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PHOTOGRAMMETRIC DIGITAL SURFACE MODELS AND ORTHOIMAGERY FOR THE CONTINUOUS COASTLINE, WALES TO PLATINUM, ALASKA

by
Jacquelyn R. Overbeck, Michael D. Hendricks, and Nicole E.M. Kinsman

September 2017

Orthoimage near Teller, Alaska (collected by Fairbanks Fodar, 2015).

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Note: *This report, including all digital data, explanations, and tables, is available in digital format from the DGGS website (http://dggs.alaska.gov, http://doi.org/10.14509/29744).*

PHOTOGRAMMETRIC DIGITAL SURFACE MODELS AND ORTHOIMAGERY FOR THE CONTINUOUS COASTLINE, WALES TO PLATINUM, ALASKA

by

Jacquelyn R. Overbeck[1], Michael D. Hendricks[1], and Nicole E.M. Kinsman[2]

Abstract

The State of Alaska Division of Geological & Geophysical Surveys contracted the acquisition of photogrammetric digital surface models (DSMs) and co-registered orthorectified aerial images (orthoimages) for the west coast of Alaska in support of coastal vulnerability mapping. This report describes the data collected continuously along approximately 3,500 km of coastline in the Norton Sound and Yukon–Kuskokwim Delta regions. Aerial photographs were collected between July 31, 2015, and May 7, 2016, with no data collection during the winter months between September 9, 2015, and May 1, 2016. The photographs were processed using Structure-from-Motion (SfM) photogrammetric techniques. Global Positioning System (GPS) checkpoints were collected via a Global Navigation Satellite System (GNSS) survey conducted between August 15 and September 14, 2015. For the purposes of open access to elevation and orthoimagery datasets in coastal regions of Alaska, this collection is being released as a Raw Data File with an open end-user license. The data will be made available as individual alongshore segments as they are processed for data viewing. Data products include an orthoimage raster and a Digital Surface Model (DSM) raster processed to 20 cm Ground Sample Distance (GSD) without vertical control. To access community-level data with higher-resolution GSD, vertical control, and minimal data gaps, see Overbeck and others (2016; http://doi.org/10.14509/29548).

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Data Acquisition

Fairbanks Fodar collected aerial photographs between July 31 and May 7, 2016, using a small aircraft (Cessna 170B) platform. The aerial survey was planned so flight lines and photograph frequency provided 60 percent side lap and 80 percent end lap photo coverage along with flying heights between 800 and 2,700 feet (244–823 m), resulting in 20 cm ground sample distance (GSD) of the aerial photos. A Nikon D800E with a 24 mm Nikkor f/1.4 lens was used to collect 36 megapixel photographs (7,360 × 4,912 pixels per image), in Joint Photographic Experts Group (JPEG) or Nikon Electronic Format (NEF), depending on location. Photos were collected at 1- to 3-second intervals. On-board global positioning system (GPS) data were acquired by a Trimble 5700 with roof-mounted antenna approximately 1 m above the camera, collecting at 5 Hertz. Each camera shutter trip placed an event marker onto the GPS datastream for precise timing and location. Detailed information on flying dates are shown in table 1.

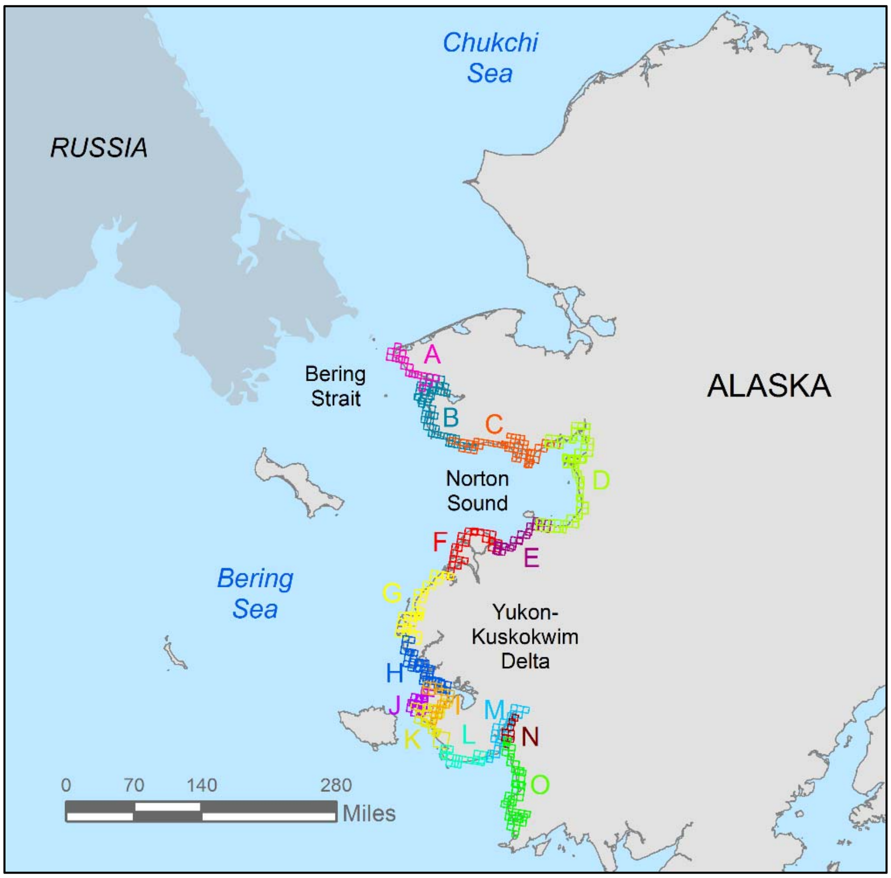

Figure 1. Data coverage map, with labelled alongshore segments.

Table 1. Parameters for alongshore data segments, with acquisition date, spatial reference, and release name.

Section	Prefix	Acquisition Dates	UTM Zone	Segment Name
Wales to Teller	Wales_Teller	August 27, 2015 – August 28, 2015	3	A
Teller to Nome	Teller_Nome	August 26, 2015 – August 27, 2015	3	B
Nome to Elim	Nome_Elim	August 23, 2015	3	C
Elim to Stebbins	Elim_Stebbins	July 30, 2015 – August 6, 2015	4	D
Stebbins to Kotlik	Stebbins_Kotlik	August 31, 2015	3	E
Kotlik to Nunam Iqua	Kotlik_NunamIqua	August 31, 2015	3	F

Nunam Iqua to Chevak	NunamIqua_Chevak	September 1, 2015	3	G
Chevak to Newtok	Chevak_Newtok	May 6, 2016	3	H
Newtok to Nightmute	Newtok_Nightmute	May 7, 2016	3	I
Newtok to Toksook Bay	Newtok_ToksookBay	September 1, 2015	3	J
Nightmute to Kipnuk	Nightmute_Kipnuk	September 9, -August 11, 2015	3	K
Kipnuk to Kongiganak	Kipnuk_Kongiganak	August 11, 2015 – August 12, 2015	3	L
Kongiganak to Bethel	Kongiganak_Bethel	August 12, 2015	3	M
Bethel to Eek	Bethel_Eek	May 1, 2016 – May 5, 2016	3	N
Eek to Goodnews Bay	Eek_GoodnewsBay	May 4, 2016 – May 5, 2016	4	O

Data Processing

Aerial survey GNSS data were processed using Waypoint's Grafnav commercial GNSS software using GPS constellation. Each project was processed using either post-processing kinematic (PPK) or precise point positioning (PPP) methods, depending on the quality of the solution, which was primarily dependent on the distance from Continually Operating Reference Stations (CORS), such that all flights resulted in data with better than 10 cm separation in forward and reverse trajectory solutions. GPS data were processed to the North American Datum 1983 (NAD83; 2011) European Petroleum Survey Group Well Known Identification Number (EPSG) 6318, and the North American Vertical Datum of 1988 (NAVD88; Geoid12A; EPOCH 2010.00).

Photos were individually processed for optimum contrast and exposure using Adobe Camera Raw. To accommodate the large data acquisition volumes, most photos were shot and processed to JPEG format.

Aerial survey GPS data (event marker coordinates) were manually correlated to image filenames using the image timestamp to create a camera external orientation file for import into Agisoft Photoscan Professional (Photoscan) software. The external orientation file provides the X, Y, Z position of the camera for each photograph taken during the survey. Aerial stereophotographs were imported into the photogrammetric software, which uses a SfM algorithm to create a three-dimensional terrain model from the stereo-imagery. The terrain model was then used to orthometrically correct the photos and produce the final orthoimage mosaic in Photoscan. Within the Photoscan software application, standard workflow steps were followed: photo-alignment, alignment optimization, dense point cloud building, mesh creation, DSM and orthoimage creation, and exporting the results.

Data Products

The data available for each of the alongshore segments consist of an orthoimage raster and DSM raster. These data are stored in NAD83 (2011) horizontal datum and projected in Universal Transverse Mercator (UTM) Zone 3 or 4 coordinate systems (meters; EPSG 6332 or 6333, respectively; table 1) relative to NAVD88 (Geoid12A; EPOCH 2010.00) vertical datum, as outlined in the accompanying metadata.

Orthoimagery

Orthoimages contain 4-band, 8-bit, unsigned raster data (red/green/blue/no data; file format–GeoTIFF; source–Fairbanks Fodar) with 20 cm GSD. No-data values are found in band 4 or shown as transparent in red/green/blue images. The file employs Lempel-Ziv-Welch (LZW) compression. Light exposures in the orthoimages are a result of daily weather conditions, which ranged from low cloud cover, rain, and full sun.

Digital Surface Model (DSM)

The single-band, 32-bit float DSMs represent surface elevations of buildings, vegetation, and uncovered ground surfaces in meters (file format–GeoTIFF; source–Fairbanks Fodar) with 20 cm GSD. The No Data value is set to -32767. The file employs LZW compression.

Data Quality

Specific dataset accuracy will be addressed in supplementary report sections released with each alongshore coastal segment (see table 1, Release Names); parameters computed for each dataset are described below. Known issues with elevation data derived from aerial photography are consistent between all datasets and are also addressed below. Continuous coastline data are in their raw format; for community-level orthoimagery and elevation data where vertical controls have been rigorously applied, see Overbeck and others (2016; http://doi.org/10.14509/29548).

Accuracy

Horizontal and vertical accuracies of the orthoimagery and DSMs are evaluated using photo-identifiable checkpoints (37 total) and elevation checkpoints (75 total) collected by RECON, LLC (Overbeck and others, 2016). ***Elevation data have not been vertically shifted to best fit checkpoint elevations***. Instead, GPS points have been used to assess the data quality only. The approach will allow the user to make informed decisions about how to vertically adjust the DSMs to best align with local vertical datums and/or meet project accuracy requirements. Data are not consistent across the entire region, meaning that two adjacent datasets may cover the same spatial region and contain different elevation values on the same point. The positional and vertical accuracies of each alongshore segment are evaluated separately, although there is spatial overlap between the datasets.

Accuracy assessment values that will be reported for each alongshore segment are the mean residual between non-vegetated ground control and checkpoints and the DSM. Positional (horizontal) accuracy has been determined by identifying ground control points visually and comparing their location to the GPS-collected ground control, quantified as the horizontal radial root mean square error ($RMSE_r$; ASPRS, 2015). The positional accuracy at 95% confidence level was also computed according to ASPRS (2015). Vertical accuracy was determined at the 95% confidence level according to ASPRS (2015), using checkpoints for non-vegetated and vegetated locations separately. Some checkpoints were collected over uneven ground such as boulder piles, which were considered “other” ground classification and used for positional accuracy alone. The number of ground control and checkpoints within each region will be reported for each alongshore segment.

Surface Model

Elevation data are digital surface models, not bare earth models. The elevation surface represents the land surface including vegetation, snow, houses, etc. Portions of the total dataset have snow coverage (fig. 3a) and others have dense vegetation (fig. 3b). Land cover type should be considered when using the elevation data.

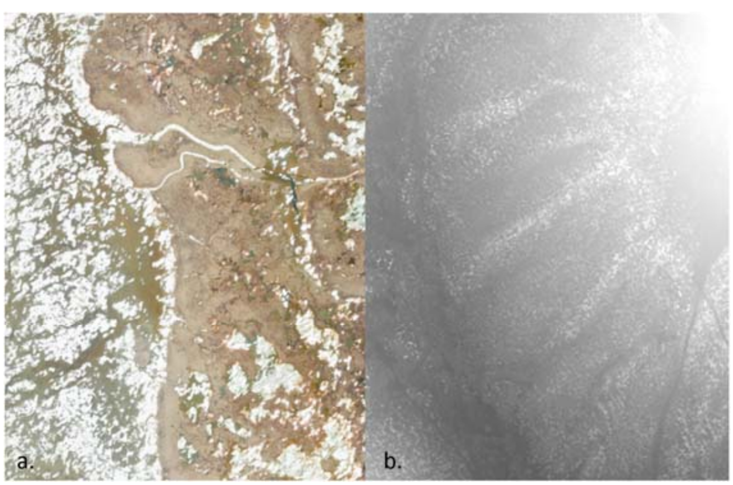

Figure 2. Snow cover on mudflats of the Yukon-Kuskokwim Delta (a), and rough surface from dense vegetation near Elim (b).

Data with Minimal Overlap

Data are not continuous for the entire area. Over certain regions with minimal overlap of aerial imagery, data holes exist within otherwise continuous data (fig. 3a). Other areas, near the edges of aerial photo coverage, have a corduroy pattern on the digital surface model with a relief of approximately 1 m (fig. 3b).

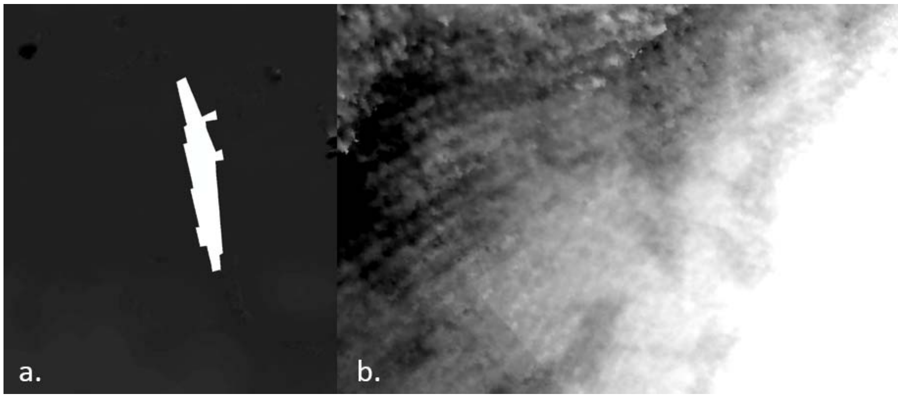

Figure 3. Data with visible hole where overlap was minimal or non-existent north of Hooper Bay (a), and example of minimal aerial photo overlap near the photo edges causing a corduroy pattern near Toksook Bay (b).

Anomalies over Water Bodies

Known anomalies exist on the DSMs over water bodies; these anomalies have not been edited or removed in this data release. Because waves in the nearshore marine or lacustrine environment move at a greater speed than photo-collection, the SfM processing technique for producing DSMs defines those points irregularly (for example, fig. 4).

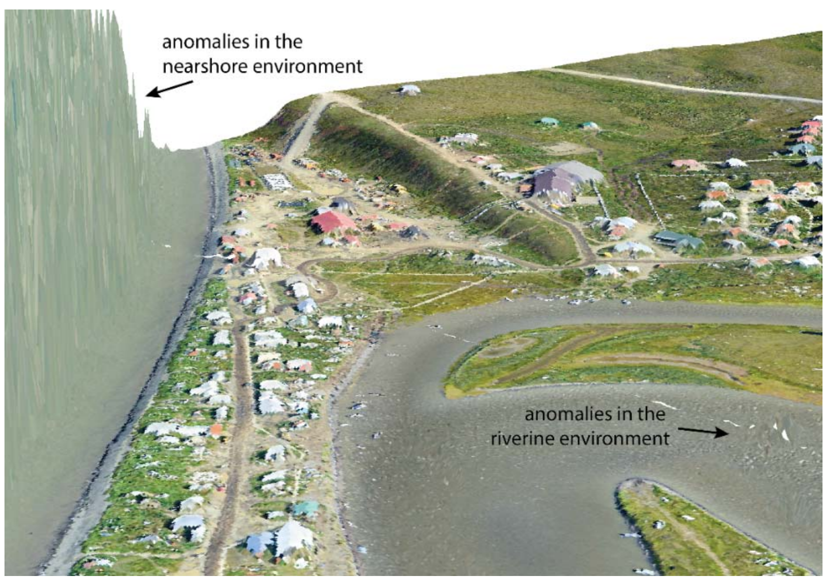

Figure 4. Example of anomalous elevation values over water at Tununak (from Overbeck and others, 2016).

Weather-related Anomalies

Cloud cover may obscure the imagery below and cause noise on the DSM, as shown in figure 5. Some data were collected where snow is in the air (i.e., actively falling or blowing)—figure 6 illustrates how features within the orthoimagery data are more difficult to distinguish under these conditions, although there were not enough GCPs over affected areas to assess the magnitude of potential elevation anomalies.

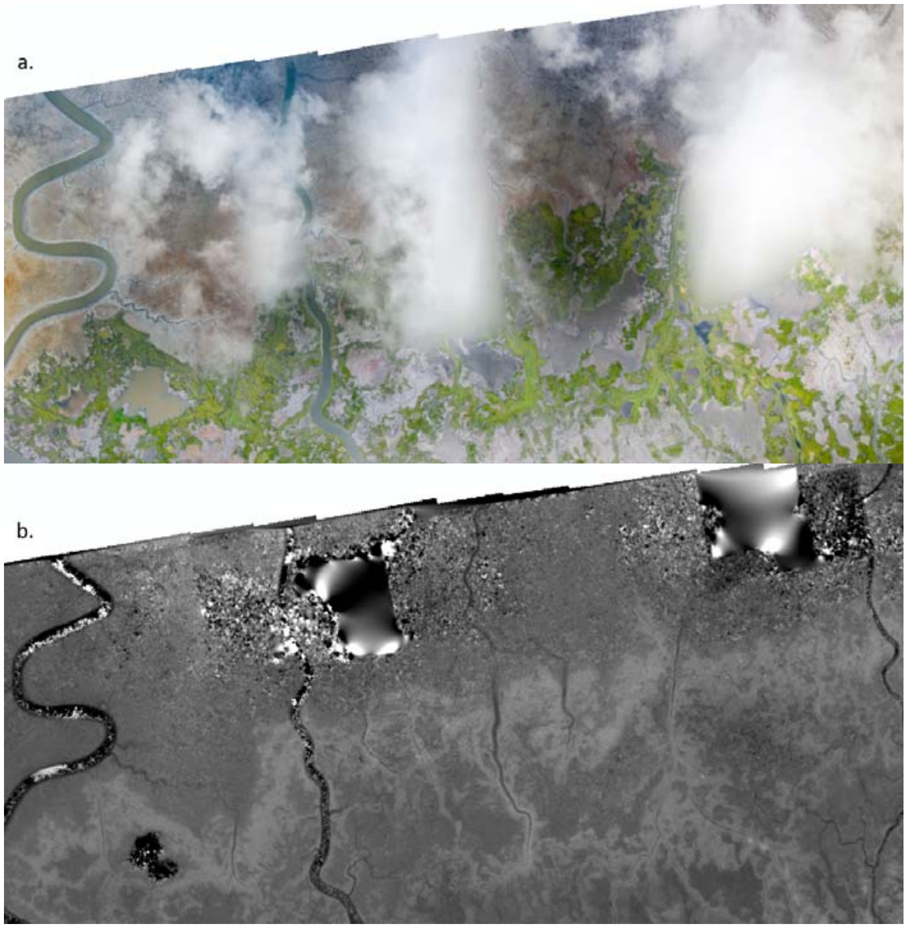

Figure 5. Clouds on Yukon-Kuskokwim Delta orthoimagery (a), and anomalous elevation data below the cloud cover (b).

Figure 6. Snow in air makes land features less distinguishable, north of Goodnews Bay.

Acknowledgments

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policies of the U.S. Government. Mention of trade names or commercial products does not constitute their endorsement by the U.S. Government.

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Contract 10-15-053

Final Report

28 July 2016

Submitted to

Alaska Department of Natural Resources

Orthoimage and DSM of mudflats and coast near Toksook Bay

Submitted by

Fairbanks Fodar

www.fairbanksfodar.com

Summary

This report describes the delivery of coastal data per terms of contract AK DNR Contract 10-15-053. ‘Coastal’ data in this context distinguishes this report and delivery from ‘village’ data collected in 2015 and delivered in January 2016. The delivered coastal data consists primarily of a DSM and orthomosaic at 20 cm posting covering roughly a 1500-2500 m swath of coastline extending roughly 1500 miles from Wales to Platinum at 9-17 cm ground sample distance acquired in 2015 and 2016 using fodar, a survey-grade SfM photogrammetric technique. Also included here are 3 of 7 villages (Goodnews Bay, Quinhagak, and Eek) added as an amendment to the contract in April 2016; the remaining 2016 village data will be delivered later along with an appendix to this report. The data delivered with this report meet or substantially exceed all specifications, including the vertical accuracy specification of +/- 39 cm, horizontal accuracy specification of +/- 49 cm, and AOI width of 1500 m (and occasionally more), with only a few exceptions as described in this report which in total amount to much less than our 5% cloud cover allowance.

1. A summary report of all completed field work with a description of each deliverable.

Field work in 2015 commenced on 30 July 2015, about a week after signing the contract, and ended on 12 September 2015. Flights totaled 14,262 miles, acquiring roughly 118,000 photos over about 94% of the intended coastline and about 85% of the overall project. As agreed, blog posts were made from the field on or shortly after each day of flying that detailed each flight, the weather, and the accomplishments that day with text and photos; most of this information will not be repeated here but links are given below and flight tracks can be found in the figures. All village data were processed and delivered beginning October 16 and in final form on 12 Jan 2016 along with a final report for those data; most of this information will not be repeated here. In spring 2016, we provided low resolution orthoimages for the entire 2015 dataset to validate coverage and discuss the 2016 AOI; the contract was subsequently amended to revise the 2015 AOI to complete the Hazen Bay coast, add a new section of coast from Bethel to Platinum, and add 7 villages. Field work in 2016 commenced on 30 April 16 and ended 8 May 18, acquiring roughly 25,000 photos to finish the coastal and inland areas, as well as 5 out of 7 villages added in the contract amendment; the remaining two villages (Bethel and Shaktoolik) will be acquired after this report is submitted and the data delivered with an appendix to this report, describing only deviations from the methods and formats described here, as well as any new ground control assessments.

Table 1. Dates of field acquisitions with links to blogs describing each flight. Our overnight bases were Unalakleet (Unk), Bethel, Nome, and St Mary's and unless otherwise indicated each flight began and ended at the same location.

30-Jul-15	Unalakleet	http://fairbanksfodar.com/success-in-unalakleet-again
5-Aug-15	Unk to Elim	http://fairbanksfodar.com/a-big-day-in-norton-sound
6-Aug-15	Unk to Stebbins	http://fairbanksfodar.com/coast-of-eastern-norton-sound-complete
10-Aug-15	Unk to Bethel	
11-Aug-15	Bethel to Kipnuk	
12-Aug-15	Bethel to Kong	http://fairbanksfodar.com/a-bit-better-weather-in-bethel
13-Aug-15	Bethel to Chevak	http://fairbanksfodar.com/a-happy-day-in-hooper-bay
14-Aug-15	Bethel to Nunam	http://fairbanksfodar.com/mapping-the-dash
19-Aug-15	Bethel to Kipnuk	http://fairbanksfodar.com/tiptoeing-over-tuntutuliak
21-Aug-15	Bethel to Toksook	http://fairbanksfodar.com/two-one-charlie-vs-the-toxic-avenger
22-Aug-15	Bethel to Unk	
23-Aug-15	Unk to Nome	http://fairbanksfodar.com/theres-no-place-like-nome
26-Aug-15	Nome to Cape Rodney	
27-Aug-15	Nome to Wales	http://fairbanksfodar.com/wales-russians-and-snow-oh-my
28-Aug-15	Nome to Wales	http://fairbanksfodar.com/saving-the-wales
29-Aug-15	Nome to St Marys	http://fairbanksfodar.com/the-bombs-of-st-marys
31-Aug	St Marys to Yukon Delta	
1-Sep-15	St Marys to Toksook	http://fairbanksfodar.com/mapping-the-golden-pixel
6-Sep-15	St Marys to Bethel	http://fairbanksfodar.com/west-coast-villages-complete
7-Sep-15	Bethel to Baird Inlet	
9-Sep-15	Bethel to Nightmute	http://fairbanksfodar.com/a-mile-wide-and-a-micron-deep-mapping-the-coastline-from-wales-to-bethel
1-May-16	Bethel to Eek, Kong, Kwig	http://fairbanksfodar.com/eek
4-May-16	Bethel to Platinum	http://fairbanksfodar.com/goodnews-sort-of
5-May-16	Bethel to Goodnews	http://fairbanksfodar.com/more-goodnews
6-May-16	Bethel to Hazen Bay	
7-May-16	Bethel to East Nelson Is.	http://fairbanksfodar.com/not-goodnews-great-news

Deliverables described by this report include:

- Digital Surface Models. These DSMs are described in more detail later in this report and in the figures, but consist of the entire 2015-2016 coastal area acquired at 9-17 cm GSD and posted at a uniform 20 cm for the entire area. We believe their geolocational accuracy to be well within the contract spec from ASPRS 2014 guidance based on our validation efforts here and in the past. No GCPs were used in DSM creation, only validation. Only one photogrammetric block required a shift to meet specs, described later, though below we give recommendations for additional shifts to achieve optimal alignment at the 10-20 cm level (that is, sub-specifications optimization). The DSM are provided as geotiffs, tiled as described later. Point clouds in .las format were also delivered as a courtesy using a similar tiling scheme and are not described further in this report.

- Orthomosaics. The individual photos were orthorectified using the delivered DSM and resulting mosaics output as geotiffs, tiled according to a similar naming convention as the DSMs. We believe their geolocational accuracy to be well within the contract specs based on our validation assessments.
- Tile Index. A tile index for the DSM and orthomosaics is provided in KML format.
- Flight lines. Flight lines for each mission day are provided in KML format, organized by flight date.
- Metadata. Metadata is embedded within each deliverable file suitable for use in any common GIS software. Our understanding is that the State will create FGDC metadata for this delivery based on the file metadata as well as our reports and blogs, as it did for our village delivery in January 2016; we are happy to assist with further information as needed.
- Raw data. Raw data provided includes the GPS files from the Trimble 5700 used in the airplane and all raw images acquired.

2. Overview of data delivery formats and file naming schemes

Both the DSMs and orthomosaics are delivered in geotiff format as described previously, just like the village data delivery in January. The vertical datum is NAVD88 Geoid12B and projected onto NAD83(2011) UTM 3, except for eastern Norton Sound which was processed in UTM 4. The region from Bethel to Platinum crosses the UTM 3/4 boundary several times and was processed only in UTM 3.

The coastal project (that is, not including the village data delivered in January) was broken into 11 blocks and each block given descriptive names based on location, listed below. Each of these segments was treated as a single photogrammetric block for alignment and bundle adjustment to ensure optimal alignment over the largest practical area. After this, some of these blocks were further divided into sub-blocks for DSM and ortho creation on multiple computers; note again that this occurred after the alignment and bundle adjustment, so these sub-blocks are perfectly aligned with each other. For example, the Wales2Nome block was broken into eastern and western sub-blocks. These sub-blocks were further broken down into processing chunks and output tiles, both with a row-column structure appended to the file name with a resulting format of {Block}_{subblock}_{Chunk}_{Type}_{Tile}.tif where {subblock} was optional. For example, file "Kotlik2Stebbins_Chunk_1-2_dem_20cm_0-1.tif" is a DSM from the Kotlik2Stebbins block, Chunk 1-2 (out of six chunks labelled 1-2 to 6-2), and tile 0-1 of Chunk 1-2. The orthomosaics have a similar structure, appended with "_ortho_20cm", using the same block and chunk labels, but different tiles due to data structure and layout. This structure was output from Photoscan and permits easy identification of the Photoscan Project each tile came from, in case reprocessing is necessary. Note that in some of the tables below and in various notes the block names are abbreviated, eg Chevak2Nunam is C2N. Chunks were processed and output with 1-3% overlap, but tiles within them have no overlap.

The exception to the block-subblock protocol described above occurred at Goodnews Bay. This block was the last processed and we were going to reprocess it to improve some issues with alignment that were in spec but could be improved. However, the State was eager to have all data in hand ahead of the deadline so rather than re-align the entire block we re-aligned only the northern half to save time. Without the mountains of the southern-half providing scale, the nearly flat northern half processed about 75 cm lower vertically, though spatially alignment was fine. Because different input data were used for the southern and northern sub-blocks, there are spatially-correlated noise differences on the order of 10-20 cm between them. Thus these two sub-blocks are not perfectly aligned as the others are, but are still well within spec, as shown in the figures. Reprocessing these fully as a single block would restore them to perfect alignment.

So the exceptions to this tiling nomenclature rule are the Hazen Bay and northern Goodnews Bay DSMs, which were raised in elevation and re-output from Global Mapper in a row-column format denoted by letters and number (eg, B-5). Each tile has an associated tile extent boundary in the provided KML file.

3. Details of executed data collection and data processing steps, explanation of any deviations from original Project Execution Plan, all processing steps including software and equipment used.

To our knowledge, no deviations occurred from the Project Execution Plan. All data were collected at a tide lower than MHW. Details of our data collection are provided in great detail in the blogs referenced above, which as agreed serve as a reference for this work. The equipment used in processing has been fully described in our quote, our Project Execution Plan, prior reports and in this paper (Nolan, Matt, Chris Larsen, and Matthew Sturm. "Mapping snow depth from manned aircraft on landscape scales at centimeter resolution using structure-from-motion photogrammetry." *The Cryosphere* 9, no. 4 (2015): 1445-1463), but in short consists of a Nikon D800E and a Trimble 5700 attached together to ultimately to provide photo centers accurate to within about 10 cm, flown in a Cessna 170B at a planned height of 2700' AGL but often as low as 1000' depending on weather. Flight lines were planned at 500 m spacing, but moved closer to accommodate lower flying heights in bad weather, and 4-6 lines were planned or flown over the entire coast. The processing workflow is also described fully in that paper, but in short includes using Agisoft Photoscan as the primary photogrammetric tool. Relevant settings in Photoscan include Aligning images at High, Optimizing, Building a Dense Point Cloud at High with Moderate Filtering, Building a Mesh at High, Building a DEM using the Mesh at 20 cm, and Building an Orthomosaic using the DEM at 20 cm. Once the data were all created, the blocks were compared to each other and to GCPs for both overall validation and network continuity. We found that all data were in spec and no further processing or shifting of the data occurred, except for the 2016 Hazen Bay block which we raised 35 cm and the northern section of Goodnews Bay block which we raised 75 cm.

4. Summary of field operations, including flight lines and data collection times.

Dates of field collections are given in Table 1 and each of the raw photos provided is stamped with EXIF data which includes time accurate to within a few seconds. All of the flight lines are provided in KML format.

Field operations are described in great detail within the blogs referenced in Table 1, but in short they consisted of a daily schedule of checking the weather in the early morning, making a decision as to which mission had the greatest likelihood of success given the weather, and either executing a mission or not. Every phase of all operations were conducted solely by Dr Matt Nolan, including mission planning, weather checking, flying and acquiring data, post-flight data validation, and subsequent data processing.

5. Coordinates of all ground control points that were used in the production of the final deliverables.

No GCPs were used in the production of the data delivered here and no new GCPs were collected by us. We did use the GCPs provided by the State to validate the data.

6. Full accuracy assessment for each delivered product consistent with the quality control laid out in the Project Execution Plan.

We assessed accuracy in three ways: 1) comparison to GCPs, 2) comparisons to previously delivered village data, and 3) comparisons at block overlaps. We assessed DSM misfit at every GCP provided in the coastal areas, but not necessarily every village GCP. Given that the bulk of the GCPs were located in villages and that the village data had already been reduced to those GCPs, we used villages DSM and orthos as pseudo-GCPs to get better statistics than actual GCPs alone could do; we chose only 1-2 villages, as noted, for each block for convenience. Similarly, we created raster difference DSMs at every block overlap to make assessments where no GCPs existed. At the end of each block we included one or more flight lines to extend into the adjacent block to help ensure continuity and provide better comparisons but without duplicating too much processing. We did not trim these data to provide the State with maximum of information. While the extended overlap regions are largely all within spec, some care needs to be taken when interpreting overlap misfits because often there are fewer flight lines utilized in these regions (sometimes only 1 flight line) and if the State uses these data in a WMS server as a single mosaic rather than blocks some care should be taken to trim the blocks where their widest swaths meet. The table below gives an overview of our results and is supported by numerous figures included at the end of this report. The 46 GCPs used in validation had a mean vertical misfit of 14 cm with a standard deviation of 22 cm. Only two GCPs were found outside of spec. Sinuk, was found outside spec (by 2 cm) and we assume given the misfit of the other 7 assessments in this block, including block overlaps, were all less than 25 cm that this point was an anomaly. Similarly, the Bald Head misfit was found to be 65 cm, and given that it was placed in a rock cairn and the other 7 assessments in this block, including block overlaps, were found to be < 25 cm, we again assume this point was an anomaly.

Data quality was also assessed by inspecting each tile visually. Overall, data quality is superb within the AOI and there should be no issues for using these data for their intended purpose and much more. Minor corduroy ripples can be found throughout at the 1-5 cm level; this is the level of random noise. There were perhaps half a dozen small gaps in coverage amounting to less than 1% of total area. There are three instances of processing artifacts in the form of a gap 3-5 pixels wide extending across several kilometers; most of these occurred outside the AOI and where it intersected the AOI it amounts to less than 0.01% of the total area. The origin of these artifacts is still unclear, but delivered as is in the interest of time. Spatially correlated errors are minor, caused by slight misalignment of one or more photos, and we found no instances where these exceeded 20 cm height error or about 5 pixels spatial error, amount to much less than 5% of the total area. Our experience has shown that such errors can really only be quantified by creating difference DEMs using a second acquisition. These results and prior experience have shown that the internal precision of the data is in the 10-20 cm range, such that spatially correlated errors can cause apparent differences of 20-40 cm in difference DEMs. However, even in the extreme cases, because these spatially-correlated errors stand out visually in a difference DEM, signals on the order of several centimeters change can still be detected through careful analysis in combination with the orthomosaics. On steep hillsides, careful examination of shaded reliefs can reveal seam lines between chunks, as the chunks overlap by 1-3% and their edges are constrained differently in mesh creation, but the offsets are only several centimeters at most.

Comparison with the delivered 2015 village data generally revealed minor misfits, all within spec. The coastal data used a mixture of both village and coastal data so it is not expected that they should be identical. Village data were typically acquired on a single day whereas each block of coastal data used data acquired on 2-6 days. Thus with coastal data, GPS from different days are used in the bundle adjustment, which attempts to make the best sense of any systematic errors in GPS data acquired on different days, and this is likely the biggest source of misfit. Further, village data were vertically fit to the GCPs, which likely led to some of them being overfit. Thus some care must be taken when using the 2015 village data for comparisons as any observed misfits may be due to the village data, which in many senses is the weaker photogrammetric solution due to its smaller area and lack of mountains. In one case, the Stebbins & St Michaels combined villages, there were no photo identifiable GCPs and it appears this already-accepted village suffers from the notorious WGS84-NAD83 offset.

The raster were not trimmed to the AOI boundary and thus we have substantially over-delivered inland of what was contracted. We did not rigorously assess the amount of bonus data, but it is likely on the order of 25%. Here various artifacts are larger and gaps more numerous, due to the decrease in sidelap on this inland edge. No significant variations in extent occurred in this delivery compared to the low resolution orthoimage we provided in February. The main reason for not cropping the AOI besides it being potentially useful was due to a shoreline vector not yet being made from these data, but additionally because we tried to start our lines at the water's edge to capture as much mudflat as possible, as discussed in our planning meetings. Thus our measurements of whether full width extents were delivered are in general based on a starting point ocean-ward of the actual MHW mark. There were only a few locations where full width extent was not achieved, notably in the mountainous area near Wales and Goodnews Bay, the southeast side of Nelson Island, and a 30 mile stretch on the south side of Toksook Bay where bad weather forced us to fly our lines lower repeatedly, amounting to under 3% of total area. As agreed, mountainous areas were not a priority and as far as we could determine (given how diffuse the MHW is in some locations), there are no gaps in MHW coverage throughout the entire AOI and an excellent vector of MHW location can be measured by a savvy and patient expert.

Other than the several small gaps and minor artifacts noted above and in the figures, we found no significant errors within the data and that all specs are exceeded. Given the generally poor weather, essentially every gap, minor artifact, and thin swath can be considered a cloud cover issue and out of the 5% allowance we believe these to amount to under 0.5% in total, though we did not calculate this rigorously and on balance this is dwarfed by the approximately 25% overdelivery in inland extent. The primary effect of our QA/QC was to catch blunders in processing. None of the blunders discovered caused the data to be out of spec, but we felt compelled to provide the best data possible. These took the form of outputting at the wrong resolution (always too high), missing some imagery as input, projection errors in GPS or photogrammetric processing, and the like, which were all solved by investigation and reprocessing. Thus though we did not use the GCP for the processing itself, they were useful in catching these blunders and we therefore believe that some form of ground control will always be useful, especially in large projects like these with ample opportunities for blunders.

Though the data were delivered several weeks before the contractual deadline, production speed could be significantly improved through lessons learned. By far the biggest delay in delivering these data was delivering the village data six months ahead of the contractual deadline to accommodate the State by providing the most publicly useful data first. That effort processed roughly 1/3 of the total photos and took 3.5 months, though a significant portion of that time was post-delivery effort. Because processing the coastal data incorporated the bulk of the village photos, the village delivery caused a duplication of effort of several months. Power outages due to winter storms and summer lightening probably caused another month of pure delay. These outages not only cause 4-5 days of processing to be repeated on several computers, but often they caused corruptions to earlier steps of processing already saved, and this corruption was only discoverable at the end of the second attempt of 4-5 days processing. This means reprocessing the earlier step a second time and the interrupted for a third time. Standard UPS have proven insufficient to prevent these interruptions reliably, as they do not have the power storage to power these large server computers long enough to hibernate depending on task and memory usage. Hardware failures and flaky hard disks also caused notable delays in troubleshooting and reprocessing. And of course the various blunders and improvement tweaks caused reprocessing efforts that suffer from all of the above. Despite these delays, processing still only took 5 months from start to delivery, which is a significant accomplishment in its own right for such a data set of such unprecedented magnitude and quality, though in the future an expedited delivery could likely be made within 3 month's time.

Table 2. Summary of validation assessments. See Figures for more details on these assessments. Negative vertical misfit mean that the DSM was higher than GCPs. Horizontal misfit of < 20 cm means that the GCP is as good as can be measured by eye (within a pixel). Many GCPs have no photoidentifiable targets in the orthomosaic, but all of those were found to be in the correct area based on the GCP field photos.

Block #	Block Name	GCPs, Overlap, or Village	Vertical Misfit	Horizontal Misfit
1	**Wales2Nome**	Lost River	-0.12	< 20 cm
		KTS2	0.08	coastal is ~40 cm south
		KTS3	0.25	coastal is ~20 cm south
		KTS7	-0.02	coastal is ~30 cm south
		Sinuk	0.51	< 20 cm
		Wales Village	0.15	< 40 cm
		Brevig Village	0.05	coastal is ~30 cm south
		N2E Overlap	< .2	"+/- 20 cm
2	**Nome2Elim**	ELI5	-0.1	< 20 cm
		Rocky Point	0.3	Not photoidentifiable (but looks right)

		Darby	0.2	< 20cm
		Bluff	0.1	Not photoidentifiable (but looks right)
		Soloman	0.09	Not photoidentifiable (but looks right)
		Elim	0	<20cm
		OME1	0.25	< 20 cm
		OME7	-0.16	coastal is ~20 cm south
		OME8	0.1	coastal is ~ 40 cm south
		Eli5	-0.1	< 20 cm
		Nome village	0	< 20 cm
		Elim village	0	< 20 cm
		W2N overlap	< .2	"+/- 20 cm
		Norton overlap	0	< 20 cm
3	**Norton UTM4**	Bald Head	0.658	not photoidentifiable (but looks good)
		Egavik	0.127	not photoidentifiable (but looks good)
		Oliver	0.277	not photoidentifiable (but looks good)
		Reindeer		
		Tolstoi	0.244	not photoidentifiable (but looks good)
		Ungalik	0.021	not photoidentifiable (but looks good)
		k2S overlap	0	< 20 cm
		N2E overlap	0	< 20 cm
4	**Kotlik2Stebbins**	Romanof	0.14	not photoidentifiable (but looks good)
		Kotlik village	0.1	< 20 cm
		Stebbins village	NA	Stebbins is 1.4 m off due to projection
		Norton overlap	0	< 20 cm
		Yukon overlap	-0.3	yukon is ~35 cm west of kotlik
5	**Yukon Delta**	Alakanuk	0.19	<20cm
		Emmonak	0.3	not photoidentifiable
		Emmonak Village	0.25	< 40 cm
		Kotlik village	0.25	
		K2S Overlap	0.3	yukon is ~35 cm west of kotlik
		C2N Overlap		N/A no overlap
6	**Chevak2Nunam**	Black	0.13	not photoidentifiable (but looks right)
		Melatolik	-0.05	not photoidentifiable
		Scammon	0.17	< 20 cm
		Towak	0.32	not photoidentifiable (and poor vertical gcp)
		Kokechik	0.19	not photoidentifiable

		Nunam	0.27	not photoidentifiable
		Hooper Bay	-0.14	< 20 cm
		Cheevak	0.01	< 20 cm
		Nunam Village	0.1	<20cm
		Hooper Village	0.1	< 20cm
		Yukon overlap	N/A	
		Hazen Bay overlap	-0.35	< 20 cm
7	**Hazen Bay**	Kashanuk	0.16	<20 cm
		Opagyarak	0.28	< 20 cm
		Manokinak	0.32	< 20 cm
		Naskonat	0	not photoidentifiable (but looks right)
		Newtok	0.1	< 20 cm
		Metarvik	0	not photoidentifiable (but looks right)
		Newtok village	0.1	< 20 cm
		C2N overlap	0	< 20 cm
		East Nelson overlap	-0.35	< 20cm
8	**East Nelson**	Metarvik	0.197	not photoidentifiable (but looks right)
		Chakchak	0.48	< 20 cm
		Hazen overlap	0	< 20 cm
		B2T overlap	NA	ramp in single pass
		Toksook overlap	0	< 20 cm
9	**Toksook**	Erhchakrtuk	0.26	not photoidentifiable (but looks right)
		Toksook	0.2	< 20 cm
		Tununak	-0.37	not photoidentifiable (but looks right)
		Toksook village	0.02	< 20cm
		Tununak	0.02	< 20 cm
		Hazen overlap	NA	no overlap
		B2T overlap	-0.2	
10	**Bethel2Toxic**	Koskovak	0.38	
		Kong	-0.04	< 20 cm
		Kwig	0.27	< 20 cm
		Loon	0.34	< 20 cm
		Nightmute	0.06	< 20 cm
		Kong village	-0.05	< 20 cm
		Toksook overlap	0.2	< 40 cm
		East nelson overlap	NA	ramp in single track

11	**Goodnews**	0609_001	-0.095	< 20 cm
		0609_003	-0.208	< 20 cm
		0609_0011	0.016	20 cm (but loose sheet metal)
		0609_0013	-0.137	< 20 cm
		0609_0014	-0.211	< 20 cm

Table 3. Suggested vertical and horizontal shifts for optimal sub-spec alignment.

	Block	**Move North**	**Move East**	**Move Up**
1	Wales2Nome	-0.25	0	0.15
2	Elim2Nome	-0.1	0	0.1
3	Norton_UTM4	0	0	0.1
4	Kotlik2Stebbins	0	0.2	0
5	YukonDelta	0	0.25	0.25
6	Chevak2Nunam	0	0	0.1
7	HazenBay	0	0	0
8	EastNelson	0	0	0.2
9	Toksook	0	0	0
10	Bethel2toxic	0	0	0.15
11	Goodnews	0	0	-0.1

7. All field notes, as well as all original raw data.

Our field notes consist solely of the blogs referenced in Table 1. The original data provided includes the Trimble 5700 data and the raw image files collected from the air. The Trimble data are all in a single directory using the original file names and the photos are organized in folders by acquisition date, separated further with folders by data card (eg, “CF1” or “SD3”) if applicable.