Commercial Satellite Data Acquisition Program

BlackSky Principal Investigator Evaluation Summary

Goddard Space Flight Center
Greenbelt, MD

Commercial Satellite Data Acquisition Program BlackSky Principal Investigator Evaluation Summary

Signature/Approval Page

Approval by:

Melissa Yang Martin Commercial Satellite Data Acquisition Program Manager Earth Science Division Headquarters/NASA	Date

Accepted by:

Dana Ostrenga Commercial Satellite Data Acquisition Project Manager Earth Science Division GSFC/NASA	Date

Preface

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Abstract

The evaluation summarized in this report was conducted by Principal Investigators (PIs) funded by NASA's Commercial Satellite Data Acquisition (CSDA) Program. The purpose of the evaluation is to determine the utility of the BlackSky data for the NASA Earth science research and applications community. The results of the evaluation help to inform NASA program management on the ability of the data to further augment NASA science.

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Authored and prepared by

Christopher Neigh
BlackSky Evaluation Lead and Electro/Optical Subject Matter Expert
National Aeronautics and Space Administration

Frederick Policelli
CSDA Project Scientist
National Aeronautics and Space Administration

Jaime Nickeson
CSDA Technical Science Coordinator
Science Systems and Applications, Inc.
National Aeronautics and Space Administration

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Executive Summary

In 2017, NASA's Earth Science Division (ESD) launched the Private-Sector Small Constellation Satellite Data Product Pilot, now referred to as the Commercial Satellite Data Acquisition (CSDA) program. The objective of CSDA is to identify, evaluate, and acquire commercial remote sensing data that support NASA's Earth science research and application activities. The Pilot successfully concluded in early 2020, when CSDA transitioned into a sustained program with on-ramping opportunities for new vendors as the industry emerges with new candidates and capabilities.

In this report, CSDA provides an evaluation of the usefulness of data provided by the BlackSky satellite constellation for advancing NASA's Earth system science research and applications. To conduct the BlackSky evaluation, NASA's ESD augmented 13 existing research projects that had the expertise and could potentially benefit from the commercial data being considered for longer-term purchase. Investigators from NASA's Research and Analysis Program science focus areas and their Applied Sciences Program elements participated in the evaluation. A summary of the research areas evaluated by the Principal Investigator (PI) teams is presented in Figure 4. CSDA also funded dedicated independent activities to evaluate the satellite data quality (calibration and geolocation) by subject matter expert (SME) teams to assess the quality and accuracy of the data from BlackSky.

Evaluation activities were carried out by the selected PIs from April of 2022 to June of 2023. Delivery of initial imagery products requested by the researchers began in June 2022, and a second round of newly available products and collection priority tiers became available in February of 2023. In addition to the scientific utility perspective, the vendors providing data to the CSDA Program are also evaluated on the accessibility of data, the accuracy and completeness of the metadata, and the promptness and quality of user support services. Datasets purchased during the evaluations are archived by NASA and after the evaluations are completed, they are made available to current and future government-funded researchers in accordance with the End User License Agreement (EULA). This synthesis report distills and integrates the findings of the individual research reports commissioned by NASA for the BlackSky evaluation. This report also includes recommendations that can inform future initiatives for the CSDA program.

The scientific results from the evaluations demonstrated that data from BlackSky were able to advance NASA research and applications. However, the PIs did encounter limitations that diminished the usefulness of the data. Significant issues were encountered when using the data which included: 1) lack of radiometric calibration; 2) limited spatial and temporal coverage of the BlackSky Archive; 3) geolocation accuracy was not suitable for time series analyses; and 4) tasking thresholds were unavailable for individual PIs, thus requiring continuous management of available resources. Ultimately, the agility of the constellation with PI access to tasking potentially multiple images per day and the utility of the acquired data outweighed the difficulties encountered. NASA has concluded that BlackSky data would complement existing Earth observation capabilities and BlackSky qualifies to participate in the sustained phase of the program.

1. Background

In 2017, NASA's Earth Science Division (ESD) launched the Private-Sector Small Constellation Satellite Data Product Pilot. After the completion of the Pilot, a new program was established, referred to hereafter as the Commercial Satellite Data Acquisition (CSDA) Program. CSDA was established to identify, evaluate, and acquire data from commercial sources that support NASA's Earth science research and application goals. ESD recognizes that data from commercial systems have the potential to complement existing NASA data sources to advance Earth system science and applications development for societal benefit. During the Pilot, the evaluation team assessed data provided by three private sector vendors that operated satellite constellations in low Earth orbit—Planet Labs (Planet), Maxar Intelligence, and Spire Global (Spire). The vendors were evaluated on the accessibility of data, accuracy and completeness of metadata, promptness and quality of user support services, suitability of the End User License Agreement (EULA) for standard scientific collaboration, and usefulness of the data and imagery for advancing Earth system science research and applications. Additionally, two dedicated activities were added to evaluate satellite calibration and geolocation quality of the vendor data.

Results from the Pilot evaluations demonstrated the ability of commercial data and imagery to advance NASA scientific research and applications. However, a significant issue encountered was the highly restrictive EULAs that inhibited standard scientific collaboration. NASA worked with the vendors to maintain access to data and resolve issues encountered. The results of this evaluation were published in the CSDA Program Pilot Evaluation Report, which was released in April 2020.

After the Pilot ended, it transitioned into a sustained program with on-ramping opportunities for new vendors as the industry expands with new candidates and capabilities. In June 2021, the CSDA Program's license agreements were uplifted to broaden the applicability for scientific applications across the U.S. Government. These license uplifts make the data more readily available across the government and improve both the value of these data and the opportunities for interagency collaboration.

1.1 On Ramp 2

On-ramp 2 evaluations were initiated in October 2019 with an RFI seeking capability statements from parties interested in providing data from spaceborne platforms for evaluation. To be responsive to the RFI, the commercial satellite vendors had to be U.S. companies with three or more spacecraft actively collecting data in non-geostationary orbits with full latitudinal coverage. Two vendors satisfied the RFI requirements and were asked to respond to an RFP. After review of the submitted proposals, NASA entered a BPA with Airbus Defense and Space GEO, Inc. (Airbus) U.S. in September 2021 and with BlackSky Geospatial Solutions, Inc. (BlackSky) in November 2021. The datasets available from on-ramp 2 vendors are listed in Table 1.

Table 1. On-Ramp 2 Vendors and Sensor Data Available for Evaluation

Vendor	Sensor Type	Temporal Coverage	Spatial Coverage	Number of Satellites	Bands	Resolution
Airbus	SAR	Nov 2007 - Dec 2022	Global	3	X - Band	0.24 - 40 m
BlackSky	Optical	2018 - May 2023	Global*	14	R, G, B, Pan	0.8 - 1.5 m

***Information on constellation numbers is based on the start of the evaluation. The BlackSky constellation had 2 polar orbiting satellites (BSG-1 and -2) nearing the end of their operational lifetime during our evaluation and had limited utility.**

In this report, the CSDA Program reports on the results of the evaluation team on the usefulness of the imagery provided by the BlackSky satellite constellation for advancing NASA Earth system science research and applications. The evaluation of the Airbus U.S. data has been completed and results are reported on the CSDA web site. Additional information about the CSDA vendors, user licenses, and available data can be found at https://www.earthdata.nasa.gov/esds/csda.

1.2 BlackSky Imaging Capabilities and Products Evaluated

1.2.1 Constellation

The constellation is composed of microsatellites that are based on the L3 Harris Spaceview-24 satellite bus. Each has a mass of ~56 kg with a telescope measuring 24 cm, and a nominal design lifetime of 3 years. The imager is a frame camera system with a Bayer type filter array (Figure 1), a mosaic color filter array, with each pixel having red, green or blue (RGB) filters and every other pixel having a panchromatic filter. BlackSky implements their own proprietary demosaicing algorithm with neighboring pixels having their values weighted to focal pixels to produce ~1 m resolution 4-band imagery. A "color correction algorithm" is applied to the RGB bands and a

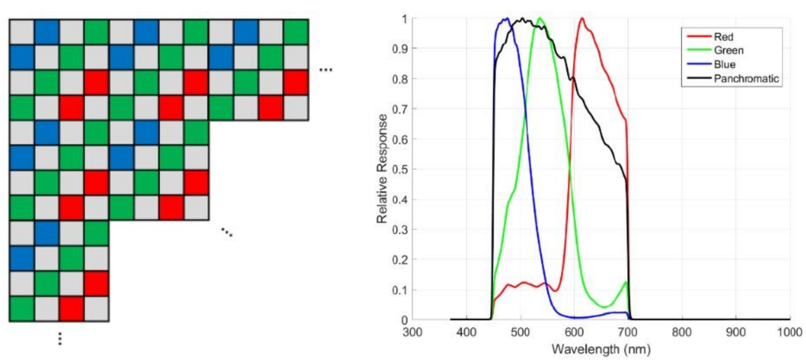

Figure 1. Left: Red, green, blue, and grey color filter array interleaves panchromatic pixels (shown in grey). Right: typical relative spectral response curves for the constellation.

"dynamic range adjustment" algorithm is applied to the panchromatic band. The RGB adjustment has 3 components: 1) RGB histogram subtraction - 1st percentile of each RGB band, half of that value is subtracted from the respective bands; 2) gamma scaling - clips the image to a predetermined range between a minimum (0.02 percentile) and maximum (99.98 percentile), then performs a gamma scaling for a non-linear brightening of the image intensity; and finally, 3) linear scaling - to maximize the dynamic range of the 12-bit image. The panchromatic band has similar gamma and linear scaling adjustments.

1.2.2 Products

BlackSky processes the data through up to three processing levels that include Proto, Anthro and Ortho. Proto is the most basic level and all images are processed to at least this level. Proto processing reduces sensor-to-sensor variation by correcting for defects or artifacts, improves the geolocation and assesses the cloud score of the image. Proto data were not available as a commercially delivered product for investigators at the onset of the evaluation. The BlackSky Anthro processing enhances the image contrast with the dynamic range adjustment steps mentioned above. Anthro processing is the default product that BlackSky applies to delivered imagery. Ortho processing applies an orthorectification to account for spatial distortions associated with sensor tilt and terrain.

Table 2. Detailed specifications of the BlackSky constellation during the CSDA evaluation period.

BlackSky Imagery Specifications and Constellation

Sensor Specifications

Sensor Type	Framing Camera RGBW Color Filter Array	
Spectral Bands (nm)	450 - 520	Blue
	500 - 590	Green
	590 - 700	Red
	450 - 700	Pan
Dynamic Range / Bit Depth	12-bit	
Product Data Type	16-bit Unsigned Integer (uint16)	

BlackSky Constellation

Constellation IDs	Launch Date	Inclination Angle (deg)	Single Collection Footprint (approximate)	Altitude (km) - Apogee x Perigee	Latitudinal Collection Range	Satellite Generation	De-commission Date
BlackSky Global 1	29-Nov-2018	97.246	4.6 km x 6.8 km	412.0 x 394.0	85.3°N to 85.3°S	2	25-Sep-2023
BlackSky Global 2	12-Mar-2018	97.44	4.6 km x 6.8 km	570.7 x 567.2	85.3°N to 85.3°S	2	
BlackSky Global 4	19-Aug-2019	45.015	4.6 km x 6.8 km	514.2 x 500.4	53.5°N to 53.5°S	2.1	
BlackSky Global 7	7-Aug-2020	52.897	4.1 km x 6.2 km	404.0 x 391.2	53.5°N to 53.5°S	2.1	14-Aug-2023
BlackSky Global 8	7-Aug-2020	52.876	4.1 km x 6.2 km	408.7 x 392.4	53.5°N to 53.5°S	2.1	
BlackSky Global 9	22-Mar-2021	44.92	4.1 km x 6.2 km	443.2 x 437.5	53.5°N to 53.5°S	2.1	
BlackSky Global 14	18-Nov-2021	42.012	4.1 km x 6.2 km	440.3 x 416.5	53.5°N to 53.5°S	2.1	
BlackSky Global 15	18-Nov-2021	41.922	4.1 km x 6.2 km	464.2 x 434.6	53.5°N to 53.5°S	2.1	
BlackSky Global 12	2-Dec-2021	53.146	4.1 km x 6.2 km	449.6 x 445.0	53.5°N to 53.5°S	2.1	
BlackSky Global 13	2-Dec-2021	53.147	4.1 km x 6.2 km	460.1 x 437.0	53.5°N to 53.5°S	2.1	
BlackSky Global 16	9-Dec-2021	41.906	4.1 km x 6.2 km	453.0 x 445.2	53.5°N to 53.5°S	2.1	
BlackSky Global 17	9-Dec-2021	41.891	4.1 km x 6.2 km	449.4 x 439.8	53.5°N to 53.5°S	2.1	
BlackSky Global 18	2-Apr-2022	53.129	4.1 km x 6.2 km	453.2 x 447.9	53.5°N to 53.5°S	2.1	
BlackSky Global 20	2-Apr-2022	53.121	4.1 km x 6.2 km	453.6 x 442.7	53.5°N to 53.5°S	2.1	
BlackSky Global 5	24-Mar-2023	42.159	4.1 km x 6.2 km	451.2 x 442.8	53.5°N to 53.5°S	2.1	
BlackSky Global 19	24-Mar-2023	42.128	4.1 km x 6.2 km	440.8 x 440.6	53.5°N to 53.5°S	2.1	

Repeat frequency varies by latitude, with a majority of the constellation in mid-inclination orbits of ±53.5°. This results in the ability to collect ~8 images per day within this latitude range. Products available from BlackSky leverage the staring and frame camera capabilities of the instruments. Single frame images (Proto/Anthro), Stereo, Low Light, Area Coverage and Burst products were available during our evaluation, as listed in Table 3. Stereo imagery is collected as two images by one satellite within the same orbit with convergence angles from 15° to 50°, or as directed by the user. Low light is imagery that is collected at or near sunrise or sunset with a minimum -4° solar elevation (below the horizon) and the integration time is extended to increase signal. The burst product is the rapid collection of 5 images in succession within 10 seconds.

1.2.3 Tasking

The Spectra tasking interface provides a web-based geospatial platform to enter text of coordinates, drop points on a map, or upload areas of interest. Multiple options are available to display basemaps for the user to easily orient themselves within their study domain. It enables access to archived imagery, viewing image footprints, quicklooks and metadata to screen data with a number of parameter filter options. On-demand tasking is available through this interface, with orbital planning shown 2 weeks into the future at any given point (with a 3 km radius buffer) the user provides. Additional criteria can be provided to constrain image tasking parameters, for

Table 3. Image products and tasking tiers.

Products	
Proto	Imagery corrected for sensor artifacts and geolocation only
Anthro	Imagery enhanced with dynamic range adjustment (DRA)
Stereo	Two images collected at different view angles
Area Coverage	Two adjacent images with 20% overlap
Burst	Five images of the same area collected in rapid succession
Low light	Collection with solar elevation angle ranges of -4° to 10°
Tasking Tiers	
Standard, Global Access, Preferred	

*All products were available with additional orthorectification.
*Imagery ordered from the BlackSky Archive were discounted.
*Higher costs were associated with higher priority tasking tiers.

example acceptable maximum cloud fraction (minimum allowable default was 30%), convergence angle for stereo and resolution for example. The interface offers low latency for both tasking and delivery, with tasks that can be placed less than 15 minutes before overpass time and delivery of data within 1 hour of capture.

2. Evaluation Process and Criteria

NASA ESD selected 13 projects (Appendix A) to perform the BlackSky utility evaluation. Researchers covered four of NASA’s six Research and Analysis (R&A) Program focus areas, including Climate Variability and Change, Water and Energy Cycle, Carbon Cycle and Ecosystems, and Earth Surface and Interior. The projects also covered Applied Sciences Program elements which are now housed within NASA’s Earth Action Program, which includes disasters, water resources, agriculture and wildland fires. The 13 project teams selected formed the BlackSky commercial data evaluation team.

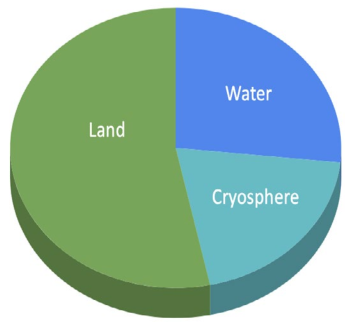

Figure 2. Proportion of scientific disciplines of evaluators.

NASA ESD also selected additional research teams specializing in calibration and geolocation to independently assess the radiometric calibration and geolocation accuracy of vendor-provided imagery. The evaluation Principal Investigators (PIs) were required to submit interim, midterm, and final reports and to attend monthly discussions to ensure they had sufficient information and data access to complete their evaluation. Figure 2 presents the breakdown of the evaluation teams by broad science disciplines.

Appendix A provides a listing of the research projects contributing to the BlackSky evaluation.

2.1 Evaluation Criteria

The CSDA program provided evaluators the following categories for reporting on their findings from the BlackSky data evaluation for both the quality and utility of the data.

A. *Access, Metadata and Support*
   I. Accessibility of vendor supplied data
   The ease and efficiency with which data can be searched, discovered, and downloaded from vendor systems.
   II. Accuracy and completeness of metadata
   The accuracy and completeness of metadata that accompanies the imagery and data provided by the vendor.
   III. Quality of support services, including documentation
   The availability, responsiveness, and technical expertise required to answer PI inquiries.

B. *Usefulness of the data for advancing Earth system science Research and Applications*
The ability of vendor-supplied data to support Earth system science Research and Applications

C. *Quality of Vendor Supplied data*
The quality of data attributes, such as radiometric calibration, geolocation accuracy, and platform intercalibration.

2.2 Program Activities

The evaluation was facilitated by conducting periodic reviews and surveys, PI all-hands, weekly technical interchange meetings, and community engagement. The project timeline is depicted in Figure 3.

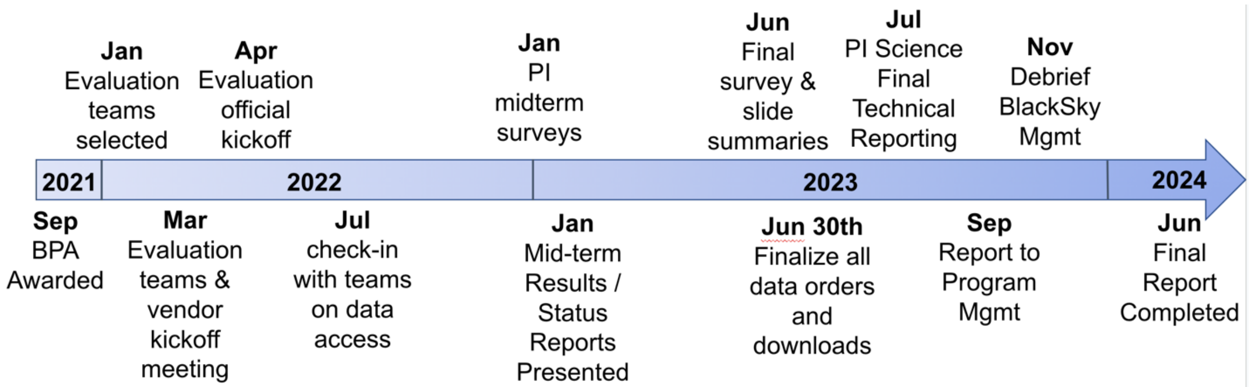

Figure 3. Timeline of Evaluation activities since awarding the purchase agreements.

2.3 Periodic Reviews and Surveys

All evaluation PIs were required to participate in periodic reviews and report on the usefulness of the data and current research progress. The PIs were asked to submit progress reports in July 2022 and January 2023, followed by a final report due in June. A midterm meeting was held in Jan 2023 that allowed the PIs to share preliminary results. In addition to the reports, PIs were asked to submit quad charts and complete surveys. All reports and surveys were synthesized in this final summary report.

2.4 PI All-hands and Vendor Meetings

There were four main scheduled meetings – a kick-off meeting, a vendor meeting, a hybrid midterm meeting, and a final debrief. These cross-disciplinary meetings served as check-ins, where the PIs presented and shared their preliminary findings, issues, and concerns while assessing the BlackSky datasets. For some of the PIs, it was their first experience working with commercial data, thus these meetings proved to be useful to ensure they received the proper support for their analyses. There were also a few additional training and information gathering meetings with BlackSky that were scheduled on-demand as needed.

2.5 Monthly Team Interchange Meetings

Monthly video conference calls were set up to facilitate technical interchange among the evaluation team members to provide updates and to resolve issues related to data access, quality, completeness, or processing. Participants were asked to identify issues and share information they believed might be relevant to others. The conference calls were an effective means of ensuring the timely identification of and response to issues, such as questions about the Anthro data processing, calibration, and tasking issues. The monthly team tag-up meetings also allowed the CSDA staff an opportunity to gather and relay issues from the PI projects to the vendors directly to accelerate problem-solving.

2.6 Community Engagement and Feedback

As the capabilities and numbers of commercial vendors grow, it is important to continuously monitor the development of new commercial technology, acquire relevant data to complement existing and future missions, and evaluate these data over time. The CSDA team continues to provide status updates, answer questions about data and data access, and provide information about future procurement opportunities for other constellation providers at various science conferences and workshops throughout the year. The community engagement serves as an open forum for dialogue between experts across the science data research stratum and helps to showcase NASA's progress and commitment to building stronger bonds with the commercial sector.

3. Key Findings

The evaluation was focused on assessing the utility of BlackSky data for advancing four of NASA's R&A science focus areas and Applied Science program elements. A summary of the research areas represented by the evaluation PIs is presented in Figure 4.

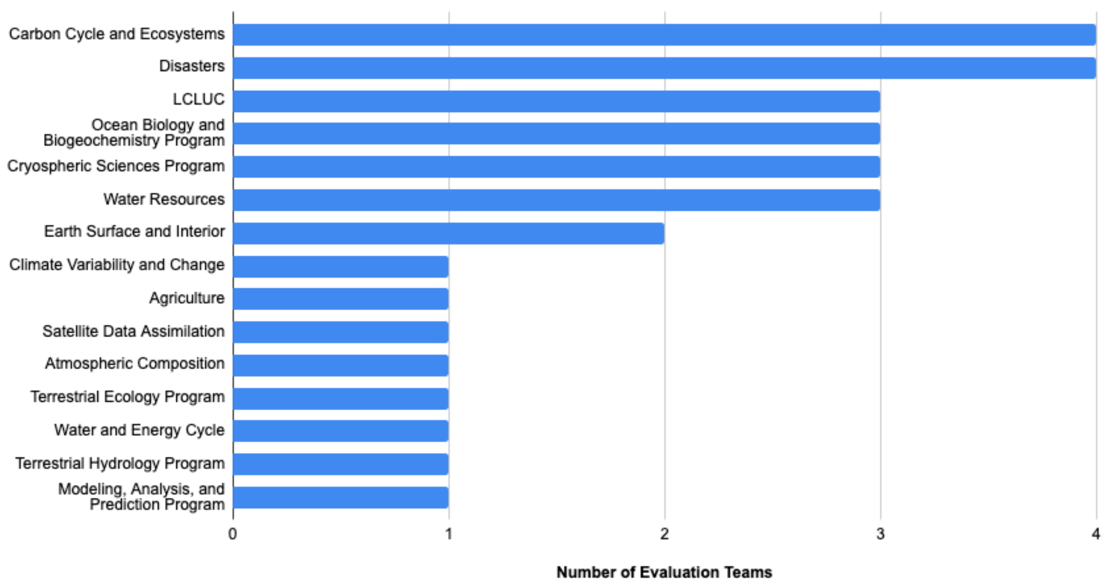

Figure 4. Evaluation research areas were varied, and some evaluations covered more than one research area.

The BlackSky data sets that were evaluated were acquired through the U.S. Government End User License Agreement (EULA) and were available only to the science team during the period of the evaluation. Following the evaluation period, the data will be made available to NASA funded science investigators through the CSDA Satellite Data Explorer (SDX). The BlackSky imagery and constellation are described in Table 2, with evaluation criteria outlined in section 2.1. The key findings address the objectives of the evaluation and are described in the following sections.

3.1 Data Access, Metadata and Support

The BlackSky Spectra platform provided data access for the PI evaluators to access the archive, and to schedule and monitor tasking requests made by the PIs and the evaluation team as a whole. The BlackSky Spectra Tasking portal and their Customer Success team received high marks from the evaluation team due to the ease of tracking tasked imagery, previewing and downloading images and their prompt response to questions. All the PIs gave the platform high marks for its ease of use and intuitive structure to perform their work. BlackSky provided documentation on metadata, sensor calibration, and instrument characteristics, which enhanced the ability of PI teams to reach their findings. BlackSky also provided multiple briefings on how to use the Spectra Tasking platform and provided tips and shortcuts to enhance the user experience. Over 8,600 globally distributed images (Figure 5 below) were acquired for the NASA evaluation and 88% of that collection were images tasked by the evaluation team. Most of the data were tasked at the lower cost Standard tasking tier throughout the evaluation which had varying degrees of competition for imaging resources. Higher tasking tiers with higher cost were used sparingly and only after multiple attempts were made at the lower tasking tiers. The highest and most expensive tasking tier during our evaluation, the "Preferred" tasking tier, was used sparingly, because at this tier, the PIs are not allowed to define a maximum acceptable cloud coverage threshold, meaning if an image was collected that had 100% cloud cover, it would be delivered and billed to NASA. BlackSky also provided a tasking application programming interface (API) that was not broadly used because it lacked administrative oversight to limit PI tasking of shared resources.

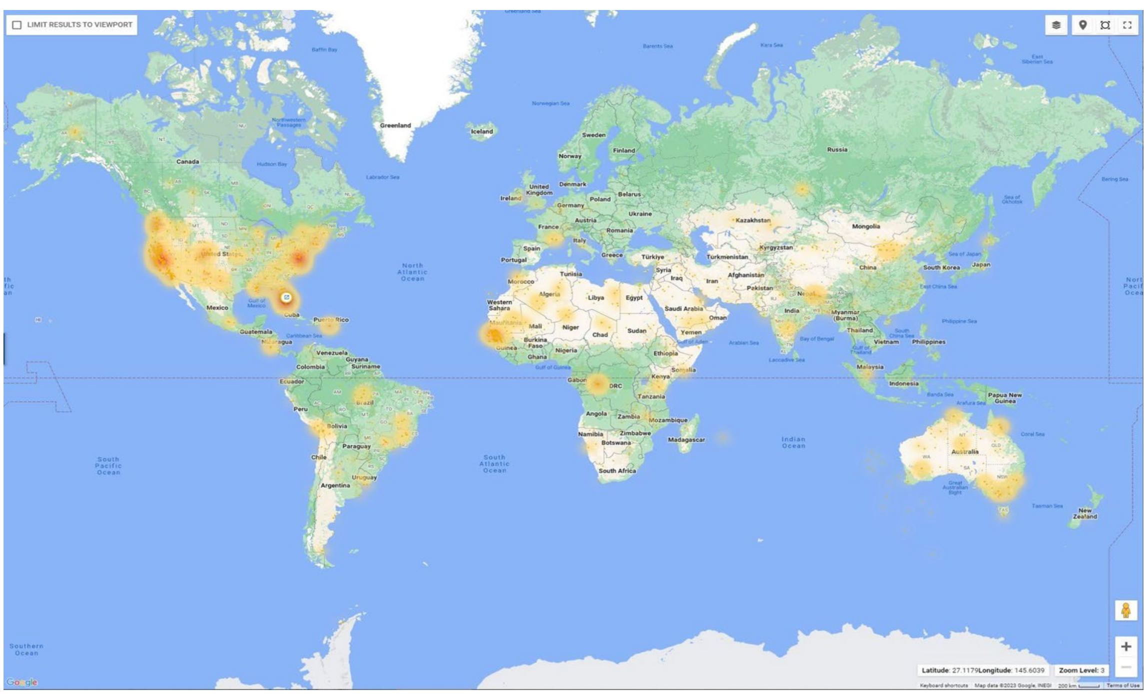

Figure 5. Heatmap of BlackSky imagery acquired for evaluation. The total NASA archive is 8,604 images (3.9 terabytes compressed). All BlackSky data are stored in the NASA cloud.

The BlackSky user support services received high marks from most of the investigators. BlackSky user services were generally prompt and responsive to most of the PI requests. Multiple technical exchange meetings were held with science evaluators and BlackSky technical personnel. These meetings slowly progressed with PIs and SMEs formulating written questions that were sent to BlackSky technical staff. There were little or no meaningful written responses, with most of the questions being answered by BlackSky in verbal form during technical meetings.

The BlackSky production team worked with NASA PIs to make the Proto data product available for the evaluations when these products were not considered to be a viable commercial product by BlackSky. The BlackSky production team also worked with PIs studying the cryosphere when they found over-saturated imagery that did not meet Anthro product standards. A few tests were performed by tasking images over snow and ice with integration time adjustments to attempt to improve the saturation issue, without much success. The BlackSky customer support team also worked with evaluators on optimizing the BlackSky API to task a globally distributed sample of sites. Overall, investigators found that the information contained in the metadata was sufficient for their needs, however, some improvements were made during the evaluation. For example, integration time was added to the metadata.

3.2 Data Utility for NASA Science

The utility of BlackSky data differs among the Earth science focus areas. In general terms, the usefulness of the data is high for land remote sensing studies, however the application of these data for long-term global studies is limited by the spatial extent of the data in the BlackSky archive. Due to the small footprint size (~4 x ~6 km), and other unknown factors, few images were found in the BlackSky's Archive that could meet our investigator's study domain time and space requirements for science evaluation. This necessitated tasking for most of the evaluation data. To simplify the results of the evaluations, the reporting is grouped into Cryosphere, Land, and Water investigations (see Appendix A).

3.2.1 Cryosphere

Two of the fourteen studies were dedicated to using BlackSky data to evaluate their utility for the science of snow and ice dynamics. The NASA funded projects involved in this type of evaluation for CSDA were: 'Evaluation of high-resolution snow covered area mapping in mountain ecosystems from Satellite imagery' and 'Commercial Sensor Evaluation for Detection and Mapping of Snow Algae'. Many cryosphere science objectives were evaluated that included: snow cover area mapping; snow algae pigment detection (Figure 6) and mapping changes in snow albedo; and creating digital elevation models (DEMs) for use in determining snow depth and glacier volume.

The investigations found several benefits and strengths of using BlackSky data. The high spatial resolution (~1 m) was advantageous for mapping snow cover in small mountain meadows and in forested terrain. The high temporal repeat enabled sub-daily observations of rapid seasonal snowmelt, which provides detailed information on snow dynamics that impact hydrology and the local ecology from changing snow cover patterns. The stereo capabilities from both the Burst and Stereo products have the potential to provide DEMs to track glacier volume and snow depth with further optical and camera model refinement.

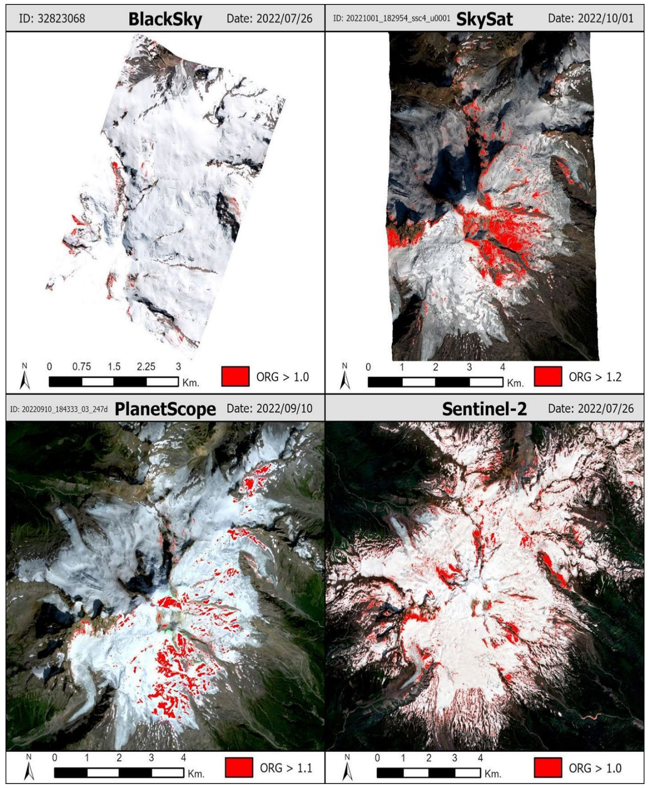

Figure 6. From P.I. Khan et al., comparison of a BlackSky image of Mt. Baker, Washington to other commercial data SkySat, and PlanetScope, and to Sentinel-2 data. The red-colored areas are pixels with an optimized red green index (ORG) used to map snow algae pigments. A value > 1 (A and D), 1.2, 1.2 (B) and 1.1 (C) ORG, red-colored areas, suggest *light absorbing particles are present on the snow surface. Saturated BlackSky pixels produced an underestimate of the actual extent of snow algae.*

A few limitations of the data were also found. Many images over the cryosphere were saturated (Figure 7) due to the integration time (exposure time) of the BlackSky imagery, as mentioned in section 1.2. BlackSky's small footprint and geolocation accuracy issues made collection of an entire glacier/mountain on the same day infeasible. PIs also found that self-competition occurred if tasking requests were submitted too close to each other. The limited imaging capacity at latitudes beyond ±53.5°, due to BlackSky having just two polar-orbiting satellites, resulted in more competition for resources in most cryosphere regions and reduced the success rate of tasking there. Due to this, some investigators spent a fair amount of time refining and monitoring their tasking requests. Several investigators wanted access to BlackSky's Proto imagery (without dynamic range adjustment applied) and thought these data should be provided as a standard product. The camera models that were provided to cryosphere science investigators were not accurate enough to produce sub meter accuracy DEMs needed to track ice volume change, and no model was provided to correct for radial optical distortion of the telescopes, which was found to be on the order of >10 m at DEM edges in results from Utqiagvik (formerly Barrow), Alaska. DEMs could be produced in an automated manner using the NASA Ames Stereo Pipeline, but they were not accurate enough for cryosphere science (snow depth, glacier volume change) with the information provided by BlackSky.

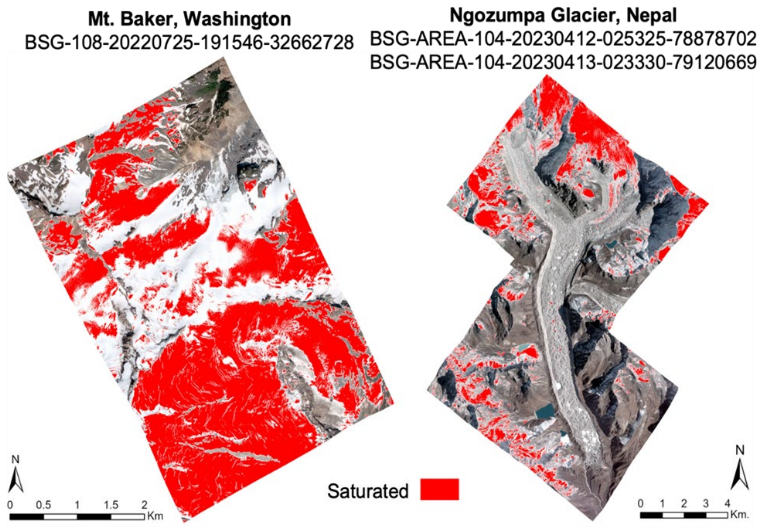

Figure 7. Saturation comparison of two Proto images. The left image is from Mt. Baker, where the image is almost entirely snow covered. However, there are small regions of snow that are not saturated. On the right is the Ngozumpa Glacier, a debris covered glacier in Nepal where only the regions with large areas of snow cover appear saturated.

3.2.2 Land

Eight of fourteen studies assessed the capability of BlackSky imagery to be useful to NASA science research of the land surface. NASA programs involved in this evaluation included: Land-Cover Land-Use Change (LCLUC); Terrestrial Ecology (TE); NASA Harvest; and the Earth Science Technology Office (ESTO) Decadal Survey Incubator (DSI). The range of evaluations was broad, including: assessment of Landsat (30 m) global hotspots of forest disturbance; burned area mapping capabilities; wildland urban interface (WUI) characterization; monitoring of fire-fuel dynamics; assessing post-fire vegetation dynamics using deep learning models; crop nitrogen uptake estimation; sub-hectare agriculture field boundary delineation; mapping individual trees; shrub crown identification; woody canopy cover mapping; tree height estimation; and utility for tectonics research. There were many benefits and strengths of using BlackSky data for these studies. To our knowledge, this was the first demonstration of a commercial capability to task ~1 m data for a globally distributed sample of +1,000 locations within one year that resulted a high collection success rate (86%).

The latency of the data availability post-acquisition was equally impressive, data were often available for download and/or viewing within 30-45 minutes of collection. The very high spatial resolution is advantageous for qualitative visual interpretation (detailed burned area, Figure 8 below, and delineation of smallholder agriculture field boundaries) and tree crown properties (phenology leaf-on/leaf-off and general height with stereo processing). The BlackSky Stereo products have the potential to provide DEMs for determining vegetation structure, but due to previously mentioned limitations regarding camera model and optical distortion information, these products have limited utility.

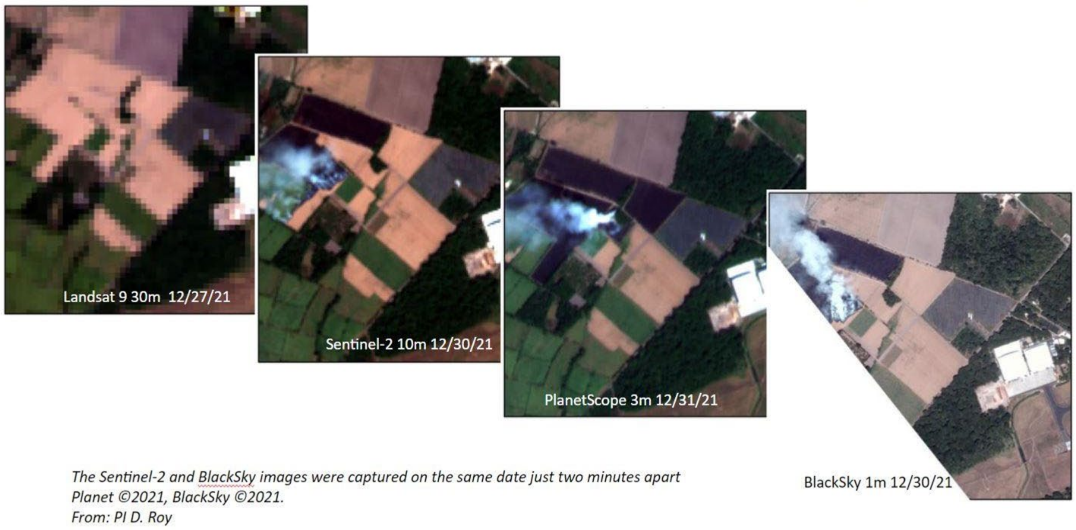

Figure 8. From PI Roy et al., comparison of multi-resolution differences of the evolution of a burned area near El Salvador International Airport displayed in true color.

A few limitations were found when evaluating BlackSky for land surface studies. The lack of bands in the near infrared (NIR) and shortwave infrared (SWIR) eliminated the possibility of calculating vegetation indices. Additionally, BlackSky imagery are not provided in reflectance units, no atmospheric correction is applied, a variable integration time and a dynamic range adjustment contrast stretch is applied (Anthro data product) that is not invertible. The highly variable spectral magnitudes (extreme saturation in bright bare soil/artificial surfaces was found) due to the dynamic range adjustment limits the ability to train models for automated classification. The BlackSky constellation also has limited imaging capacity over arctic/boreal biomes, greater than ±53.5° latitude, and low tasking success rates were found from cloud cover and tasking competition from other users. Several cases of failures in orthorectification were found in remote areas, or when the images were cloudy or snowy and a limited number of control points could be identified. The geolocation uncertainty (offsets >20 m) results in poor multi-temporal registration and ±10 m errors in the rational polynomial coefficient (RPC) models. Some investigators found the cloud percentage, haze and water metadata estimates to be incorrect and no flags were available for shadows.

3.2.3 Water

Four of the thirteen evaluations assessed the capabilities of BlackSky imagery for NASA science research of water and near coastal ecosystems. NASA programs involved in this evaluation included: Land-Cover Land-Use Change (LCLUC); Ocean Biology and Biogeochemistry (OBB) and Water Resources. The objectives of these studies included: aquatic science and applications, assessment of radiometric quality; algal bloom detection capabilities; determining band-specific signal-to-noise ratios (SNRs); evaluating use in deep learning models for surface water detection; assessing the impact of ~1 m resolution on inundation mapping; and mapping and detection of changes in submerged aquatic vegetation.

NASA investigators found many advantages when using BlackSky data. They found the very high-spatial resolution (~1 m) is advantageous in river systems for qualitative assessment of turbidity (Figure 9), and in coastal ecosystems for identifying and mapping sparse seagrasses.

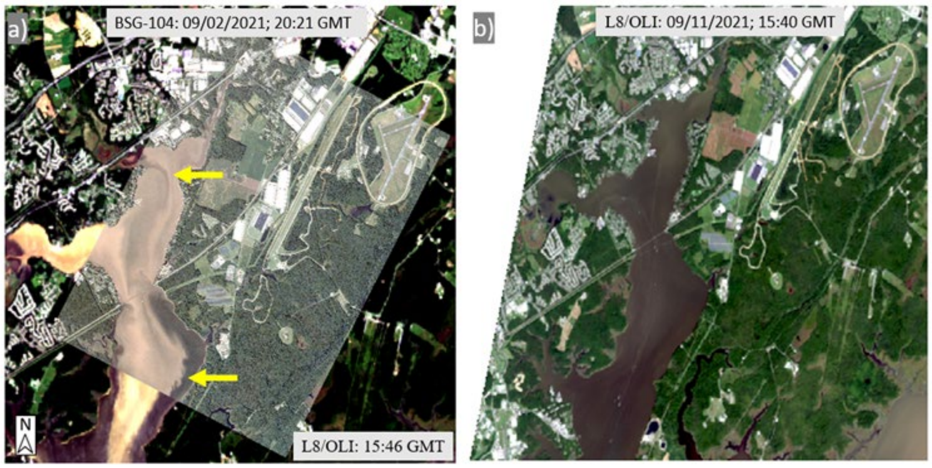

Figure 9. From PI Pahlevan et al., comparison of Landsat 8 Operational Land Imager (OLI) to BlackSky Global 104. A) High (post-hurricane Ida) and B) low turbidity scenes over the Bush River, a tributary to the Chesapeake Bay in Maryland.

The resolution combined with a rapid temporal repeat, in some cases five images or more on a daily cadence, provided unprecedented algal bloom and flood monitoring capacity. The PIs found the image quality to be sufficient for qualitative monitoring of harmful algal blooms (HABs) and that a single site model could be trained to identify submerged aquatic vegetation. BlackSky SNRs over inland lakes were ~50 for blue and green bands and < 50 for red. As a reference, Landsat 7 Enhanced Thematic Mapper Plus (ETM+) SNRs are < 50 and Landsat 8 Operational Land Imager (OLI) SNRs are ~400, 200 and 120 for the blue, green and red bands, respectively. The relative success in tasking frequency enabled the generation of seasonal and annual submerged aquatic vegetation distribution maps.

A few limitations were found in using these data for some aquatic science applications. Quantitative monitoring of water quality conditions is currently unfeasible, i.e., production of chlorophyll-a, total suspended solids, turbidity etc. maps require adequate sensor radiometric performance. The BlackSky small footprints, the lack of a NIR band as well as geolocation errors, also made it difficult to perform surface water mapping over large areas. Overall, dead pixel artifacts were evident in BlackSky Global satellites -1, 2, 4, 9,12, and 20, whereas BlackSky Global 13-18 imagery exhibited fewer to no defective/dead pixels. The cloud, haze and water masks that BlackSky provided were found to be inaccurate. Investigators found that high latitude studies of sea ice would be difficult to perform with these data due to reduced constellation coverage and thus enhanced competition for imaging resources at high latitudes. Some investigators suspected the high variation in image-to-image spectral magnitude would limit the ability to train models for automated classification.

3.3 Data Quality

The quality of BlackSky imagery were also evaluated by subject matter experts (SMEs) with expertise in the assessment of radiometric and geometric quality of optical imagery suitable for scientific research. The complete quality assessment is provided in a separate report, *Commercial Satellite Data Acquisition Program BlackSky Radiometric and Geometric Quality Assessment Summary*.

For the Product Information categories, BlackSky was found to provide a Basic level of product details and documentation, a good grade for product format, flags and metadata for the Global satellite sensor products. The user interface and data availability and accessibility was graded as Good. There was no metrology information provided publicly or made available and thus this category was deemed Not Assessable. The NASA SMEs also were not able to review the BlackSky sensor radiometric calibration information because it was not provided and is not accessible by the public, and this was also marked as Not Assessable. NASA's geolocation experts graded the geometric performance as Good.

A summary of the results of SME quality assessment is presented in the quality matrix provided in Figure 10.

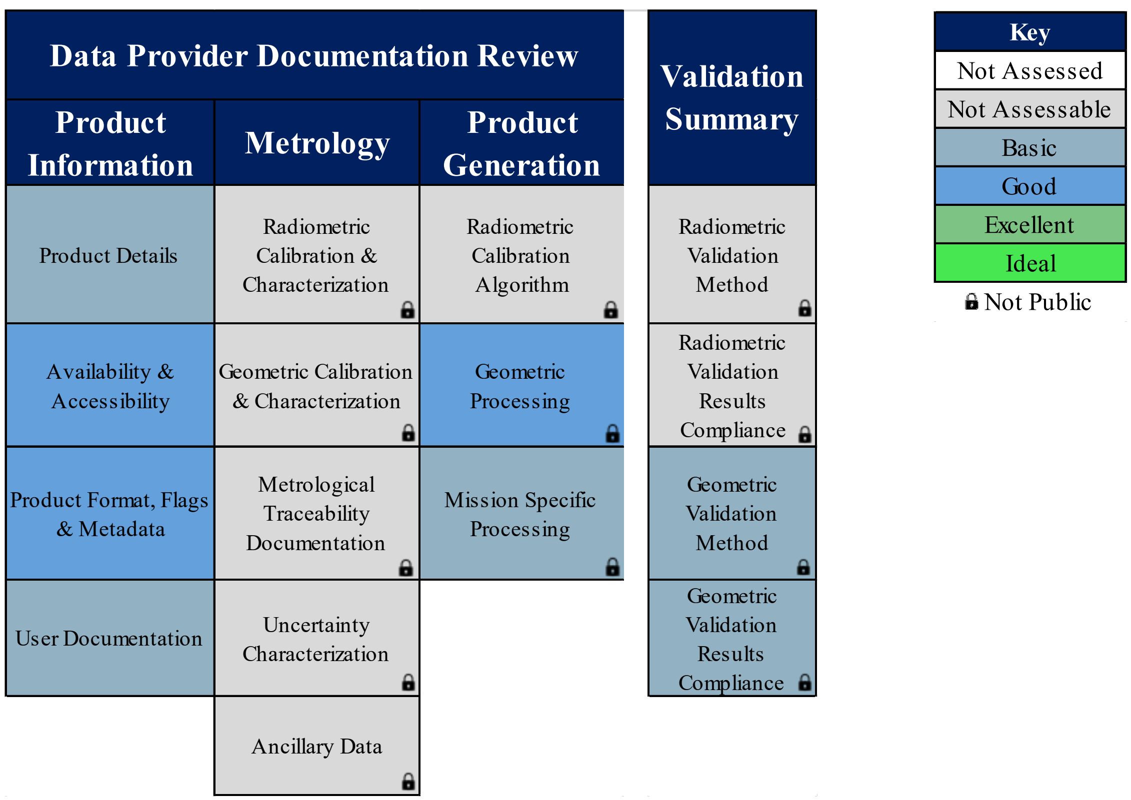

Figure 10. Cal/Val summary maturity matrix.

3.4 Calibration and Geolocation Assessments

Benefits and strengths were found with the geometric assessment. Spatial response for all sensors and all bands was found to be 2.48 pixels in the row direction and 2.63 pixels in the column direction in terms of full width half maximum of the constructed line spread functions. The Modulation Transfer Function (MTF) at Nyquist frequency is 0.021 for all bands in the row direction, and 0.012 in the column direction as shown in Figure 11. We make a cautionary note

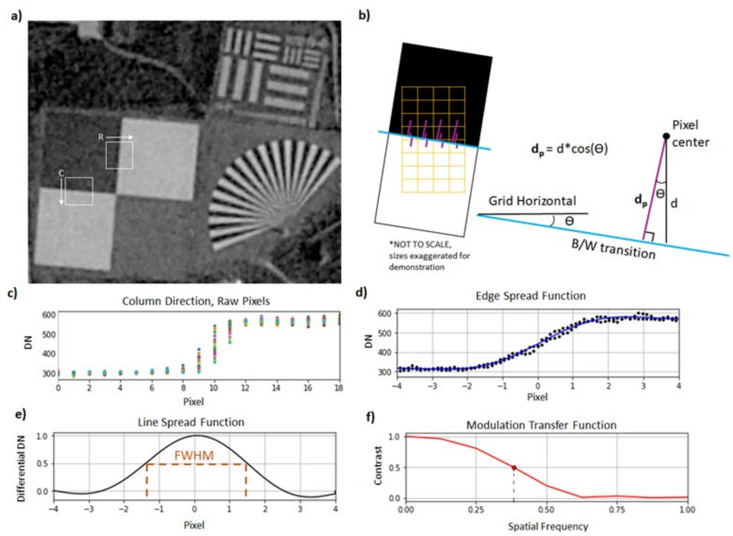

Figure 11. Geometric SME Lin et al. - (Left) FWHM and MTF assessment.

about the radiometric performance since they demosaic their extended Bayer color mosaic filter output not only from other pixels but also from other bands nearby.

Several limitations were found by the SMEs. The provided imagery consists of uncalibrated digital numbers for each band. The lack of calibration limits retrieval of geophysical properties such as land surface reflectance or atmospheric aerosol properties. To assess radiometric properties, Proto data, which precedes the artificial enhancement (Anthro processing), was analyzed for scenes acquired over the Libya 4 desert calibration site and the WLEF telecommunications tower located in a forested region of north central Wisconsin near Park Falls. The Proto data show many artifacts in the radiometric performance (negative and variable dark current) possibly due to integration time, a large variability of the calibration coefficient between sensors and instability of the calibration for the same sensor. The absolute geolocation accuracy (APA) overall does not meet the BlackSky claim of an accuracy of 10 m CE90 in USA and AUS and of 20 m CE90 elsewhere, as shown in Figure 12. The temporal geolocation stability found in this analysis indicates that the data are not suitable for time-series analyses.

For more details on the radiometric and geometric quality assessment, please refer to the BlackSky Quality Assessment Summary report.

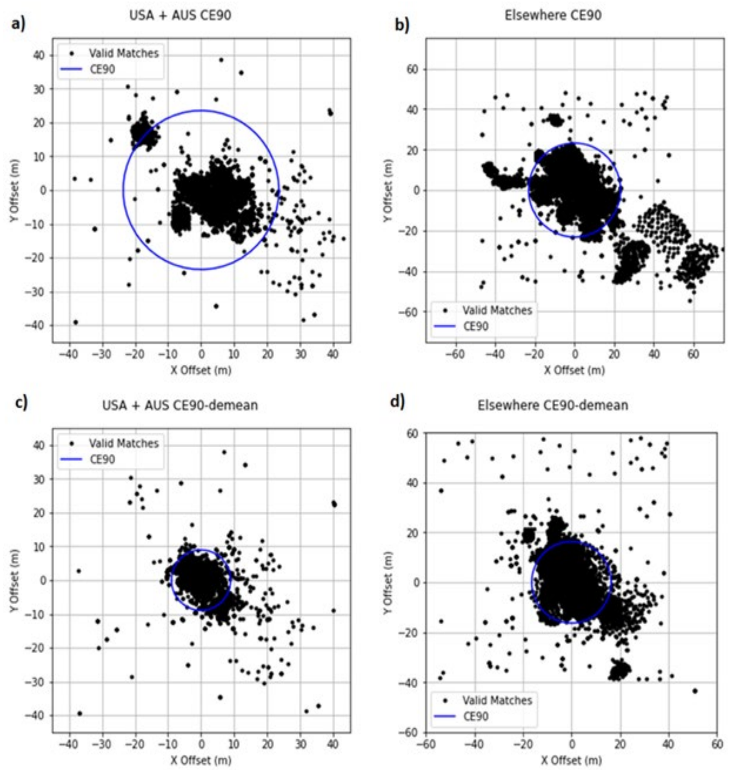

Figure 12. Plots of relative offsets for USA and Australia (a, c) and elsewhere (b, d). Top row plots CE90, bottom plots CE90-demean. Valid matches are plotted as black dots, and the CE90 circle as blue circles

4. Recommendations

NASA funded investigators were able to evaluate a variety of data from BlackSky platforms for existing research activities. The characteristics of the data that enabled successful outcomes of the research included high spatial resolution, availability of red, green and blue bands (RGB), and PI-directed tasking.

Recommendation: BlackSky data were demonstrated to have sufficient utility for object detection, segmentation, and classification of features for NASA research and application activities spanning multiple thematic areas. In contrast, time series-based studies and studies requiring large area coverage were difficult to conduct due to the tasking nature of the constellation, small footprint of observations, and limited spatial and temporal coverage of the BlackSky Archive. It is therefore recommended that the vendor continue to improve data coverage through routine background observations over areas of scientific interest. The overall utility was determined to be sufficient, based on their very high spatial resolution, availability of diurnal imaging and PI-directed tasking. As a result, NASA has concluded that the BlackSky data would indeed complement NASA's existing Earth Observation capabilities and BlackSky would qualify to participate in the sustained phase of the program.

5. Conclusions

Over the course of a year, fourteen PIs representing eight NASA science focus areas evaluated BlackSky imagery for Earth science studies. Overall, the PIs found these data useful for science, but numerous improvements could be made to enhance these products and improve their scientific utility. Results from the BlackSky evaluation indicate the data are of sufficient quality for Earth science research and applications. Many of the PIs recommended that NASA purchase BlackSky data if funds are available. 70% confirmed a notable benefit of access to these data, and they provided several recommendations if NASA were to pursue a sustained-use purchase agreement with BlackSky. A significant majority of these evaluations demonstrated the usefulness of these commercial data for advancing scientific research and applications. However, the evaluators encountered limitations that either diminished the usefulness (e.g., limited archive and declining polar coverage) and/or increased the amount of work needed to access, preprocess, and analyze data (e.g., dynamic range adjustment, documentation, image saturation/integration time, optical distortion model, etc.). Overall, the utility of the evaluated data outweighed the difficulties encountered, and it was determined that BlackSky U.S. would be a complement to NASA's existing Earth observation capabilities, thus successfully completing the evaluation phase of the program.

Investigators suggest that BlackSky make the Proto data a commercial product; add a near infrared band; improve the geolocation accuracy and precision of the ortho processing to enable large area mapping and time series analyses; ensure that all tasked imagery are georeferenced; improve the cloud mask and cloud metadata; simplify the process of providing API keys to users; and consider provision of a top of atmosphere or surface reflectance product.

If a sustained use data buy is pursued by NASA, the PIs had cautionary comments: The archived data are not dense enough, which requires active tasking and monitoring of image acquisitions due to clouds and competition between other constellation users. U.S. researchers are currently able to take advantage of the National Reconnaissance Office (NRO) Electro Optical Commercial Layer (EOCL) contract to access BlackSky archive imagery. BlackSky data are sparsely distributed, and their archive at the time was found to have limited utility for this evaluation. Currently it is not clear how PIs from the federal civilian user community will directly task BlackSky under the EOCL contract. Direct access to tasking and active participation in managing orders was the primary user benefit over other commercial vendors for this 1 m imagery.

Appendix A. Listing of Evaluation Research Projects

Research using BlackSky data:

Water

- Evaluating BlackSky's commercial imagery for aquatic science applications (PI: Nima Pahlevan et al. - NASA GSFC, SSAI)
- Evaluation of data acquired by BlackSky Satellites for use in Identification of Melt Pond Formation on Arctic Sea Ice and Submerged Aquatic Vegetation in US coastal waters (PI: Victoria Hill et al. - Old Dominion University)
- Assessing BlackSky Data for surface water detection (PI: Beth Tellman et al. - University of Arizona)
- Evaluation of BlackSky imagery in detecting cyanobacteria blooms (PI: Chuanmin Hu et al. - University of South Florida)

Land

- Multi-Resolution Quantification and Driver Assessment of Hot Spots for Global Forest Disturbance (PI: Sasha Tuyukavina - University of Maryland)
- Evaluation of BlackSky Optical Imagery for burned area mapping applications (PI: David Roy et al. - Michigan State University)
- Very high resolution crop nitrogen uptake estimation (PI: Inbal Becker Reshef et al. - University of Maryland)
- Multi-source Wildland Urban Interface Characterization Enhanced with Machine Learning Technique: Dynamics and Hazard Assessment (PI: Yufang Jin - University of California, Davis)
- BlackSky Satellite Data for Terrestrial Ecosystem Studies (PI: Niall Hanan et al., - New Mexico State University)
- Carbon Cycle for Semi-Arid Regions (PI: Compton Tucker et al. - NASA GSFC)*
- Vegetation structure reconstruction with commercial stereo imagery: line scanner vs. frame imager and evaluation of technology trades (PI: Christopher Neigh et al. - NASA GSFC)
- BlackSky Assessment related to UAVSAR Imager (PI: Andrea Donnellan et al. - NASA JPL)

Cryosphere

- Evaluation of high-resolution snow covered area mapping in mountain ecosystems from Satellite imagery (PI: Nicoleta Cristea - University of Washington)
- Commercial Sensor Evaluation for Detection and Mapping of Snow Algae (PI: Alia Khan - Western Washington University)

Calibration and Geolocation Assessment

- Evaluate the calibration of BlackSky satellite data (PI: Eric Vermote, NASA GSFC)
- BlackSky Image Geometric Performance Assessment (PI: Gary Lin, NASA GSFC)
- Calibration analysis of BlackSky using MAIAC (PI: Alexei Lyapustin, NASA GSFC)

*CSDA Program selected for discipline evaluation support