.96r + 0.00 (R^2=0.95)
0.99r + 0.01 (RANSAC)



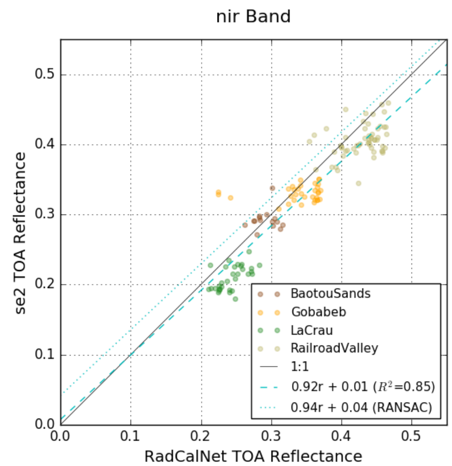


Table 2: RadCalNet validation results for Dove Classic. From 36 crossovers for the January - September 2021 calibration period covering the Gobabeb, LaCrau, and Railroad Valley sites.

Dove Classic

Band	Absolute Accuracy %	Precision %	Uncertainty % (1-sigma)
blue	-6.08	7.44	9.61
green	5.20	8.48	9.94
red	8.88	8.88	12.56
nir	4.85	8.37	9.67

Table 3: RadCalNet validation results for Dove-R. From 15 crossovers for the January - September 2021 calibration period covering the LaCrau and Railroad Valley sites.

Dove-R

Band	Absolute Accuracy %	Precision %	Uncertainty % (1-sigma)
blue	-5.03	5.01	7.10
green	-3.34	3.30	4.70
red	-4.56	1.08	4.69
nir	-1.45	5.13	5.33

Table 4: RadCalNet validation results for SuperDove. From 125 crossovers for the January - September 2021 calibration period covering the Baotou, Gobabeb, LaCrau and Railroad Valley sites.

Dove-R

Band	Absolute Accuracy %	Precision %	Uncertainty % (1-sigma)
coastal_blue	-0.84	5.75	5.81
blue	-2.67	5.84	6.43
green_i	-6.94	5.54	8.88
green_ii	1.49	6.99	7.14
yellow	2.46	6.93	7.35
red	-0.74	7.01	7.05
sentinel_red_edge_i	3.91	6.57	7.65
nir	6.66	7.54	10.06

Table 5: Example RadCalNet validation results for SkySat s4 sensor 2 from 18 crossover scenes for the September 2020 - September 2021 calibration period covering the Baotou Sands, Gobabeb and Railroad Valley sites.

Dove-R

Band	Absolute Accuracy %	Precision %	Uncertainty % (1-sigma)
blue	-2.99	6.93	7.55
green	6.20	7.65	9.85
red	2.63	7.28	8.82
nir	4.98	6.82	7.31

GLOBAL CROSSOVERS VALIDATION DATASET

In addition to validating against RadCalNet, Dove-R and SuperDove satellite calibrations are also validated using the half of the crossovers dataset set aside for validation purposes, representing one half of the total number of crossovers. In this case the TOA reflectance products are analyzed with the calibration updates applied and the analysis repeated for the validation dataset. Otherwise the analysis process follows that for the calibration stage and covers the same time period. Results for a single SuperDove satellite, 2408, are shown in Table 5 and Figure 21.

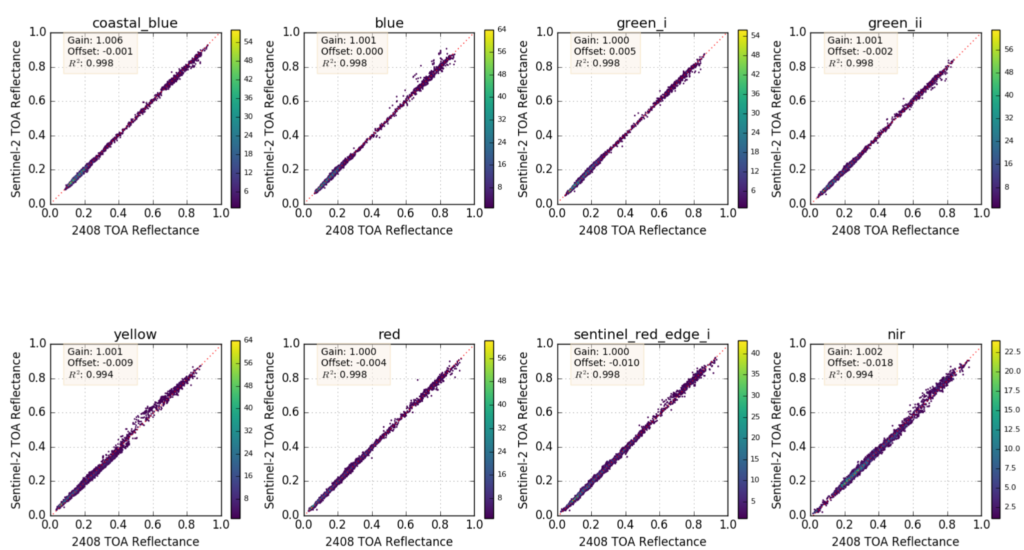
Table 5: SuperDove validation results for satellite 2408 based on an independent set of crossovers from the January - June 2021 calibration time period with the calibration updates applied.

Dove-R

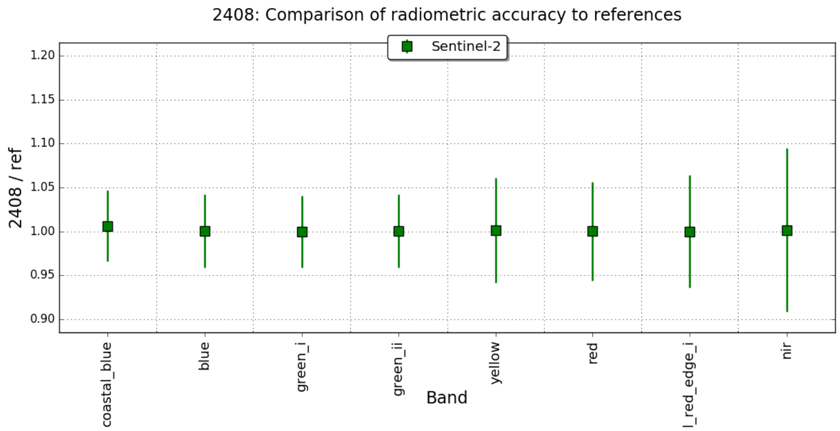
Band	Gain	Offset	Uncertainty %	R-Squared Value
coastal_blue	1.0064	-0.0005	4.01	0.998
blue	1.0005	-0.0002	4.19	0.998
green_i	0.9999	-0.0052	4.09	0.998
green_ii	1.0007	-0.0025	4.18	0.998
yellow	1.0013	-0.0092	5.95	0.994
red	1.0001	-0.0043	5.64	0.998
sentinel_red_edge_i	1.0000	-0.0101	6.43	0.998
nir	1.0016	-0.0177	9.31	0.994

Figure 21: SuperDove validation based on an independent set of crossovers from the January - June 2021 calibration time period with the calibration updates applied. (a) Scatter plots of the modes from crossover samples, along with the (b) per-band accuracies and (c) sample statistics.

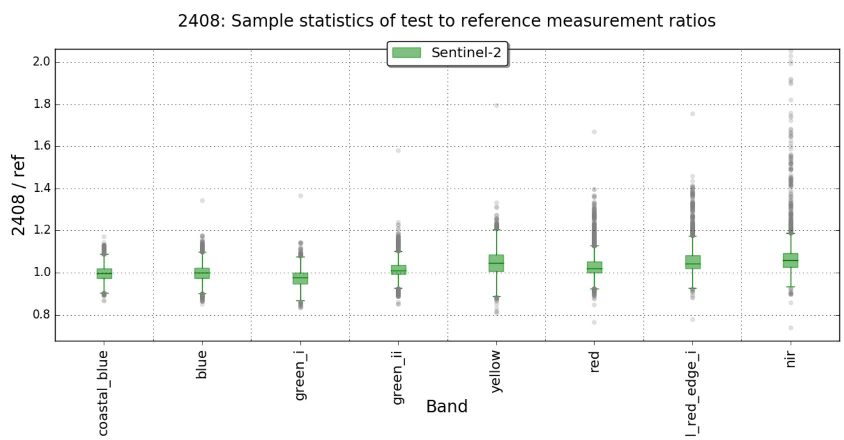
(a)



(b)



(c)



CONCLUSIONS

Providing daily imagery of the entire surface of the Earth at medium and high resolution requires a large fleet of satellites that span both an evolution of capability over multiple design generations, as well as multiple launches of "flocks" of a given design used to replace older satellites. For any analysis requiring an absolute knowledge of the radiances measured by these satellites, accurate and consistent calibration of all of the satellites is a necessity. Coupled with the inherent difficulties in scaling any processes for managing a large, diverse fleet of satellites, ensuring accurate, consistent calibrations across Planet's entire fleet is challenging.

In this white paper we have shown how Planet addresses these challenges by calibrating against a single reference source, Sentinel-2, for all our satellites, and by automating both the calibration/validation process as well as the monitoring of satellite health between calibration updates. Due to close similarity between Dove-R and SuperDove sensor band responses with Sentinel-2, we are able to utilize any simultaneous crossovers anywhere in the world, while SkySats and the older Dove Classic satellites rely on crossovers over well-characterized calibration sites. Any improvement in the characterization of these sites and the addition of more covering a wider dynamic range of reflectances would be beneficial to our calibrations. In all cases we rely on RadCalNet for validation of the calibrations, with supplemental validation through independent sets of global crossovers for Dove-R and SuperDove. Additional RadCalNet sites, particularly ones at different points in the dynamic range from the existing ones, would increase the number of crossovers included in the validation and help reduce the uncertainty in our results.

For monitoring of satellite health, regular collection of moon images and comparison to the ROLO model allow us to apply small, intra-flock adjustments to improve fleet consistency and to react to longer term trends in sensor response. Future improvements in the ROLO model may make it possible to use it directly as an independent calibration source. Table 6 summarizes the calibration approach for PLanet's current fleet of satellites.

Table 6: Summary of on orbit calibration process for the Planet satellite fleet.

Process	Dove Classic*	Dove-R*	SuperDove	SkySat**
Simultaneous crossovers for on orbit calibration	With Sentinel-2 over calibration sites	With Sentinel-2 globally	With Sentinel-2 globally	With Sentinel-2 over calibration sites
Lunar monitoring	Since late 2016	Since late 2018	Since early 2019	None
Reported validation***	Comparison with RadCalNet data	Comparison with RadCalNet data	Comparison with RadCalNet data	Comparison with RadCalNet data

* Updated radiometric calibration with the release of the PSScene product (late 2021)
** Updated radiometric calibration to be release later
*** For L1 Image Quality reports from Q3 2021 onwards

The methodology covered here is now used for all Planet Dove satellites, including recalibration being applied to all imagery available as PSScene products in Planet's back catalog. The current radiometric calibration coefficients applied to SkySats were calculated using vicarious calibration methods and last updated in September 2020. Updated calibration coefficients calculated using the new process described here will be applied to SkySats by mid 2022.

Future improvements to the calibration process will include additional automation to help provide more timely, and possibly more frequent, calibration updates, as well as support for additional satellite designs as Planet expands its fleet.